SUBJECT CODE : 304194

As per Revised Syllabus of

SAVITRIBAI PHULE PUNE UNIVERSITY

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T.E. (E & Tc) Semester - VI

POWER DEVICES & CIRCUITS

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PREFACE

The importance of **Power Devices & Circuits** is well known in various engineering fields. Overwhelming response to our books on various subjects inspired us to write this book. The book is structured to cover the key aspects of the subject **Power Devices & Circuits.**

The book uses plain, lucid language to explain fundamentals of this subject. The book provides logical method of explaining various complicated concepts and stepwise methods to explain the important topics. Each chapter is well supported with necessary illustrations, practical examples and solved problems. All chapters in this book are arranged in a proper sequence that permits each topic to build upon earlier studies. All care has been taken to make students comfortable in understanding the basic concepts of this subject.

Representative questions have been added at the end of each section to help the students in picking important points from that section.

The book not only covers the entire scope of the subject but explains the philosophy of the subject. This makes the understanding of this subject more clear and makes it more interesting. The book will be very useful not only to the students but also to the subject teachers. The students have to omit nothing and possibly have to cover nothing more.

We wish to express our profound thanks to all those who helped in making this book a reality. Much needed moral support and encouragement is provided on numerous occasions by our whole family. We wish to thank the **Publisher** and the entire team of **Technical Publications** who have taken immense pain to get this book in time with quality printing.

Any suggestion for the improvement of the book will be acknowledged and well appreciated.

Authors
Dr. J. S. Chitode
Dr. S. M. Kulkarni

Dedicated at the lotus feet of Lord Vitthal and Mother Rukmini.

SYLLABUS

Power Devices & Circuits - (304194)

Credit	Examination Scheme :
03	In - Sem(Theory) : 30 Marks
	End - Sem(Theory) : 70 Marks

Unit I Study of Power Devices

Construction, VI characteristics (input, output and transfer if any), switching characteristics of SCR, GTO, Power MOSFET and IGBT, Performance overview of Silicon, Silicon Carbide & GaN based MOSFET and IGBT, various repetitive and non-repetitive ratings of SCR, GTO , Power MOSFET & IGBT and their significance, requirement of a typical triggering / driver (such as opto isolator) circuits for various power devices, importance of series and parallel operations of various power devices (no derivation and numerical). **(Chapter - 1)**

Unit II AC to DC Power Converters

Concept of line & forced commutation, Single phase Semi & Full converters using SCR for R and R-L loads and its performance analysis and numerical, Effect of source inductance, Significance of power factor and its improvement using PWM based techniques, Three phase Full converters using SCR for R load and its performance analysis, Single Phase PWM Rectifier using IGBT, Three Phase Controlled Rectifier Using IGBT, Difference between SCR based conventional rectifiers and IGBT based rectifiers. **(Chapter - 2)**

Unit III DC to AC Converters

Single phase half and full bridge square wave inverter for R and R-L load using MOSFET / IGBT and its performance analysis and numerical, Cross conduction in inverter, need of voltage control and strategies in inverters, classifications of voltage control techniques, control of voltage using various PWM techniques and their advantages, concept and need of harmonic elimination / reduction in inverters, Three Phase voltage source inverter for balanced star R load with 120 and 180 degree mode of operation, device utilization factor, Advanced Converters like matrix inverter, multi-level inverters and their topologies and its driver circuits (no derivation and numerical). **(Chapter - 3)**

Unit IV DC to DC Converters

Classification of choppers, Step down chopper for R and RL load and its performance analysis, Step up chopper, various control strategies for choppers, types of choppers (isolated and non isolated) such as type A, B, C, D & E, switch mode power supply (SMPS) viz buck, boost and buck-boost, Fly back, Half and full Bridge isolated and non-isolated interleaved bidirectional topologies, and concept of integrated converter and design of LM3524 based choppers, concept of maximum power point tracking (MPPT). **(Chapter - 4)**

Unit V Power Devices Protection and Circuits

Over voltage, over current, di/dt and dv/dt protection circuits and their design, Various cooling techniques and heat sink design, Resonant converters such as Zero current switching (ZCS) and Zero voltage switching (ZVS), Electromagnetic interference such as radiated and conducted EMI, Difference between EMI and EMC, EMI sources and soft switching and minimizing / shielding techniques for EMI, Various EMI and EMC standards, Importance of isolation transformer. **(Chapter - 5)**

Unit VI Power Electronics Applications

AC Voltage Controller using IGBT & SCR, Fan Regulator, Electronic Ballast, LED Lamp driver, DC motor drive for single phase separately excited dc motor, BLDC motor drive, Variable voltage & variable frequency three phase induction motor drive, On-line and Off- line UPS, study of various selection criteria and performance parameters of batteries in battery operated power systems, battery charging models and modes for EVs, Architecture of EVs battery charger, PFC stage circuit topologies with details of Full-bridge boost rectifier and Full-bridge interleaved for EV battery charger, case study of power electronics in electric vehicle and photovoltaic solar system. **(Chapter - 6)**

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UNIT I

1 Study of Power Devices

Syllabus

Construction, VI characteristics (input, output and transfer if any), switching characteristics of SCR, GTO, Power MOSFET and IGBT, Performance overview of Silicon, Silicon Carbide & GaN based MOSFET and IGBT, various repetitive and non-repetitive ratings of SCR, GTO , Power MOSFET & IGBT and their significance, requirement of a typical triggering / driver (such as opto isolator) circuits for various power devices, importance of series and parallel operations of various power devices

Contents

1.1 Silicon Controlled Rectifier (SCR) SPPU : May-07, Dec.-11,13,18, April-17

1.1.1 Construction of SCR

- We know that SCR is a four layer device. Fig. 1.1.1 (a) shows the symbol of the SCR. It has three terminals : Anode (A), Cathode (K) and Gate (G). A small positive voltage between gate and cathode turns on the SCR.
- Fig. 1.1.1 (b) shows the detailed structure. The p^+ layer is doped at $10^{19}/cm^3$. The player is doped at $10^{17}/cm^3$. The p and p^+ layers from anode (A) of the SCR. The thickness of the p-layer is 30 to 50 μ m. The n^- layer is lightly doped. The doping level of this layer is $10^{14}/cm^3$. The width of n^- layer is 50 to 1000 μm. This layer absorbs depletion layer of the junction J_2.

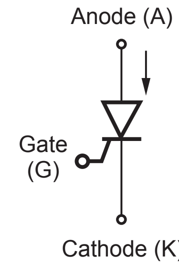
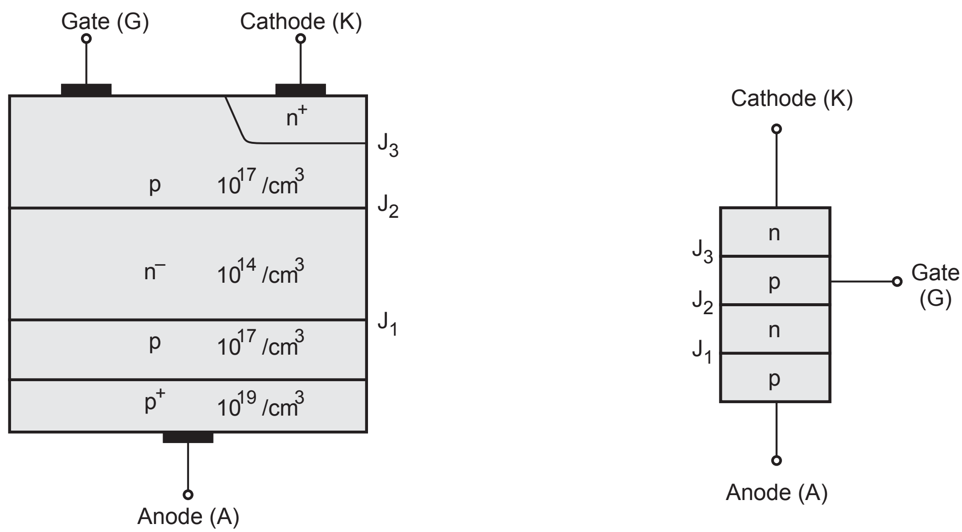


Fig. 1.1.1 (a) Symbol



(b) Structure of SCR **(c) Simplified structure of SCR**

Fig. 1.1.1

- When SCR is forward biased (V_{AK} positive), junction J_2 is reverse biased. And J_1 and J_3 are forward biased. The depletion layer of J_2 is absorbed by n^- layer when SCR is forward biased. The width of n^- layer decides forward blocking capability of the SCR. The next p-layer, having doping level of $10^{17}/cm^3$ forms the gate of SCR. The width of this layer is 30 to 100μ m. The next, i.e. n^+ layer (doping level of $10^{19}/cm^3$) forms the cathode of SCR.
- Fig. 1.1.1 (c) shows the simplified structure of SCR. The gate - cathode junction is J_3. When this junction is forward biased, (i.e. gate signal applied) SCR can be turn-on. Due to gate signal, current starts flowing across J_3. Some carriers flow across J_2 also.

Hence, internal regeneration starts and SCR turns on. This process is explained in detail with the help of two transistor analogy in next section.

1.1.2 Merits, Demerits and Applications of SCR

Merits of SCR

i. Very small amount of gate drive is required since SCR is a regenerative device.

ii. SCRs with high voltage and current ratings are available.

iii. On-state losses in SCRs are reduced.

Demerits of SCR

i. Gate has no control, once the SCR is turned on.

ii. External circuits are required to turn-off the SCR.

iii. Operating frequencies are very low.

iv. Snubbers (RC circuits) are required for dv/dt protection.

Applications of SCR

i. SCRs are best suitable for controlled rectifiers.

ii. AC regulators, lighting and heating applications.

iii. DC motor drives, large power supplies and electronic circuit breakers.

Review Questions

1. *Give the constructional details of a SCR. Sketch it schematic steady state diagram and the circuit symbol.* **SPPU : May-07, Marks 8; Dec.-11, Marks 6, Dec.-13, Marks 5**
2. *Draw the construction of SCR.* **SPPU : May-18, Marks 8**
3. *Explain construction and steady state characteristics of SCR.* **SPPU : April-17, Marks 6**

1.2 SCR Characteristics and Modes of Operation of SCR

SPPU : May-2000,01,02,03,06,07,08,10,11,13,17,18, Dec.-01,03,04,06,08,09,10,11, April-17,19,

The working of the SCR can be discussed into three modes : Reverse blocking mode, forward blocking mode and forward conduction mode. Fig. 1.2.1 shows the V-I characteristics of the SCR.

The characteristics shown in the Fig. 1.2.1 are called static characteristics. The anode to cathode current I_{AK} is plotted with respect to anode to cathode voltage V_{AK}. The voltage 'V_{BO}' is the forward break over voltage. 'V_{BR}' is the reverse break-down voltage. And I_{g1}, I_{g2}, I_{g3} are the gate currents applied to the SCR.

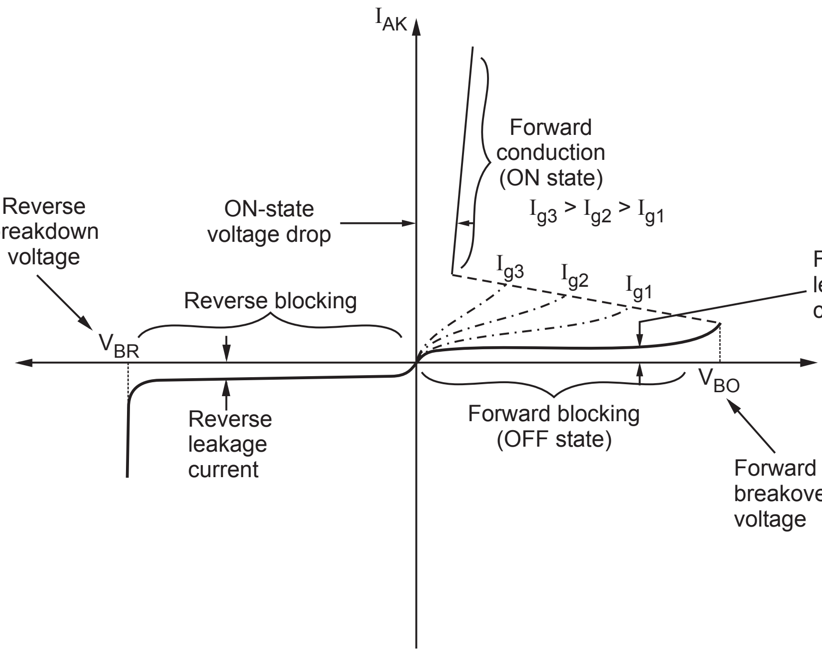


Fig. 1.2.1 Steady state or static V-I characteristics of a SCR

1.2.1 Reverse Blocking Mode

Fig. 1.2.2 shows the situation when the thyristor will be in reverse blocking mode.

In the above figure, observe that the anode (A) is made negative with respect to cathode (K). The gate is kept open. There are three PN junctions in the SCR : J_1, J_2 and J_3. Due to this reverse bias, junctions J_1 and J_3 are also reverse biased. And junction J_2 is forward biased. The SCR does not conduct due to this reverse bias. A very small current flows from cathode to anode. This current is called *reverse leakage current* of the SCR. This mode is called reverse blocking mode. Fig. 1.2.1 shows the characteristic of SCR in reverse blocking mode. Observe that reverse voltage increases but very small current flows. At reverse break down voltage (V_{BR}), the reverse current increases rapidly. At the time of reverse breakdown, the high voltage is present across the SCR and heavy current flows through it. Hence large power dissipation takes place in the thyristor. Due to this dissipation, the junction temperature exceeds the permissible value and the SCR is damaged. Hence a reverse voltage across the SCR should never exceed V_{BO}. it should be Vbr i guess?

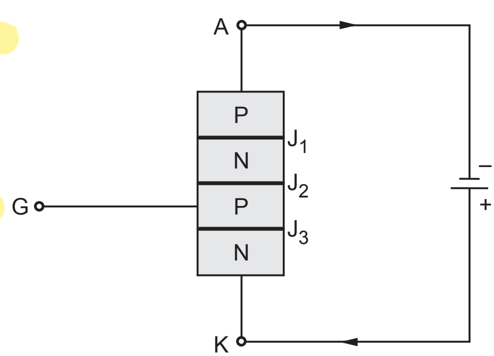


Fig. 1.2.2 A reverse biased SCR

During the reverse blocking mode, the positive gate signal should not be applied. If the positive signal is applied between gate and cathode, junction J_3 is forward biased. Hence current starts flowing through it. This current adds to reverse leakage current of the SCR. Hence dissipation is also increased.

1.2.2 Forward Blocking Mode

The SCR is said to be forward biased when anode is made positive with respect to cathode as shown in Fig. 1.2.3. Due to this forward bias the junction J_1 and J_3 is forward biased and J_2 is reverse biased. Hence the forward voltage is to be hold by junction J_2. A very small current flows from anode to cathode. This current is called forward leakage current. This current is of the order of few milliamperes. In the forward blocking mode, the thyristor is forward biased but it does not turn-on. In the forward blocking mode a very small forward leakage current flows. In the forward blocking mode the voltage (V_{AK}) can be increased till V_{BO}. This situation is shown in Fig. 1.2.1. When the forward voltage reaches V_{BO}, the SCR turns on. The SCR goes from forward blocking mode to forward conduction mode. Normally gate drive is applied for this purpose. The highest voltage to be sustained in forward blocking mode is forward break-over voltage, V_{BO}.

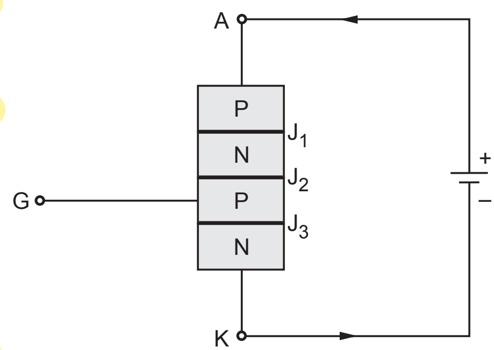


Fig. 1.2.3 SCR in forward biased condition

When the voltage increases above V_{BO}, the SCR goes into forward conduction mode (i.e. turns-on) even if gate drive is not applied. Thus SCR is not damaged if voltage $V_{AK} > V_{BO}$, rather it is turned-on.

1.2.3 Forward Conduction Mode

When the SCR is forward biased, then it can go into forward conduction by following techniques :

i) When $V_{AK} > V_{BO}$

ii) When gate drive is applied

iii) When $\frac{dv}{dt}$ exceeds permissible value

iv) When gate cathode junction is exposed to light

Here note that the SCR can go in the forward conduction mode only if it is in the forward blocking mode earlier.

i) When $V_{AK} > V_{BO}$

The SCR is driven into forward conduction mode when anode to cathode voltage (V_{AK}) exceeds the forward break-over voltage (V_{BO}). The SCR is said to have *turned-on* when it operates in forward conduction mode. When $V_{AK} > V_{BO}$, the SCR is driven in forward conduction even if gate is open. From Fig. 1.2.3, it is clear that junction J_2 is reverse biased during forward blocking mode $(V_{AK} < V_{BO})$. When V_{AK} exceeds V_{BO}, the avalanche break-down of junction J_2 takes place even if gate drive is not applied. Hence heavy current starts flowing through the SCR and anode to cathode voltage falls to very small value. This is shown in Fig. 1.2.1. The dotted line (...........) indicates switching of SCR from forward blocking state (i.e. OFF) to forward conduction state (i.e. ON). The anode to cathode current of the SCR is only limited by the load. Fig. 1.2.4 shows such situation :

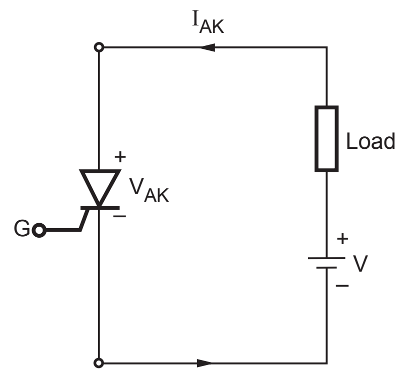


Fig. 1.2.4 Use of SCR in forward conduction

When the SCR conducts in the forward conduction mode, it is said to have turned 'ON'. The anode to cathode voltage is less than 2 volts. This voltage is normally neglected in calculations. Then the current through the load and SCR will be,

$$I_{AK} = \frac{V}{Load} \quad \text{... (1.2.1)}$$

Thus the SCR current is only limited by the load, once the SCR turns 'on'.

ii) When gate drive is applied

A positive gate to cathode signal is applied whenever the SCR is to be driven into forward conduction mode (ON state). This is also called *gate triggering* of the SCR. Such situation is shown by the typical circuit of Fig. 1.2.5. The SCR is in forward blocking mode when gate drive is not applied. When the positive gate to cathode voltage is applied, current flows from gate to cathode. This current adds to the forward leakage

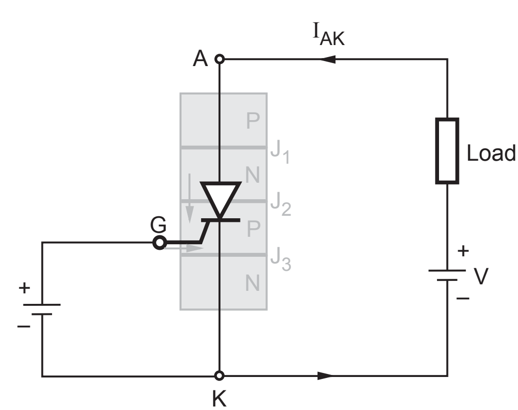


Fig. 1.2.5 Gate triggering is used to turn-on the SCR

current. Hence avalanche break-down of junction J_2 takes place at lower anode to cathode voltage also. Thus SCR is driven into forward conduction mode (ON state) even if $V_{AK} < V_{BO}$. Fig. 1.2.1 shows the characteristic by center (–·–·–·–) lines when gate drive is applied. Observe that, as the gate current is increased, the SCR turns-on at lower values of anode to cathode voltages. All these anode to cathode voltages are less than V_{BO}. Thus gate triggering is the most convenient way of triggering the SCR.

Once the thyristor goes into forward conduction mode, the gate has no control over the conduction of thyristor. The current I_{AK} is only limited by the load, i.e.,

$$I_{AK} = \frac{\text{V}}{\text{Load}}$$

The SCR cannot be driven back into forward blocking mode by removing the gate drive. There are some other techniques. We will discuss those techniques next.

iii) When $\frac{dv}{dt}$ exceeds permissible value

Here $\frac{dv}{dt}$ is the rate of change of anode to cathode voltage with respect to time. Whenever the SCR is in forward blocking state, only forward leakage current flows through the SCR. In such state an equivalent internal capacitor is formed inside the SCR from anode to gate and gate to cathode. Fig. 1.2.6 shows such internal circuit. Whenever the voltage applied across the SCR changes rapidly, a transient current flows through the SCR. This transient current flows due to rapid voltage variations $\left(\frac{dv}{dt}\right)$ and internal capacitance. This current adds to the forward leakage current. And hence the SCR turns on even if $V_{AK} < V_{BO}$ or gate drive is not applied.

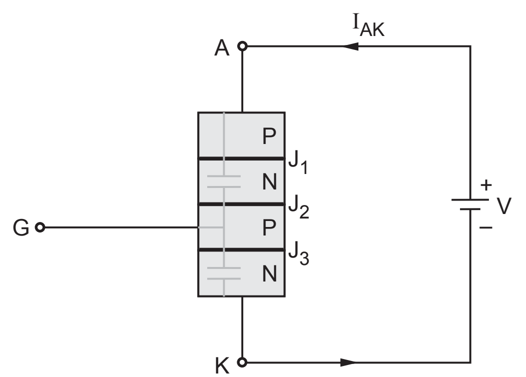


Fig. 1.2.6 SCR turns on by $\frac{dv}{dt}$ due to current flow in equivalent internal capacitor

The $\frac{dv}{dt}$ turn-on makes false triggering (unwanted) of the SCR. It is never used for triggering. Every SCR has $\frac{dv}{dt}$ rating. It is expressed in volts per microseconds $(\text{V} / \mu\ \text{s})$. The voltage variations across the SCR must be kept less than permissible value of $\frac{dv}{dt}$ to avoid false triggering. Normally a small resistance is connected between gate and cathode to avoid false triggering of SCR due to $\frac{dv}{dt}$. This resistance acts as a external path for leakage current generated by the internal capacitor.

iv) When a gate cathode junction is exposed to light

When the gate cathode junction is exposed to a beam of light, the current flows in the junction due to photons of light. This current acts as a gate drive to the SCR and it is driven into conduction. This type of triggering is normally used in light activated SCRs (LASCR).

1.2.4 Latching and Holding Currents

Now let us briefly discuss the two important currents which flow through the SCR. These currents are : latching current and the holding current.

1.2.4.1 Latching Current (I_L)

Consider that the SCR is in forward blocking state. Then the SCR can be turned-on by applying a gate drive. Then the SCR goes into forward conduction mode (ON state). For the SCR to remain in the 'ON' state, the anode to cathode current (I_{AK}) must be greater than *latching current*. i.e.,

$I_{AK} \geq I_L$; to remain in ON state after triggering. Fig. 1.2.7 shows the V-I characteristics of the SCR showing latching current.

Observe that latching current is the lowest current which flows through the SCR to remain in forward conduction (ON state) after triggering. If the current through the SCR is less than latching current, then the SCR goes back into forward blocking state as soon as gate drive is removed. This is said to be SCR is not *latched* (i.e. not turned-on).

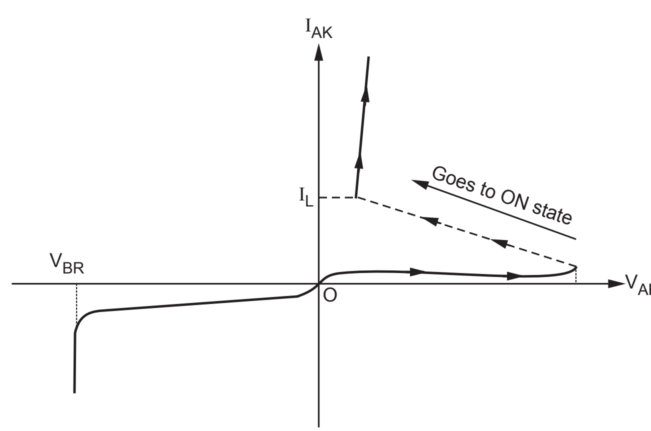


Fig. 1.2.7 V-I characteristics of the SCR showing latching current

From the above discussion, the latching current can be defined as follows :

> *Latching current is the minimum forward current that flows through the SCR to keep it in forward conduction mode (i.e. ON state) at the time of triggering. If forward current is less than latching current, SCR doesnot turn-on.*

The latching current is of the order of 10 to 15 milliamperes.

1.2.4.2 Holding Current (I_H)

Consider that the SCR is in forward conduction state (i.e. ON state). The SCR goes into forward blocking state when current through it falls below *holding current* (I_H). i.e., if $I_{AK} < I_H$; SCR turns-off. Fig. 1.2.8 shows the V-I characteristics of the SCR showing holding current.

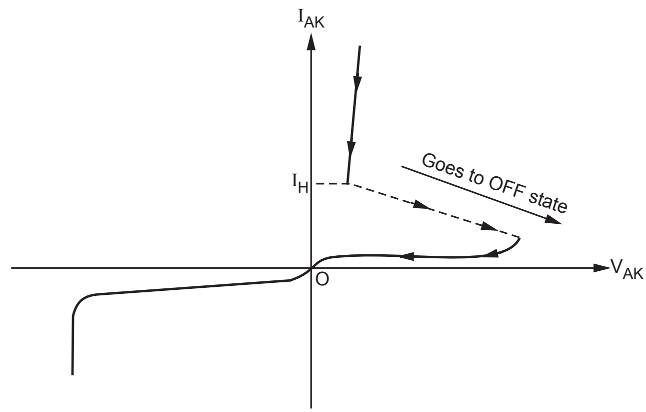


Fig. 1.2.8 V-I characteristics of the SCR showing holding current

Observe that the holding current is the lowest current below which SCR turns-off. In other words we can say that, for the SCR to remain in ON-state, its forward current should not reduce below holding current. From the above discussion, the holding current can be defined as follows :

> *Holding current is the minimum forward current that flows through the SCR to keep it in forward conduction mode. When forward current reduces below holding current, SCR turns-off.*

The holding current of the SCRs is of the order of 8 to 10 milliamperes.

1.2.4.3 Comparison (Difference) between Holding and Latching Currents

The definitions of holding current and latching current appear similar but they are totally different. The differences are mentioned below :

1. Latching current is effective at the time of turning-ON, whereas holding current is effective at the time of turning-OFF the SCR.
2. Latching current is the minimum current that should flow at the time of triggering to turn-ON the SCR. Whereas once the SCR is already in ON-state, its current should not reduce below holding current otherwise it turns-OFF.
3. Latching current is greater than holding current even though their magnitudes are much related.

1.2.5 Two Transistor Model of SCR

The operation of the SCR can be explained with the help of two transistor model. Fig. 1.2.9 shows how the two transistor model of the SCR is formed.

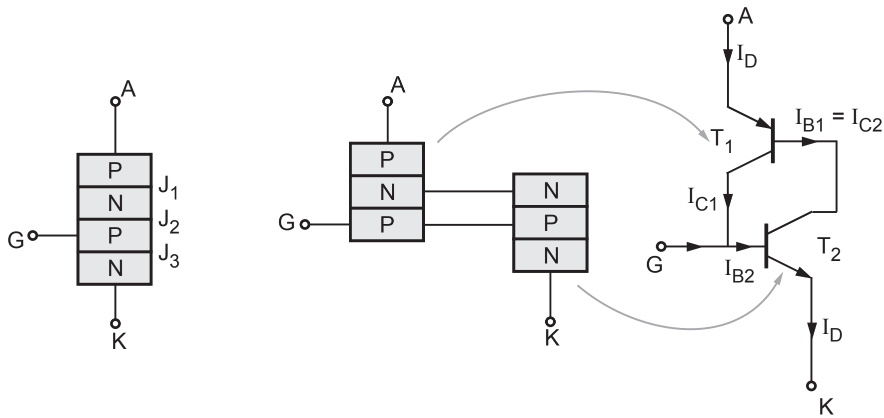


Fig. 1.2.9 A two transistor model of the SCR

As shown in Fig. 1.2.9 (b), the middle two layers are split into two separate parts. Because of this, the two transistors are formed. These transistors are shown in Fig. 1.2.9 (c). The transistor T_1 is pnp, whereas T_2 is npn. The base of T_1 is connected to collector of T_2. Similarly base of T_2 is connected to collector of T_1. These transistors are in common base configuration. When the SCR is forward biased and gate is open, various currents flow as shown in Fig. 1.2.19 (c). As shown in this figure, the anode to cathode current is I_D. The collector current, emitter current and leakage currents of T_1 are related as,

$$I_{C_1} = \alpha_1 I_{E_1} + I_{CO_1} \quad \text{... (1.2.2)}$$

Here $I_{E_1} = I_D$ and I_{CO_1} is leakage current of T_1. Similarly for T_2,

$$I_{C_2} = \alpha_2 I_{E_2} + I_{CO_2} \quad \text{... (1.2.3)}$$

Here $I_{E_2} = I_D$ and I_{CO_2} is leakage current of T_2.

Therefore equation (1.2.2) and (1.2.3) can be written as,

$$\left.\begin{array}{l} I_{C_1} = \alpha_1 I_D + I_{CO_1} \\ I_{C_2} = \alpha_2 I_D + I_{CO_2} \end{array}\right\} \quad \text{... (1.2.4)}$$

In Fig. 1.2.9 (c), observe that the current I_D flows through the collectors of T_1 and T_2. Hence we can write,

$$I_D = I_{C_1} + I_{C_2}$$

Putting the values from equation 1.2.4 in above equation,

$$I_D = \alpha_1 I_D + I_{CO_1} + \alpha_2 I_D + I_{CO_2}$$

$$\therefore \quad I_D = (\alpha_1 + \alpha_2) I_D + I_{CO_1} + I_{CO_2}$$

$$\therefore \quad I_D = \frac{I_{CO_1} + I_{CO_2}}{1 - (\alpha_1 + \alpha_2)} \qquad \text{... (1.2.5)}$$

$I_{CO_1} + I_{CO_2}$ can be considered as total reverse leakage current of junction J_2. This current can be denoted by the I_{CO}. Then above equation can be written as,

$$\boxed{I_D = \frac{I_{CO}}{1 - (\alpha_1 + \alpha_2)}} \qquad \text{... (1.2.6)}$$

Here I_{CO} is the reverse leakage current of the reverse biased junction J_2. And α_1 is the common base current gain of T_1 and α_2 is common base current gain of T_2. Initially when forward voltage is small, $(\alpha_1 + \alpha_2)$ is very small and less than 1. Hence forward blocking current as given by equation 1.2.6 is also small. As forward voltage applied across the SCR increases, the values of α_1 and α_2 also increase. When $(\alpha_1 + \alpha_2)$ tends unity, then I_D approaches infinity as given by equation 1.2.6. At this instant, internal regeneration starts and the SCR goes into forward conduction (ON-state) mode. The current through the SCR is only limited by the external load.

Once the SCR goes into conduction, the two transistor model is no more applicable. Here note that the internal regeneration takes place in the SCR due to avalanche breakdown of reverse biased junction J_2. It does not take place when SCR is reverse biased. When the current through the SCR falls below holding current, the forward blocking state is regained. Then α_1 and α_2 of transistors are also reduced to small values.

When the gate current I_g is applied, then equation 1.2.6 will be written as,

$$\boxed{I_D = \frac{I_{CO} + I_g}{1 - (\alpha_1 + \alpha_2)}} \qquad \text{... (1.2.7)}$$

Thus the forward leakage current (I_D) is increased due to gate drive (I_g). This leakage current flows through junction J_2 and its avalanche break-down occurs at lower forward voltage. Thus with the gate drive, the SCR is turned on at voltages less than V_{BO}. Hence gate becomes convenient way of triggering the SCR. Once the SCR is turned-on, the gate has no control over its conduction.

1.2.6 Examples for Understanding

Example 1.2.1 *The SCR shown in Fig. 1.2.10 has the latching current of 20 mA and is fired by the pulse of width 50 μ sec. Determine whether the SCR triggers or not.*

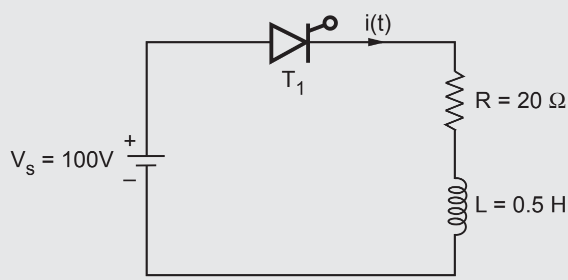


Fig. 1.2.10 Circuit of example 1.2.1

Solution : A step of voltage is applied to the R-L load when SCR turns on. The current through the RL circuit for step input is given as,

$$i(t) = \frac{V_s}{R}\left(1-e^{-t\frac{R}{L}}\right) \qquad \text{... (1.2.8)}$$

Fig. 1.2.11 shows the gate pulse and current waveform. Here observe that the SCR will be latched (triggered) if $i(t)$ is greater than latching current when gate triggering pulse is removed after 50 μ sec. Hence let us calculate current $i(t)$ through the SCR at 50 μsec,

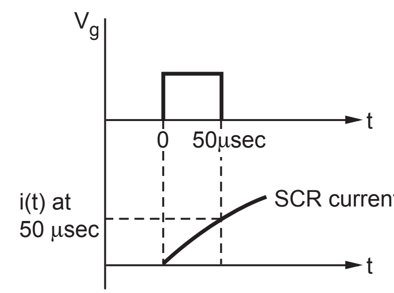


Fig. 1.2.11 After 50 μ sec, $i(t) > I_L$ to trigger the SCR properly (triggered)

$$i(t) = \frac{100}{20}\left(1-e^{-50\times10^{-6}\times\frac{20}{0.5}}\right) = 10 \text{ mA}$$

Here note that current through the SCR is 10 mA. It is not reached to the latching current level and trigger pulse is removed at 50μsec. Hence the SCR will not be triggered.

Example 1.2.2 *A SCR is connected in series with a RL load and is fed from a 115 V, 60 Hz AC supply. The load resistance is 25 Ω and load inductance is 0.25 H. If a firing pulse of 60 μs is applied at a firing angle of 45°, what is the maximum permissible latching current of the SCR to ensure turn-on.*

Solution : Fig. 1.2.12 shows the circuit diagram. The input voltage is,

$$V_s = V_m \sin\omega t = 115\sqrt{2}\sin 45° = 115$$

Thus the input voltage at the time of turning on is 115 V.

Current through RL circuit is given as,

$$i(t) = \frac{V_s}{R}(1-e^{-t\frac{R}{L}})$$

$$= \frac{115}{25}(1-e^{-t\frac{25}{0.25}})$$

$$= 4.6\,(1-e^{-100\,t})$$

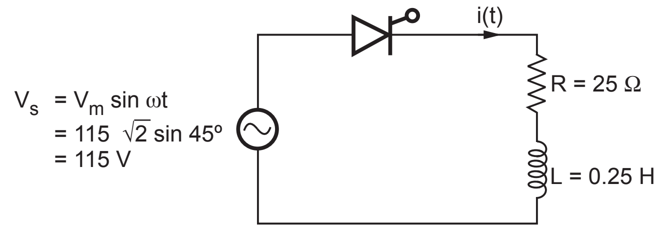


Fig. 1.2.12 RL circuit

Since the firing pulse is of 60 μsec, the current at the end of firing pulse is,

$$i(t) = 4.6(1-e^{-100\times 60\times 10^{-6}}) \text{ with t = 60 μsec}$$

$$= 27.5 \text{ mA}$$

Thus the maximum latching current must be 27.5 mA to ensure turn-on.

Example 1.2.3 *The latching current of an SCR used in a phase controlled circuit, comprising an inductive load of R = 10 Ω and L = 0.1 H is 15 mA. The input voltage is 325 sin 314 t. Obtain the minimum gate pulse width required for reliable triggering of the SCR if gated at $\frac{\pi}{3}$ angle in every positive half cycle.*

Solution : Fig. 1.2.13 shows the circuit diagram of this example.

Thus SCR is triggered at $\frac{\pi}{3}$. Hence applied voltage at this angle will be,

$$V_s = 325 \sin\frac{\pi}{3} = 281.458 \text{ volts.}$$

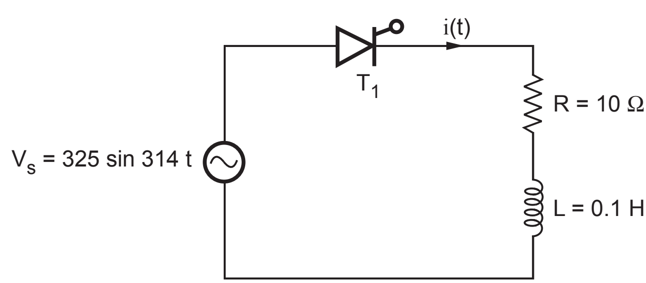


Fig. 1.2.13 Circuit of example 1.2.3

Thus 281.458 volts is applied at the time when SCR is triggered. For short duration (till SCR turns on) this voltage can be considered constant. The current through load is then given by equation 1.2.8 as,

$$i(t) = \frac{V_s}{R}\left(1-e^{-t\frac{R}{L}}\right)$$

In this equation we have to determine the pulse width when SCR triggers successfully. SCR will be triggered successfully when $i(t) = I_L$ = 15 mA. Putting other values in above equation.

$$15 \times 10^{-3} = \frac{281.458}{10}\left(1 - e^{-t\frac{10}{0.1}}\right)$$

Solving the above equation,

$$t = 5.33 \ \mu \text{ sec}$$

Thus, the minimum gate pulse should be 5.33 μ sec to reliably turn-on the SCR

Example 1.2.4 *A SCR has a forward breakover voltage of 175 volts when a gate pulse of 2 mA is made to flow. Find the conduction angle if a sinusoidal voltage of 350 V peak is applied.*

Solution : When the gate pulse is applied, the SCR turns on at 175 volts. The applied voltage is,

$$v_s = 350 \sin \omega t$$

when v_s reaches to 175 SCR will turn on. i.e.

$$175 = 350 \sin \omega t$$

Hence the value of conduction angle (ωt) will be,

$$\therefore \quad \omega t = 30°$$

Thus, at 30°, SCR will turn-on.

1.2.7 Examples with Solution

Example 1.2.5 *In the SCR circuit shown in Fig. 1.2.14 below, the SCR has a latching current of 50 mA and is fired by a pulse of length 50 μ sec. Show that without resistance R, the SCR will fail to remain on, when the firing pulse ends and then find the maximum value of R to ensure firing.*

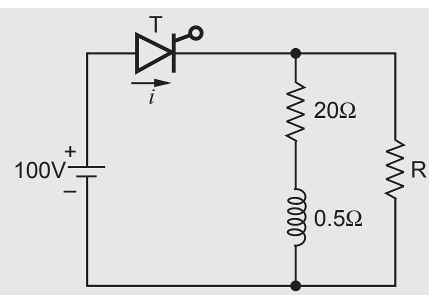


Fig. 1.2.14 SCR circuit of example 1.2.5

Solution : To show that SCR does not latch

Here first consider the SCR circuit without resistance R. This circuit is shown below in Fig. 1.2.15.

For this circuit the given data is,

$$V_s = 100$$

$$R = 20 \ \Omega$$

$$L = 0.5 \text{ H}$$

$$I_L = 50 \text{ mA}$$

$$\text{Pulse width} = 50 \ \mu s$$

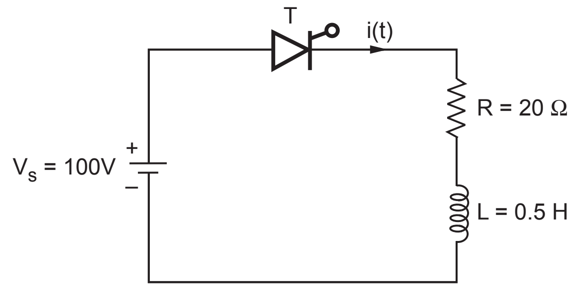


Fig. 1.2.15 SCR circuit of example 1.2.5 without R

Now let us check whether the SCR current rises above latching current in the firing pulse duration of 50 μs. The current in the RL circuit is given by equation (1.2.8) as,

$$i(t) = \frac{V_s}{R}\left(1-e^{-t\frac{R}{L}}\right)$$

Putting the value of R, L and V_s

$$i(t) = \frac{100}{20}\left(1-e^{-t\frac{20}{0.5}}\right) = 5(1-e^{-40t})$$

The current after t = 50 μs will be,

$$i(t=50\mu s) = 5(1-e^{-40\times 50\times 10^{-6}}) = 9.99\times 10^{-3} \approx 10 \text{ mA}$$

Thus during the firing pulse width of 50 μs, the SCR current rises upto 10 mA. Since this current is less than latching current of 50 mA. SCR will fail to remain on when firing pulse ends.

To determine value of R

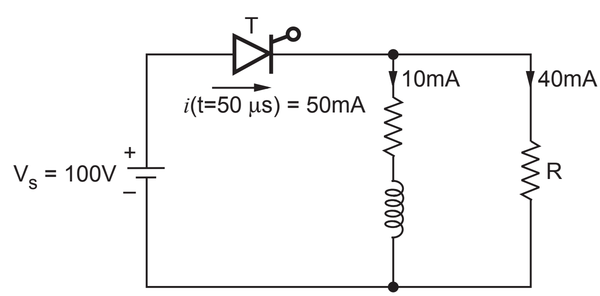


Fig. 1.2.16 Currents at t = 50 μs

The additional resistance connected in parallel with RL circuit increases the current through SCR. SCR takes 10 mA current when firing pulse of width 50 μs ends. To latch the SCR, 50 mA current should be passed through it. Hence additional 40 mA current can be passed through 'R' as shown in Fig. 1.2.16.

If we neglect the voltage drop in the SCR, full V_s will appear across R.

Hence,

$$V_s = 40\,mA \times R$$

$$\therefore \quad R = \frac{V_s}{40\,mA} = \frac{100}{40\times 10^{-3}} = 2500 \ \Omega$$

Thus a maximum R = 2.5 kΩ will ensure firing of the SCR.

Example 1.2.6 *A SCR is connected in series with RL load and is fed from a 120 V, 60 Hz AC supply. The load resistance is 15 Ω and load is 0.75 H. What is the maximum allowable latching current of the SCR if the gate trigger circuit output pulse is of 100 μs duration at a delay angle of 45°.*

Solution : Fig. 1.2.17 show the circuit diagram.

Current through RL circuit is given as,

$$i(t) = \frac{v_s}{R}\left(1-e^{-t\frac{R}{L}}\right)$$

$v_s = V_m \sin \omega t$

$= 120\sqrt{2} \sin 45°$
$= 120$ V

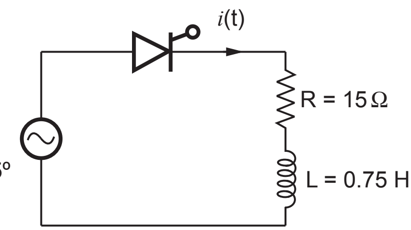


Fig. 1.2.17

$$\therefore \quad i(t = 100\ \mu s) = \frac{120}{15}\left(1-e^{-100\times10^{-6}\times15/0.75}\right)$$

$$= 16 \text{ mA.}$$

Thus at end of 100 μs trigger pulse, SCR current will reach to 16 mA. Hence latching current must bt at least 16 mA to keep the device in ON condition. Thus,

$$I_L = 16 \text{ mA.}$$

Example for Practice

Example 1.2.7 : *A SCR is connected in series with a 0.5 H inductor and 20 Ω resistance. A 100 V DC voltage is applied to this circuit. If the latching current of the SCR is 4 mA, find the minimum width of the gate trigger pulse required to properly turn-on the SCR.*

[Hint and Ans. : $4\times10^{-3} = \frac{100}{20}\left(1-e^{-t\frac{20}{0.5}}\right)$; $t = 20\,\mu$**sec]**

Review Questions

1. *Explain the terms latching current and holding current and compare them.*

   SPPU : May-10,13, Marks 4; Dec.-10, Marks 6

2. *Explain the operation of the SCR with the help of two transistor analogy. Derive an expression for anode currents in term of the current gains and leakage currents of the transistors.*

   SPPU : May-2000,02,03,06,08,10, Dec.-04,08,09, Marks 6; May-01, Dec.-01,03,06, Marks 8; May-13, Marks 5

3. *Draw forward and reverse characteristics of SCR. Show I_L, I_h, V_{BO} and V_{BR} on the characteristic.* **SPPU : May-2000, Dec.-11, Marks 4; Dec.-13, April-17, May-17 (In sem) Marks 5**

4. *Describe the different modes of operation of a thyristor with the help of static V-I characteristics.* **SPPU : May-07, Marks 4, Dec.-09, May-10,11, Marks 6**

5. *Draw two transistor analogy of SCR. Show that :*
   $I_A = (I_{CBO1} + I_{CBO2})/(1 - (\alpha_1 + \alpha_2))$
   Also explain regenerative action of transistors in SCR. **SPPU : Dec.-11, May-17, Marks 7**

6. *Draw steady state characteristics of SCR. Explain I_L, $I_H V_{BO}, V_{BR}$, and show them on the characteristics.* **SPPU : May-17, Marks 7**

7. *Explain two transistor analogy of an SCR. Derive anode current equation of SCR* **SPPU : May-17, Marks 7**

8. *Explain the operation using two transistor analogy with expression of anode current.* **SPPU : May-18, Marks 7**

9. *Explain how the following devices can be operated as switch with necessary driving conditions : SCR* **SPPU : April-19, Marks 3**

1.3 Switching Characteristics of an SCR **SPPU : April-17, Dec.-19**

1.3.1 Different Ways to Turn-on the SCR

We know that SCR can be turned-on if the anode current is above latching current. There is regenerative action in the SCR. SCR can be turned-on by following ways :

1. Gate drive

SCR can be turned on by applying positive gate-cathode voltage. Injected gate carriers increase the anode current and regenerative action starts. As shown in equation (1.2.6), $(\alpha_1 + \alpha_2)$ approaches unity and anode current (I_D) becomes large. It is limited only by external load. Once the SCR is turned-on, there is no need of gate drive. Hence it can be removed. Normally pulsed gate drive is applied to reduce losses in the SCR gate.

2. High forward voltage

SCR turns on when its anode-cathode voltage exceeds forward break over voltage, i.e. $V_{Ak} > V_{BO}$. This is shown in Fig. 1.2.1. At these voltages, the leakage current is so high, that internal regenerative starts in the device.

3. $\frac{dv}{dt}$

SCR can be thought of as a capacitor in the forward biased state. When the anode-cathode voltage changes rapidly, leakage current through the device increases due to internal capacitor. The leads to turn-on of the SCR.

4. Light

SCR can be turned on by light, when it falls on gate cathode junction of the SCR light induces electronic hole pairs and it helps to increase leakage current.

5. High temperature

SCR turns on due to increased temperature. At higher temperature, there are more electron-hole pairs across junctions. This inverses the leakage current and the SCR turns on.

1.3.2 Turn-on Dynamic Characteristics

Fig. 1.3.1 shows the current and voltage of the SCR during turn-on. The gate pulse is applied at $t = 0$. During the *delay time* (t_d), the anode current rises very slowly and flows only near the narrow region of the gate. Observe that anode to cathode doesnot reduce during t_d. It remains to the forward blocking value. During the *rise time* (t_r), the anode current increases rapidly and anode to cathode voltage falls rapidly. The high voltage and current are present in the SCR. Hence large dissipation takes place in the SCR.

This power dissipation is called switching loss of the SCR. The current starts spreading in the remaining area of the SCR. During the *spread time* (t_p), the conduction spreads over the complete cross-section of the SCR. The anode current reaches to its maximum value. And the anode to cathode voltage falls to lowest value (i.e. less than 2 V). The dissipation in the SCR is also reduced. *The turn on time* (t_{on}) of the SCR is given as total of t_d, t_r and t_p. Thus,

$$t_{on} = t_d + t_r + t_p$$

The turn on time can be defined as,

> *The turn-on time of the SCR is defined as the time from initiation of gate drive to the time when anode current reaches to its full value.*

The turn-on time of the SCRs is about 1 to 3 microseconds. The turn-on time can be effectively reduced by applying higher values of gate currents. Because of high gate currents, more electron-holes are injected near junction J_2. Hence avalanche break-down of J_2 takes place fast. Therefore anode current rises fast. Thus effective turn-on time is reduced. To turn-on the SCR, the gate pulse is thus sufficient.

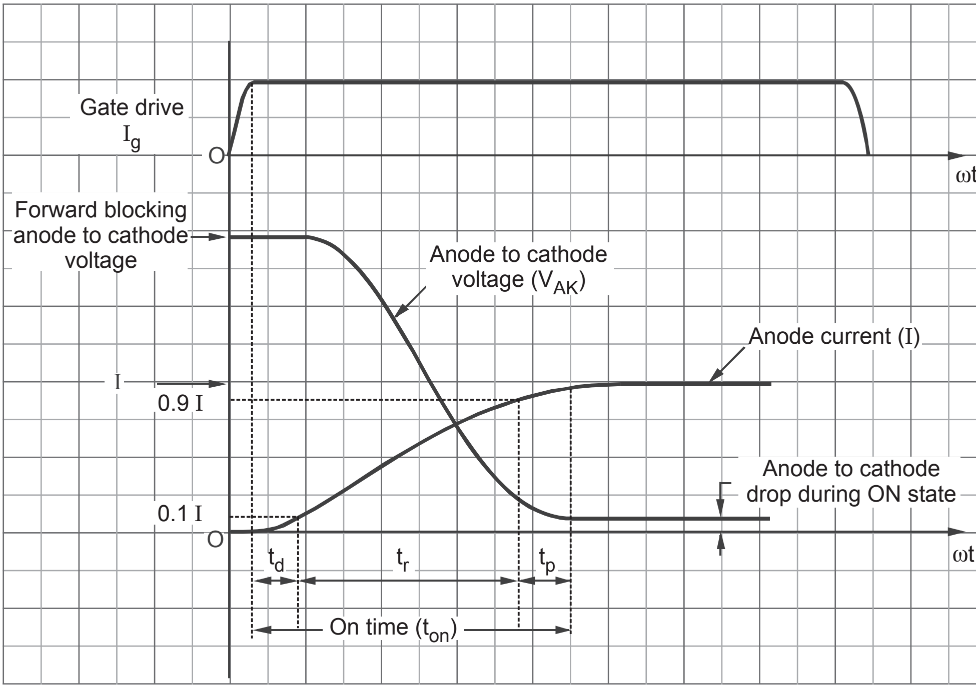


Fig. 1.3.1 Dynamic characteristics of SCR during turn-on

1.3.3 SCR Turn-off

We know that SCR can be turned-off, when its forward current falls below holding current. This can be done by two methods : i) Natural commutation and ii) Forced commutation.

i) **Natural Commutation :** In this type of turn-off, the supply voltage becomes zero or negative, hence SCR is reverse biased. Therefore it is turned-off.

ii) **Force commutation :** When the supply voltage is DC, then external commutation component are used to turn-off the SCR. The commutation components apply reverse bias across the SCR temporarily or pass impulse of negative current. Therefore SCR turns-off.

1.3.4 Turn-off Dynamic Characteristics

Fig. 1.3.2 shows the SCR current and voltage during turn-off. The SCRs are not turned off by gate. They need external circuit for turn-off. These circuits are called commutation circuits. These commutation circuits has to hold negative voltage across the SCR during turn-off period. The SCR is said to be turned-off when it regains forward blocking capability after forward conduction. In the Fig. 1.3.2 observe that anode current falls and then it becomes negative. The negative pulse of current flows through the SCR

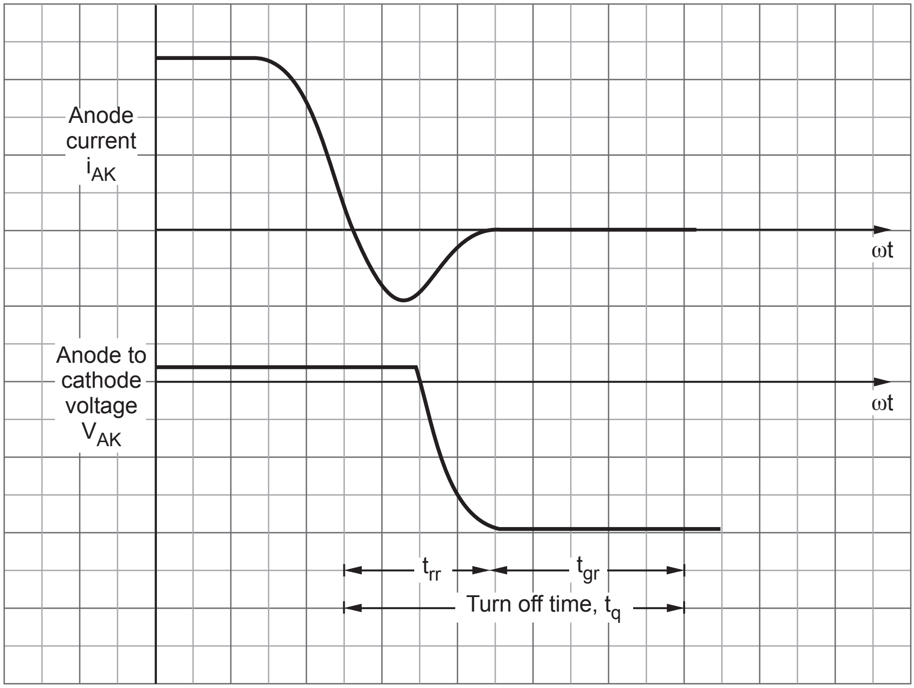


Fig. 1.3.2 Dynamic characteristics of SCR during turn-off

for short period. During the conducting state, the SCR is flooded with carriers and it acts as short circuit. The negative anode current flows through the SCR till all these carriers are removed. Then junctions J_1 and J_3 achieve their forward blocking state. The time required for this is called *reverse recovery time* (t_{rr}). At the end of t_{rr}, reverse voltage appears across the SCR and anode current becomes zero. This is shown in Fig. 1.3.2. But still, the SCR is not turned-on. The commutation circuit has to hold negative voltage across the SCR for *gate recovery time* (t_{gr}). During this time, the excess carriers near junction J_2 are recombined. If negative voltage is removed by commutation circuit before t_{gr}, then SCR may turn-on again due to these excess carrier near junction J_2. Because they act like gate drive to the SCR. Hence the turn-off is complete at the end of gate recovery time. The SCR regains its forward blocking capability. The negative voltage imposed by commutation circuit can be removed at the end of t_{gr}. *The turn-off time* (t_q) of the SCR is the total time required by reverse recovery and gate recovery. i.e.,

$$t_q = t_{rr} + t_{gr}$$

The turn-off time can be defined as follows :

> *The turn-off time of the SCR is the time required to achieve forward blocking capability after commutation is initiated.*

The turn-off time of the SCR varies from 5 to 200 microseconds. The turn-off time of the commutation circuit is called *circuit turn-off time* (t_c). And hence circuit turn-off time must be greater than the turn-off time of the SCR $(t_c > t_q)$.

1.3.5 Inverter Grade and Converter Grade SCRs

Inverter grade SCRs

The SCRs which have turn-off time less than 25 μs are called inverter grade SCRs. Such SCRs are used in inverters, choppers etc.

Converter grade SCRs

The SCRs having larger turn-off times $(t_q > 25\ \mu s)$ are called converter grade SCRs. Such SCRs are used in controlled rectifiers, AC voltage controllers etc.

Review Questions

1. *Explain the turn-on and turn-off dynamic characteristics of the SCR.* **SPPU : April-17 (In Sem)**
2. *Define the following :*
   (i) turn-on time (ii) turn-off time (iii) converter grade SCR (iv) Inverter grade SCR
3. *Draw and explain switching characteristics of SCR.* **SPPU : April-19, Marks 4**
4. *Draw the dynamic characteristics of SCR and explain the turn on and turn off process of SCR in detail ?* **SPPU : Dec.-19, Marks 7**

1.4 Gate Turn-off Thyristor

SPPU : Jan.-10

1.4.1 Structure of GTO

At the beginning of the chapter we discussed structure and working of SCR. The SCR is most commonly used member of thyristor family. But SCR needs external circuits for turn-off. Now we present another thyristor, called GTO. The GTO can be turned-off by gate drive. Thus gate has full control over the operation of GTO. Fig. 1.4.1 shows the structure of GTO.

Observe that the structure of GTO is almost similar to SCR. But there are significant differences that make GTO different than SCR. These differences are :

i. Gate and cathodes are highly interdigited with various geometric forms. This maximizes periphery of the cathode and minimize gate-cathode distance.

ii. There are n^+ regions at regular intervals in the p^+ anode layer. This n^+ layer makes direct contact with n^- layer. This is called anode short. This speeds up the turn-off mechanism of GTO.

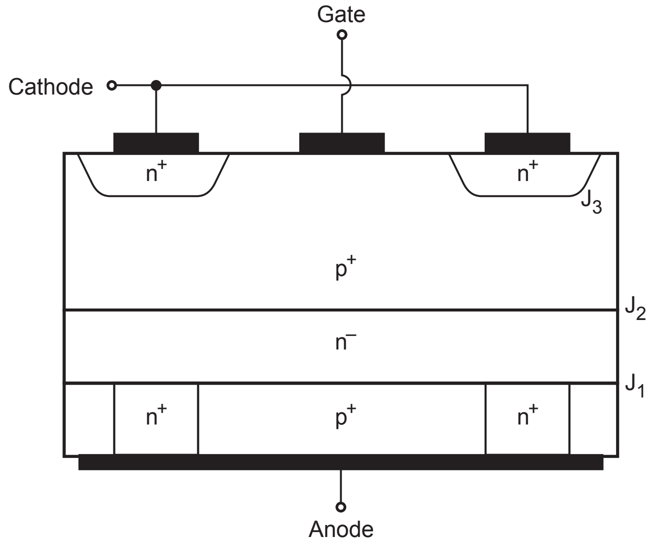


Fig. 1.4.1 Structure of GTO

iii. The operation of GTO can be explained with the help of two transistor analogy. The gain of pnp transistor is reduced. This reduces the regenerative action. Hence turn-off of GTO can be achieved by negative current from gate.

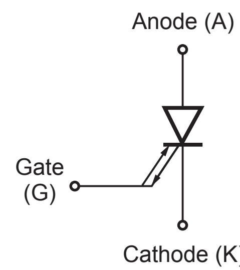


Fig. 1.4.2 Symbol of GTO

Fig. 1.4.2 shows the symbol of GTO.

Observe that there is double arrow on the gate. This indicates that bidirectional current flows through the gate. The rest of the symbol is similar to SCR.

1.4.2 Characteristics of GTO

Fig. 1.4.3 shows the V-I characteristics of GTO.

In this figure observe that the V-I characteristics of GTO in forward direction are similar to that of SCR. But in reverse direction GTO has virtually no blocking capability. Observe that GTO starts conducting in reverse direction after very small reverse (20 to 30 V) voltage. This is because of the anode short structure.

In Fig. 1.4.1 observe that junction J_3 blocks reverse voltages. But J_3 has very small reverse breakdown voltage. Thus GTO has asymmetric voltage blocking capability.

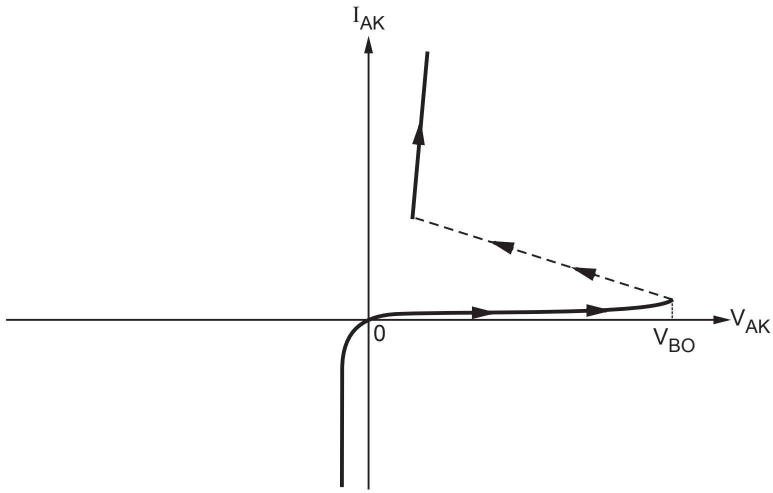


Fig. 1.4.3 V-I characteristics of GTO

1.4.3 Advantages, Limitations and Applications of GTO

Advantages

i. Higher voltage blocking capability

ii. Gate has full control over the operation of GTO.

iii. Low on-state loss.

iv. High ratio of peak surge current to average current.

v. High on-state gain.

Limitations

i. GTOs require large negative gate currents for turn-off. Hence they are suitable for low power applications.

ii. Very small reverse voltage blocking capability.

iii. Switching frequencies are very small.

Applications

i. GTOs are suitable mainly for low power applications.

ii. Induction heating and motor drives.

Review Question

1. *What is GTO ? Explain its V-I characteristics.*	**SPPU : Jan.-10, Marks 4**

1.5 Power MOSFET SPPU : May-04,08,10,11,12,17,18,19, Dec.-07,08,09,10,11,13,19

The metal oxide semiconductor field effect transistors (MOSFET) are majority carrier devices. Fig. 1.5.1 shows the symbols of MOSFETs.

Observe that there are two types of power MOSFETs : n-channel MOSFET and p-channel MOSFET. The MOSFET has three terminals : gate (G), drain (D) and source (S).

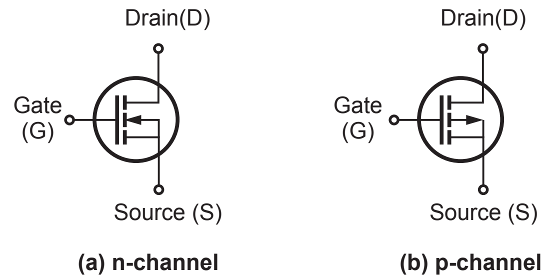


Fig. 1.5.1 Symbols of MOSFETs

When the MOSFET is turned 'on' the current flows from drain to source. The voltage is applied between gate-source to turn 'on' the MOSFET. Very small current flows from gate to source. Only voltage is to be applied to turn on the MOSFET. The MOSFET can be turned-off by removing the gate to source voltage. Thus gate has full control over the conduction of the MOSFET. The turn-on and turn-off times of MOSFETs are very small. Hence they operate at very high frequencies. Hence MOSFETs are preferred in applications such as choppers and inverters. Since only voltage drive (gate-source) is required, the drive circuits of MOSFETs are very simple. The paralleling of MOSFETs is easier due to their positive temperature coefficient (PTC). MOSFETs have high on-state resistance, $R_{DS\,(on)}$. Hence for higher currents, losses in the MOSFETs are substantially increased. Hence MOSFETs are mainly used for low power applications.

1.5.1 Structure of MOSFETs

There are two types of MOSFETs : depletion type MOSFET and enhancement type MOSFET. In both of these types the MOSFETs can be n-channel or p-channel. Fig. 1.5.2 shows the structure of n-channel enhancement type MOSFET. The source and drain are connected n^+ regions. These regions are heavily doped with the intensity of 10^{19} per cm^3 . The p-type body region forms the channel between drain and source. The body region has the doping level of 10^{16} per cm^3. The gate is not directly connected to the p-type region. There is insulating oxide (SiO_2) layer between gate metal and p-type layer. When gate is made positive with respect to source an accumulation layer is formed in the channel as shown in Fig. 1.5.3. This accumulation layer is formed because of

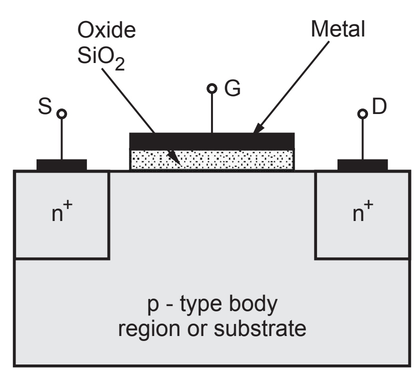


Fig.1.5.2 Structure of n-channel enchancemode MOSFET. (Drift layer is not shown)

V_{GS}. The gate terminal (metal) is positive. The other side of oxide layer is p-type of body region. Accumulation layer of electrons is generated in the body region near oxide layer. This is also called induced channel of electrons. Therefore current (i_{DS}) starts flowing through this induced channel. The current flows from drain to source. If V_{GS} = 0, then induced channel is absent and no current flows. Since channel is made of electrons, this is called n-channel MOSFET.

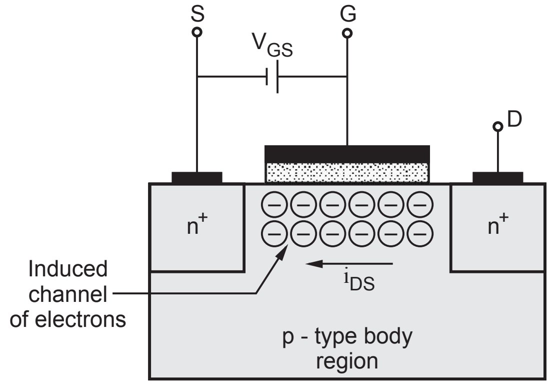


Fig. 1.5.3 Formation of inversion layer or channel

Fig. 1.5.4 shows the four layer structure of n-channel enhancement mode MOSFET. This is $n^+pn^-n^+$ structure. A drift region (n^-) is shown in this structure. The drift region is lightly doped (10^{14} per cm^3).

In the Fig. 1.5.4 structure observe that the source is connected to n^+ region as well as p-type body region. The gate also overlaps p-type region and n^+ region. The gate is isolated from these regions by SiO_2 layer. When V_{GS} is positive, an n-type channel is induced in the body region as shown in Fig. 1.5.4. Hence current (i_{DS}) starts flowing from drain to source as shown. Because of drift region, the on-state drop of MOSFET increases. The thickness of drift region determines breakdown voltage of MOSFET. In Fig. 1.5.4 observe that a parasitic BJT is formed as shown. Base of this parasitic BJT is

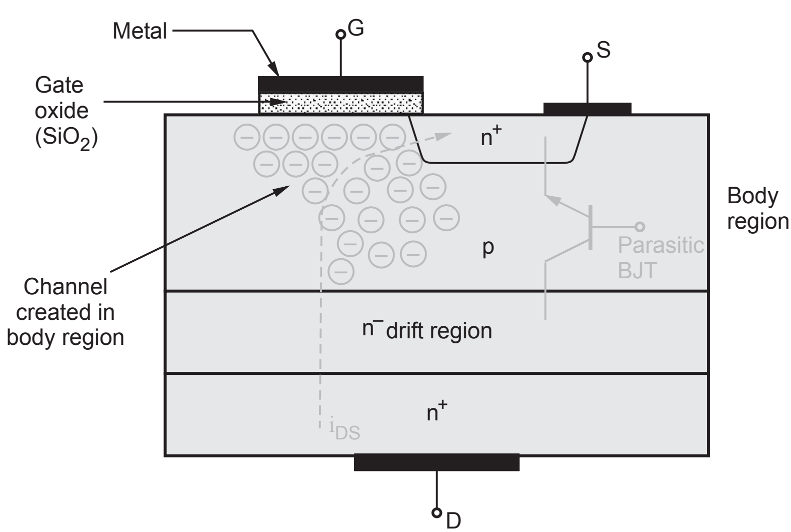


Fig. 1.5.4 Four layer structure of n-channel enhancement mode MOSFET

the p-type body region. Emitter is n^+ region and collector is n^- drift region. The emitter and base of this parasitic BJT are shorted to source. Hence it does not conduct. This is the reason for shorting p-type body region to source.

Advantages of vertical structure

1. On-state resistance of MOSFET is reduced.
2. Width of the gate is maximized. Hence, Gain of the device is increased.

1.5.2 Steady State (V-I) Characteristics of MOSFETs

Fig. 1.5.5 shows the V-I characteristics of n-channel power MOSFET. The drain current i_D is plotted with respect to drain to source voltage v_{DS}. These characteristics are plotted for various values of gate source voltages (V_{GS}). In Fig. 1.5.5 observe that there are three regions in the characteristics : Ohmic, region, active region and cutoff region. In the cutoff region, the drain current is negligible and the MOSFET is said to be in 'OFF' state. The MOSFET is driven in cutoff region by applying $V_{GS} < V_{GS(th)}$. Here $V_{GS(th)}$ is the threshold gate source voltage. When gate to source voltage is less than threshold gate source voltage, MOSFET is off, i.e. in cutoff region. The MOSFET is driven into ohmic region when $V_{GS} >> V_{GS(th)}$. In the ohmic region, the MOSFET conducts heavily. Hence it is said to be 'on' in the ohmic region. Thus by applying heavy gate to source voltage, MOSFET can be turned on. In the power electronic applications, MOSFET is never operated in the active region. In active region it acts as an amplifier. For switching applications, MOSFET is operated only in ohmic and cutoff regions. The BV_{DSS} is the drain to source breakdown voltage, when the gate is open circuitted. The MOSFET is damaged if drain to source voltage is increased above BV_{DSS}.

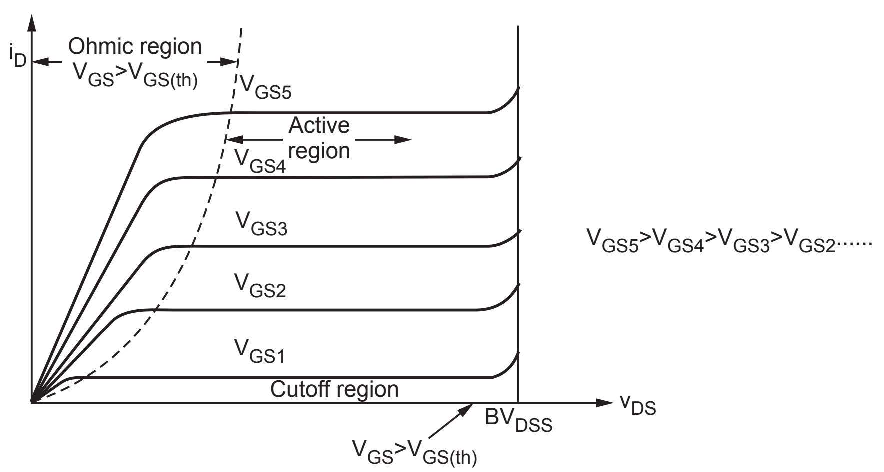


Fig. 1.5.5 V-I characteristics of n-channel power MOSFET

1.5.3 Switching Characteristics of MOSFET

The internal capacitances of MOSFET affect the turn-on and turn-off times of MOSFETs. These capacitances have no effect during steady state. Fig. 1.5.6 shows the switching model of MOSFET.

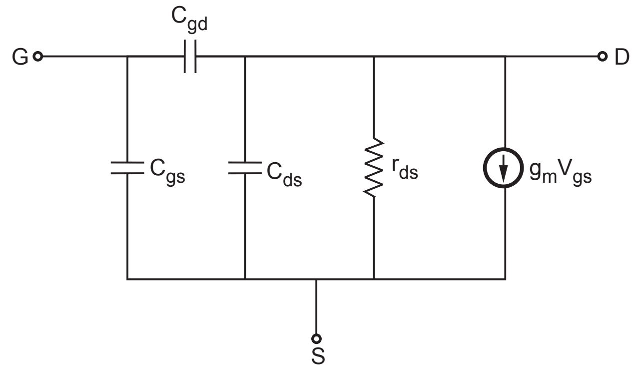


Fig. 1.5.6 Switching model of MOSFET

In the Fig. 1.5.6 C_{gs} is the gate to source parasitic capacitance and C_{gd} is the gate to drain parasitic capacitance. The MOSFET can be turned on by applying positive gate voltage as shown in Fig. 1.5.7.

When the gate voltage is applied, the gate to source capacitance C_{gs} starts charging. The *turn-on delay* ($t_{d(on)}$) is the time required to charge C_{gs} to threshold voltage (V_T). After this voltage, the drain current (i_D) starts rising. The C_{gs} charges from threshold voltage to full gate voltage (v_{gsp}). The time required for this charging is called *rise time* (t_r). Observe that during this period, the drain current rises to its full value, i.e. I_o. The

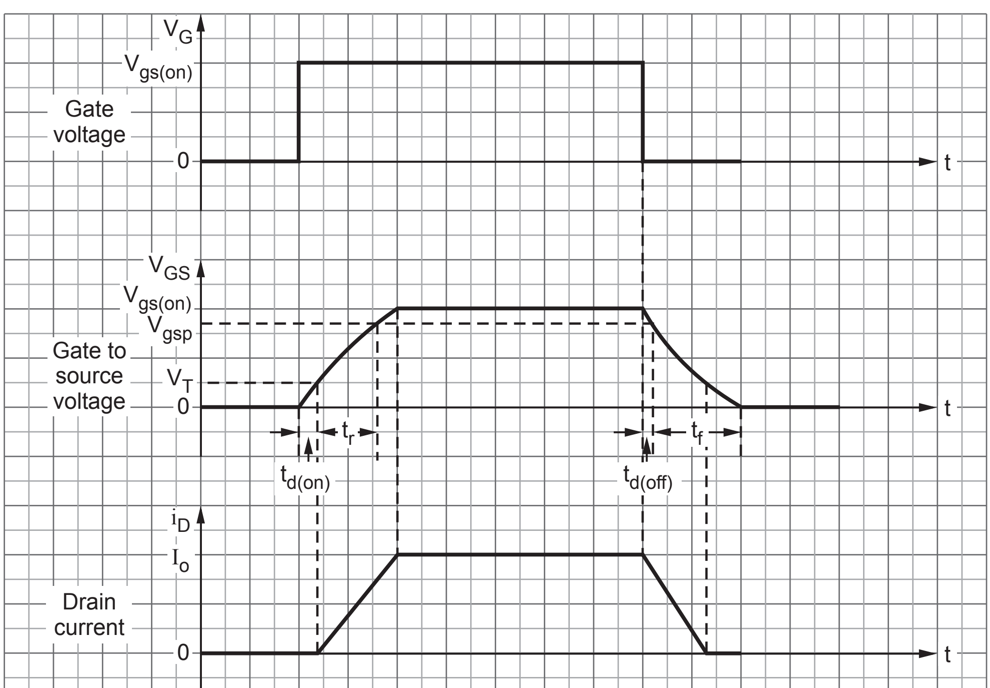


Fig. 1.5.7 Switching characteristics of MOSFET

MOSFET is then said to have fully turned on. Thus, the total turn-on time of the MOSFET is,

$$t_{on} = t_{d(on)} + t_r$$

To turn-off the MOSFET, the gate voltage is made negative or zero. The gate to source voltage then reduces from $v_{gs(on)}$ to v_{gsp}. That is, C_{gs} discharges from overdrive to pinch-off region gate voltage. The time required for this discharge is called *turn-off delay* time ($t_{d(ff)}$). The drain current also start reducing. The C_{gs} keeps on discharging and its voltage becomes equal to threshold voltage (V_T). The time required to discharge C_{gs} from v_{gsp} to V_T is called *fall time* (t_f). The drain current becomes zero when $v_{GS} \leq V_T$. The MOSFET is then said to have turned-off. The C_{gs} then discharges to zero voltage. The turn-off time of the MOSFET is equal to sum of turn-off delay time and fall time. i.e.,

$$t_{off} = t_{d(off)} + t_f$$

1.5.4 SOA of Power MOSFET

Fig. 1.5.8 shows the SOA of power MOSFET.

Three factors decide the SOA of power MOSFET,

i) Maximum drain current (I_{DM})

ii) Internal junction temperature (T_{jmax})

iii) Breakdown voltage (BV_{DSS})

- The MOSFETs does not have any second breakdown limitations as in BJT.
- For power MOSFETs, forward biased SOA and reverse biased SOA are same. There is no difference between the two.

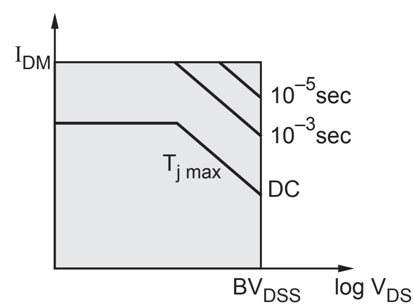


Fig. 1.5.8 SOA of power MOSFET

For switched mode applications the SOA is square. The SOA reduces as frequency of switching reduces and minimum at DC operation.

1.5.5 Merits, Demerits and Applications of MOSFETs

Merits of MOSFETs

i. MOSFETs are majority carrier devices.

ii. MOSFETs have positive temperature coefficient, hence their paralleling is easy.

iii. MOSFETs have very simple drive circuits.

iv. MOSFETs have short turn-on and turn-off times, hence they operate at high frequencies.

v. MOSFETs do not require commutation circuits.

vi. Gate has full control over the operation of MOSFET.

Demerits of MOSFET

i. On-state losses in MOSFETs are high.

ii. MOSFETs are used only for low power applications.

iii. MOSFETs suffer from static charge.

Applications of MOSFETs

i. High frequency and low power inverters.

ii. High frequency SMPS.

iii. High frequency inverters and choppers.

iv. Low power AC and DC drives.

Sr. No.	BJT	MOSFET
1.	This is bipolar device.	This is majority carrier device.
2.	Controlled by base.	Controlled by gate.
3.	Current controlled device.	Voltage controlled device.
4.	Negative temperature coefficient.	Positive temperature coefficient.
5.	Paralleling of BJTs is difficult.	Paralleling of MOSFETs is simple.
6.	Losses are low.	Losses are higher than BJTs.
7.	Drive circuit is complex.	Drive circuit is simple.
8.	Switching frequency is lower than MOSFET.	Switching frequency is high.
9.	BJTs are suitable for high power applications.	MOSFETs are suitable for low power application.
10.	BJTs are available with higher voltage and current ratings.	MOSFETs have less voltage and current ratings.

Table 1.5.1 Comparison of BJT and MOSFET

Review Questions

1. *Explain the steady state and switching characteristics of MOSFET.*
SPPU : May-10 Marks 4; Dec.-09,10, Marks 6; May-11, Marks 5; Dec.-13, May-17, Marks 7
2. *Draw the vertical cross section of power MOSFET and explain the following : i) Reason for body-source-short in MOSFET structure ii) Presence of integral reverse diode in the structure.* **SPPU : May-04, Marks 8; Dec.-07, Marks 8; Dec.-08, Marks 10, May-08, 17 Marks 10, May-12, Marks 6**
3. *Why MOSFET is preferred at high frequencies ?* **SPPU : Dec.-07, Marks 4**
4. *Explain the construction and switching characteristics of n-channel enhancement power MOSFET.* **SPPU : Dec.-11, Marks 6**
5. *Why parelleling of MOSFETs is easier than SCRs ?* **SPPU : Dec.-07, Marks 4**
6. *Draw the construction of power MOSFET and explain steady state characteristics of Power MOSFET. Compare it with SCR and IGBT.* **SPPU : May-17, Marks 7**
7. *Draw the construction of power MOSFET and explain I-V steady state characteristics of power MOSFET.* **SPPU : May-18, Marks 4**
8. *Draw and explain steady state characteristics of power MOSFET ?* **SPPU : Dec.-19, Marks 6**

1.6 IGBT

SPPU : Dec.-2000, 01,03,04,06,07,09,10,11,13, April-17,19, May-2000,01,02,03,06,07,10,11,12,13,17,18,19

The Insulated Gate Bipolar Transistor (IGBT) is the latest device in power electronics. It is obtained by combining the properties of BJT and MOSFET. We know that BJT has lower on-state losses for high values of collector current. But the drive requirement of BJT is little complicated. The drive of MOSFET is very simple (i.e. only voltage is to be applied between gate and source). But MOSFET has high on-state losses. The gate circuit of MOSFET and collector emitter circuits of BJT are combined together to form a new device. This device is called IGBT. Thus IGBT has advantages of both the BJT and MOSFETs. Fig. 1.6.1 shows the symbol of IGBT. Observe that the symbol clearly indicates combination of MOSFET and BJT.

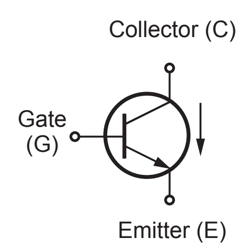


Fig. 1.6.1 Symbol of GBT

The IGBT has three terminals : Gate (G), collector (C) and emitter (E). Current flows from collector to emitter whenever a voltage between gate and emitter is applied. The IGBT is said to have turned 'on'. When gate emitter voltage is removed, IGBT turns-off. Thus gate has full control over the conduction of IGBT. When the gate to emitter voltage is applied, very small (negligible) current flows. This is similar to the gate circuit of MOSFET. The on-state collector to emitter drop is very small like BJT.

1.6.1 Structure of IGBT

The structure of IGBT is similar to that of MOSFET. Fig. 1.6.2 shows the vertical cross section of IGBT. In this structure observe that there is additional p^+ layer. This layer is collector (Drain) of IGBT.

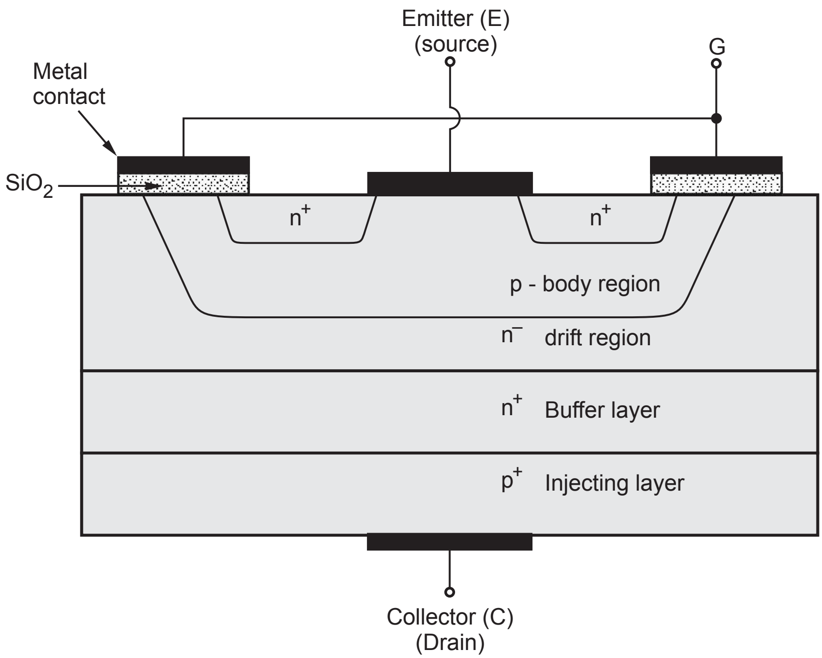


Fig. 1.6.2 Vertical cross section of IGBT

This p^+ injecting layer is heavily doped. It has the doping intensity of 10^{19} per cm^3. The doping of other layers is similar to that of MOSFET. n^+ layers have 10^{19} per cm^3. p-type body region has doping level of 10^{16} per cm^3. The n^- drift region is lightly doped (10^{14} per cm^3).

1.6.1.1 Punch through IGBT

The n^+ buffer layer is not necessary for the operation of IGBT. The IGBTs which have n^+ buffer layer are called punch through IGBTs. Such IGBTs have asymmetric voltage blocking capabilities. Punch through IGBTs have faster turn-off times. Hence they are used for inverter and chopper circuits.

1.6.1.2 Non-punch through IGBT

The IGBTs without n^+ buffer layer are called non-punch through IGBTs. These IGBTs have symmetric voltage blocking capabilities. These IGBTs are used for rectifier type applications.

1.6.1.3 Operation of IGBT

Now let us see how IGBT operates. When $V_{GS} > V_{GS(threshold)}$, then the channel of electrons is formed beneath the gate as shown in Fig. 1.6.3. These electrons attract holes from p^+ layer. Hence, holes are injected from p^+ layer into n^- drift region. Thus hole/electron current starts flowing from collector to emitter. When holes enter p-type

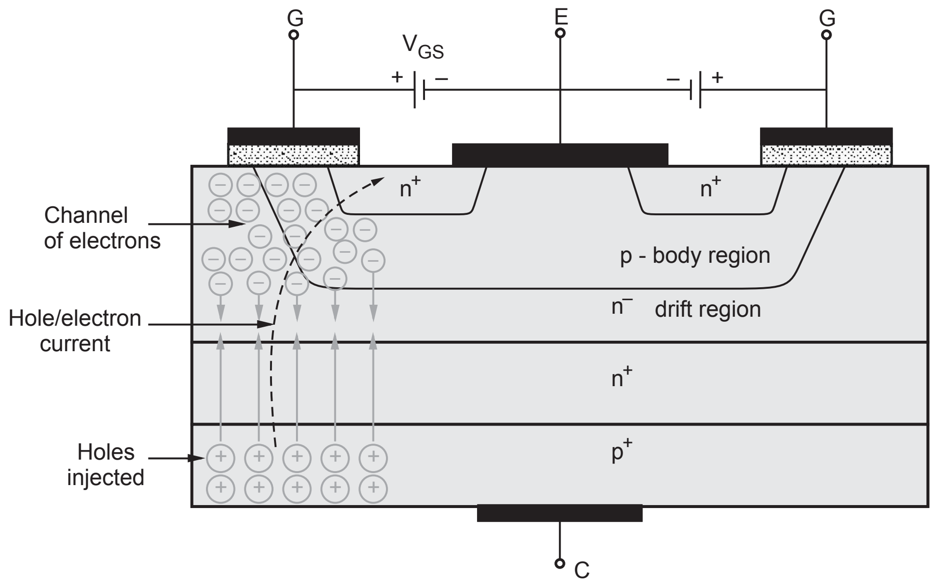


Fig. 1.6.3 A positive gate to source voltage initiates MOSFET action

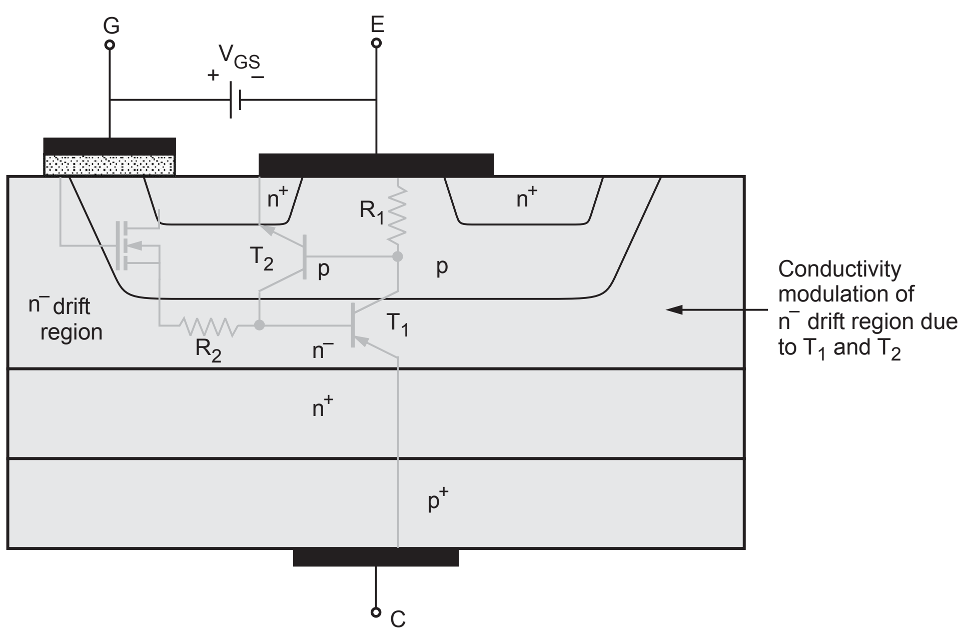


Fig. 1.6.4 Structure of IGBT

body region, they attract more electrons from n^+ layer. This action is exactly similar to MOSFET.

Now let us see how p^+ injecting layer makes the operation different than MOSFET. Fig. 1.6.4 shows the structure of IGBT showing how internal MOSFETs and transistors are formed. The MOSFET is formed with input gate, emitter as source and n^- drift region as drain. The two transistors T_1 and T_2 are formed as shown. The holes injected by the p^+ injecting layer go to the n^- drift region. This n^- drift region is base of T_1 and collector of T_2. The holes in the n^- drift region further go to the p-type body region, which is connected to the emitter. The electrons from n^+ region (which is emitter) pass through the transistor T_2 and further in the n^- drift region. Thus holes and electrons are injected in large amounts in n^- drift region. This reduces the resistance of the n^- drift region. This is called *conductivity modulation* of n^- drift region. Note that such conductivity modulation does not exist in MOSFET. The connection of T_1 and T_2 is such that large amount of hole/electrons are injected in n^- drift region. The action of T_1 and T_2 is like SCR which is regenerative. The gate serves as trigger for T_1 through internally formed MOSFET. Fig. 1.6.5 shows the equivalent circuit. In this figure observe that when gate is applied ($V_{GS} > V_{GS(th)}$), the internal equivalent MOSFET turns on. This gives base drive to T_1. Hence T_1 starts conducting. The collector of T_1 is base of T_2. Therefore T_2 also turns on. The collector of T_2 is base of T_1. Thus the regenerative loop begins and large number of carriers are injected in n^- drift region. This reduces the on-state loss of the IGBT just like BJT. This happens due to conductivity modulation of n^- drift region.

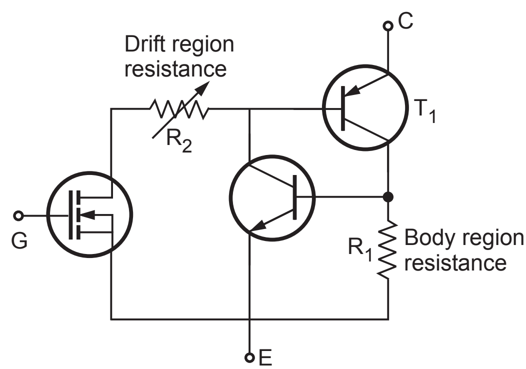


Fig. 1.6.5 Equivalent circuit of IGBT

When the gate drive is removed, the IGBT should turn-off. When gate is removed, the induced channel will be vanished and internal equivalent MOSFET will turn-off. Hence T_1 will turn-off if T_2 turns-off. T_2 will turn-off if the p-type body region resistance R_1 is very very small. Under such situation, its base and emitter will be virtually shorted. Hence T_2 turns-off. Therefore T_1 will also turn-off. Hence structure of IGBT is organized such that body region resistance (R_1) is very very small.

If R_1 is very very small, then T_2 will never conduct and the equivalent circuit of IGBT will be as shown in Fig. 1.6.6. IGBTs are thus different than MOSFETs because of conduction of current from collector to emitter. For MOSFETs, on state losses are high since resistance of drift region remains same. But in IGBTs, resistance of drift region reduces when gate drive is applied. This resistance reduces because of p^+ injecting region. Hence, on-state loss of IGBT is very small.

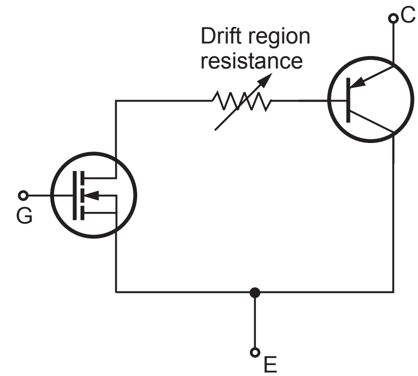


Fig. 1.6.6 Simplified equivalent circuit of IGBT

1.6.1.4 Latchup in IGBT

- Latchup means IGBT remains in ON condition even if gate drive is removed.
- **Causes of latchup :** The current in p-type body region flows vertically as well as laterally. In equivalent circuit of Fig. 1.6.5 observe that the lateral component of current flows through the body region resistance R_1. Therefore the drop across this body region resistance is sufficient to turn-on npn transistor T_2. Therefore pnp transistor T_1 is also turned on and regeneration takes place. Under this situation gate has no control over the current flow. Thus IGBT remains in ON condition even if gate drive is removed.
- **To avoid latchups :**
  i) Efforts are made to reduce the body resistance R_1. This can be achieved by using special geometries for the structure of IGBT.
  ii) The circuit should be designed in such a way that maximum specified current should not be exceeded.
  iii) Latchups can also be avoided by increasing the turn-off time and controlling h_{FE} of the pnp transistor.

1.6.1.5 Body-Source-Short and its Reason

What is body-source-short ?

In the structure of IGBT observe that the source (or emitter 'E') is connected to p-type body region as well as n^+ region. This means p-type body region is shorted to source (or emitter 'E').

Reason

In Fig. 1.6.4 observe that various layers of IGBT form internal parasitic thyristor. i.e. $(p^+ - n^+ n^- - p - n^+)$. The body-source short avoids possible turn-on of this parasitic thyristor. The base-emitter (i.e. p-type body region and n^+ region) of transistor T_2 are shorted due to body-source-short. Hence it does not conduct. It also helps in avoiding latch up in IGBT.

1.6.2 Safe Operating Area (SOA) of IGBT

Forward biased SOA (FBSOA)

- The FBSOA is the square for turn-on times less than 1 msec.
- For reduced switching times FBSOA is limited by maximum junction temperature.

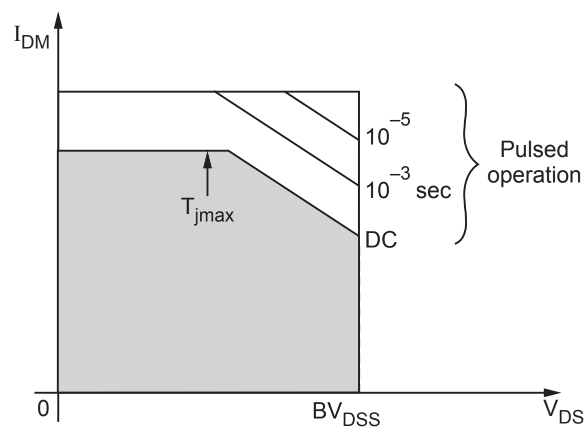


Fig. 1.6.7 FBSOA of IGBT

Reverse biased SOA (RBSOA)

- The RBSOA depends upon the reapplied rate of change of drain-source voltage.
- Observe that the RBSOA reduces as dV_{DS}/dt increases.
- The reduction in RBSOA is necessary to avoid latchups.

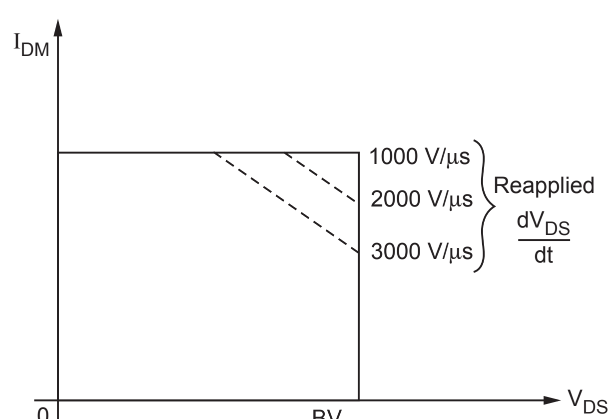


Fig. 1.6.8 RBSOA of IGBT

Superiority of SOA of IGBT

- The SOA of IGBT is square for short switching times.
- The RBSOA of IGBT indicates significantly higher values of reapplied dv/dt.
- The SOA of IGBT is wider compared to that of BJT.
- As switching frequency increases, the SOA of BJT reduces considerably.

1.6.3 Steady State (V-I) Characteristics of IGBT

Fig. 1.6.9 shows the V-I characteristics of n-channel IGBT. Sometime the collector is also called drain and emitter is also called source. The above characteristics are plotted for drain (collector) current i_D with respect to drain source (collector emitter) voltage V_{DS}. The characteristics are plotted for different values of gate to source (V_{GS}) voltages. When the gate to source voltage is greater than the threshold voltage $V_{GS(th)}$, then IGBT turns-on. The IGBT is off when V_{GS} is less than $v_{GS(th)}$. Fig. 1.6.9 shows the 'on' and 'off' regions of IGBT. The BV_{DSS} is the breakdown drain to source voltage when gate is open circuitted. The IGBT is the popular device now-a-days. IGBT has simplest drive circuit and it has low on-state losses.

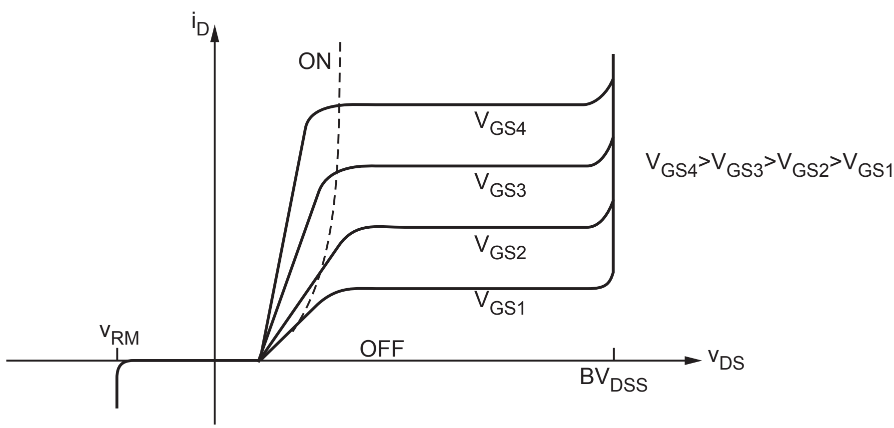


Fig. 1.6.9 V-I characteristics of n-channel IGBT

1.6.4 Switching Characteristics of IGBT

Fig. 1.6.10 shows the switching characteristics of IGBT. The gate to source voltage is normally negative. This voltage is made positive to turn-on the IGBT. When $V_{GS} > V_{GS(th)}$, the collector current starts increasing. Turn-on delay, $t_{d(on)}$ is the delay when gate drive is applied and i_c starts increasing. When i_C increases to its full value, collector emitter voltage starts falling. 't_{ri}' is the rise time of collector and t_{fv} is the fall time of voltage. Thus, turn-on time of IGBT is,

$$t_{on} = t_{d(on)} + t_{ri} + t_{fv}$$

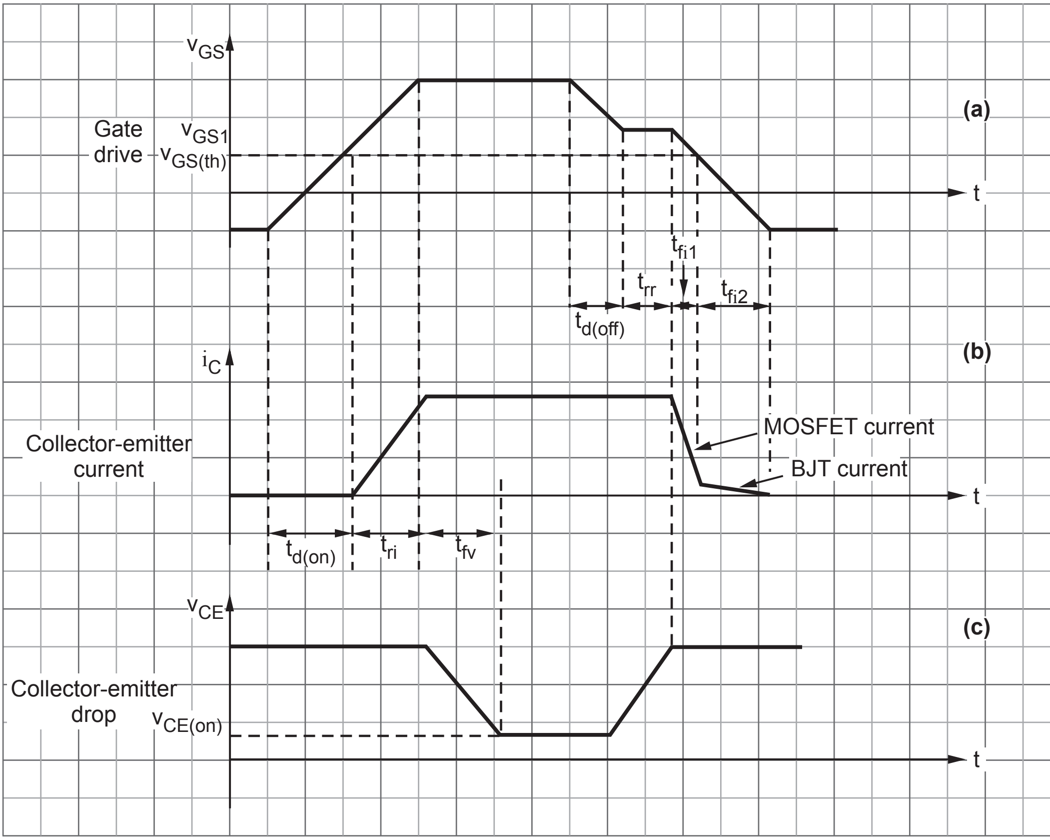


Fig. 1.6.10 Switching characteristics of IGBT

The turn-off of the IGBT is initiated by reducing the gate voltage. When gate voltage falls to the value equal to v_{GS1}, v_{CE} starts rising. v_{GS1} is the voltage where IGBT comes out of saturation. Turn-off delay, $t_{d(off)}$ is the delay time when gate voltage is reduced and v_{CE} starts increasing. When v_{CE} reaches to supply voltage, i_c starts reducing. i_C reduces fast till v_{GS} reaches to $v_{GS(th)}$. This fast decay in i_C is basically due to internal MOSFET. Then v_{GS} goes to zero and becomes negative. But i_C keeps on flowing for some time. This is internal BJT current. This current flows due to stored carriers in the drift region. Hence, turn-off time of IGBT is higher than IGBT. The turn-off time of IGBT will be,

$$t_{off} = t_{d(off)} + t_{rv} + t_{fi1} + t_{fi2}$$

Here, t_{rv} is voltage rise time

t_{fi1} is MOSFET current fall time.

t_{fi2} is BJT current fall time.

1.6.5 Merits, Demerits and Applications of IGBT

Merits of IGBT

i. Voltage controlled device. Hence drive circuit is very simple.

ii. On-state losses are reduced.

iii. Switching frequencies are higher than thyristors.

iv. No commutation circuits are required.

v. Gate have full control over the operation of IGBT.

vi. IGBTs have approximately flat temperature coefficient.

Demerits of IGBT

i. IGBTs have static charge problems.

ii. IGBTs are costlier than BJTs and MOSFETs.

Applications of IGBTs

i. AC motor drives, i.e. inverters.

ii. DC to DC power supplies, i.e choppers.

iii. UPS systems.

iv. Harmonic compensators.

1.6.6 Protection Circuits for IGBT

IGBT can be protected against,

i) Gate overvoltage protection ii) Overcurrent protection iii) Snubber circuits.

1.6.6.1 Gate Overvoltage Protection

- Fig. 1.6.11 shows the circuit diagram of gate overvoltage protection. This circuit consists of two zener diode connected in series back to back.
- Normally the gate overvoltage is ± 20 V. The two zener diodes conduct when overvoltage occurs between gate and source.
- The breakdown voltage of the zener diodes can be adjusted according to Gate-source breakdown voltage of IGBT.

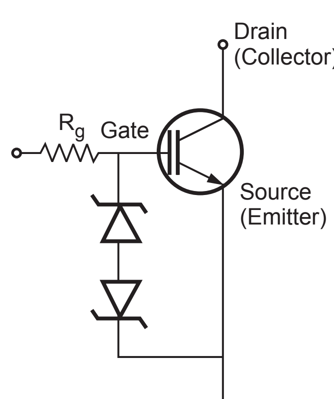


Fig. 1.6.11 Gate overvoltage protection

1.6.6.2 Overcurrent Protection

- The drain overcurrent of IGBT is continuously monitored. If overcurrent is detected, then drive of IGBT is disabled. This is normally incorporated in drive circuit of IGBT. Fig. 1.6.12 shows drive circuit of IGBT with overcurrent protection.

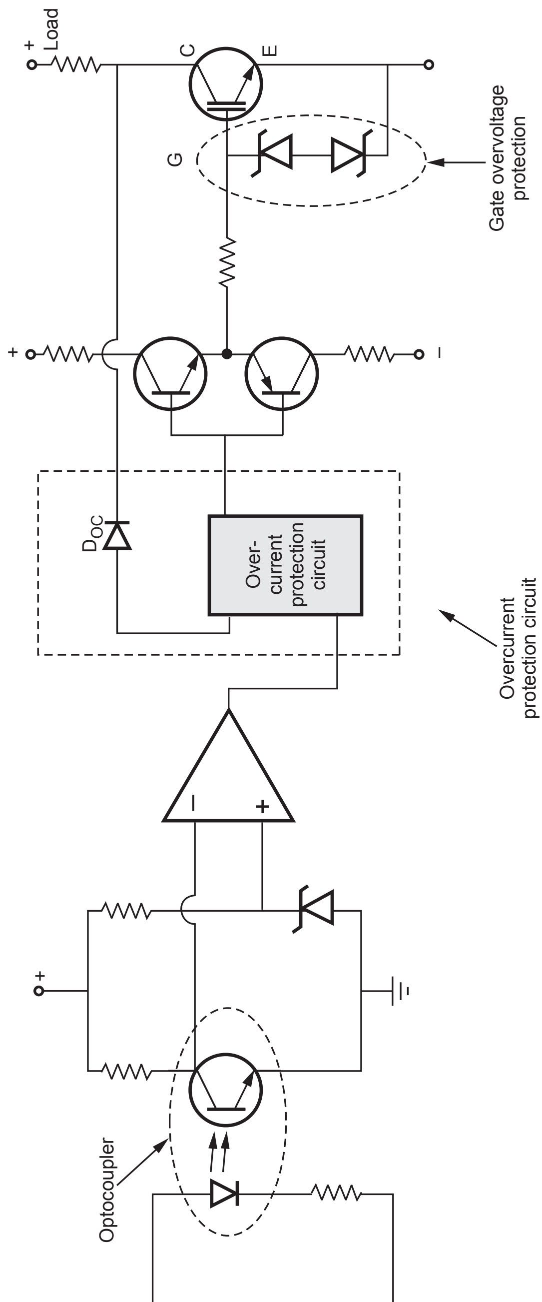


Fig. 1.6.12 Overcurrent protection

Operation

- In this circuit, the turn on/off signal is given through optocoupler.
- The overcurrent protection circuit receivers drive signal from comparator and gives it to gate of IGBT through npn-pnp pair of BJTs.
- The collector voltage of IGBT is sensed through diode D_{OC}. Normally this diode is forward biased, since collector voltage is very small.
- If there is overcurrent, then collector voltage increases and diode D_{OC} is reverse biased. This condition is sensed by overcurrent protection circuit and it simply blocks the drive given to gate of IGBT.

1.6.6.3 Snubber Circuits for IGBT

Prupose : To ensure that IGBT always operates in its safe operating area at the time of turn-on and turn-off.

If IGBT does not operate in its SOA, then it can be damaged. Thus snubber circuits protect IGBT. There are two types of snubbers : i) Turn-off snubber and ii) Turn-on snubber.

Turn-off snubber

Fig. 1.6.13 shows the circuit diagram of turn-off snubber.

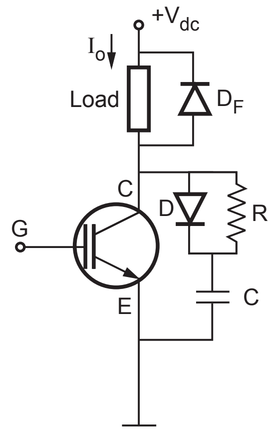


Fig. 1.6.13 Turn-off snubber

Operation

- Turn-off snubber is necessary to limit the voltage across collector-emitter when IGBT turns-off.
- The load current flows through diode D and capacitor C. This changing of capacitor limits the voltage v_{CE} at the time of turn-off.

- The resistance 'R' is used to limit the discharge current of capacitor when IGBT turns-on.
- Fig. 1.6.14 shows the switching trajectory of IGBT for various values of C.
- Here $C_0 < C_1 < C_2 < C_3$. Thus large capacitor value limits the i_C, v_{CE} to considerably small values during switching.

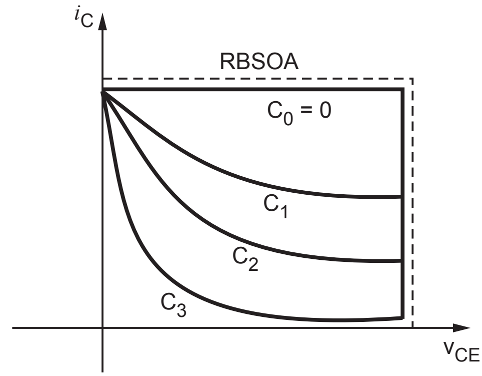


Fig. 1.6.14 Switching trajectory for various values of C

Values of R and C

The values of R and C are given as,

$$R = \frac{V_{dc}}{0.2 I_o}$$

Here V_{dc} is DC supply voltage.

I_o is load current.

$$C_s = \frac{2 E_C}{V_{dc}^2}$$

Here E_C is energy stored in capacitor.

Turn-on Snubber

Fig. 1.6.15 shows the circuit diagram of turn-on snubber.

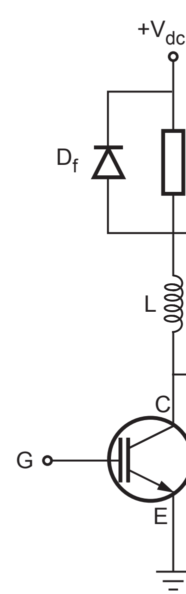


Fig. 1.6.15 Turn-on snubber

Operation

- The turn-on snubber is used to reduce the switching losses during turn-on.
- It reduces the voltage across IGBT when current is rising.
- The voltage drop across inductor L reduces the net voltage across IGBT.
- The energy stored in inductor is dissipated through resistor R and diode D.

Large value of inductance reduces IGBT voltage during turn-on but also causes high voltages during turn-off.

Hence its value must be appropriately selected for turn-on as well as turn-off.

Values of R and L

Value of inductance is given as,

$$L = \frac{\Delta V_{CE}\, t_r}{I_o}$$

Here ΔV_{CE} is reduction in voltage across IGBT.

t_r is rise time of current.

I_o is load current.

Value of resistance is given as,

$$R > \frac{2.3L}{t_{off}}$$

Here t_{off} is off state of IGBT or its turn-off time.

Example 1.6.1 *The Thevenin equivalent of an IGBT gate drive circuit is a DC source of 10 V in series with a resistance R. The IGBT parameters are C_{gs} = 100 pF, C_{gd} = 150 PF and $V_{GS\ (TH)}$ = 3 V. Calculate the value of R so that the turn-on delay, i.e. time taken for V_{GS} to rise from zero to $V_{GS(TH)}$ is 5 ns.*

Solution : Fig. 1.6.16 shows the Thevenin equivalent circuit.

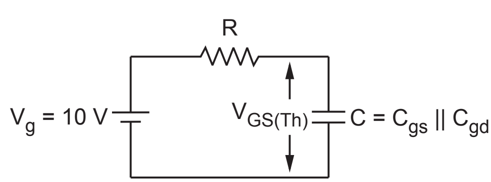


Fig. 1.6.16

Here 'C' is the parallel combination of C_{gs} and C_{gd} hence,

$$C = C_{gs} + C_{gd}$$
$$= 1000 \text{ pF} + 150 \text{ pF}$$
$$= 1150 \text{ pF}$$

The voltage across capacitor will be gate-source voltage. Hence

$$V_{GS} = v_g(1 - e^{-t/RC})$$

Here we have to determine value of 'R' for t = 5 nsec, $V_{GS} = V_{GS(Th)}$ = 3 V, C = 1150 pF and V_g = 10 V. Hence,

$$3 = 10\left(1 - e^{-5\times10^{-9}/(R\times1150\times10^{-12})}\right)$$

$$0.3 = 1 - e^{-4.3478/R}$$

$$0.7 = e^{-4.3478/R}$$

$$\therefore \quad R = 12.19\ \Omega \approx 12\ \Omega$$

1.6.7 Comparison of Power Devices

The power devices can be compared on the basis of switching frequency, gate drive circuit, power handling capacity etc. Table 1.6.1 shows the comparison of SCR, BJT, MOSFET and IGBT.

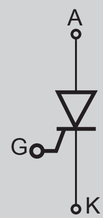
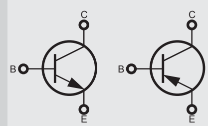
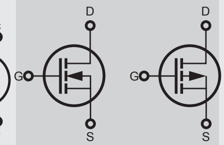
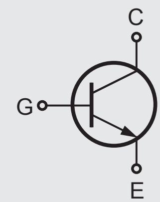
Sr. No.	Parameter	SCR	BJT	MOSFET	IGBT
1	Symbol				
2	Triggered i.e. latching or linear	Triggered or latching device	Linear trigger	Linear trigger	Linear trigger
3	Type of carriers in device	Majority carrier device	Bipolar device	Majority carrier device	Majority carrier device
4	Control of gate or base	Gate has no control once turned on	Base has full control	Gate has full control	Gate has full control
5	On-state drop	< 2 volts	< 2 volts	4-6 volts	3.3 volts
6	Switching frequency	500 Hz	10 kHz	upto 100 kHz	20 kHz
7	Gate drive	Current	Current	Voltage	Voltage
8	Snubber	Unpolarized	Polarized	Not essential	Not essential
9	Temperature coefficient	Negative	Negative	Positive	Approximately flat, but positive at high current
10	Voltage and current ratings	10 kV/ 4 kA	2 kV/1 kA	1 kV/50A	1.5 kV/400 A
11	Voltage blocking capability	Symmetric and asymmetric (both)	Asymmetric	Asymmetric	Asymmetric
12	Applications	AC to DC converters, AC voltage controllers, electronic circuit breakers	DC to AC converters, induction motor drives, UPS, SMPS, Choppers	DC choppers, low powers UPS, SMPS, brushless DC motor drives	DC to AC converters, AC motor drives, UPS, choppers, SMPS etc.

Table 1.6.1 Comparison of power devices

Review Questions

1. *Explain the characteristics of IGBT. Explain its operation.*

SPPU : Dec.-2000, Marks 5, May-10, Marks 6, Dec.-13, Marks 4

2. *Explain the characteristics of following devices : i) BJT ii) MOSFET iii) IGBT*
SPPU : Dec.-01, Marks 6; Dec.-07, Marks 8; Dec.-13, Marks 4
3. *Compare BJT, MOSFET and IGBT.*
SPPU : Dec.-11, Marks-5 April-17 (In sem), Marks 5, May-10, 11, 17, Marks 6
4. *State the advantages of IGBT over power MOSFET and power BJT.*
SPPU : May-2000, Marks 6, Dec.-2000, Marks 8; May-02,(In sem) Marks 5; April-17, May-17
5. *What is latchup in IGBT ? How it can be avoided? ?*
SPPU : Dec.-06, Marks 8; Dec.-07, May-12, Marks 6; Dec.-11, Marks 4
6. *Draw the vertical cross section and I-V characteristics of an IGBT.*
SPPU : May-01, Marks 4; Dec.-10, May-13, Marks 6
7. *Draw the forward biased SOA of the IGBT and explain how it is superior to that of power BJT.* **SPPU : May-03, Dec.-04, Marks 8, May-06, Dec.-09, Marks 6, Dec.-11, Marks 5**
8. *What is the difference between SOA of IGBT and power MOSFET ?*
SPPU : May-03, Marks 4
9. *What is the reason for body-source short in IGBT ?* **SPPU : May-06, Marks 6**
10. *Explain any one protection circuit for IGBT.* **SPPU : May-07, Marks 4**
11. *Compare and contrast with SCR.* **SPPU : May-18, Marks 4**
12. *Draw the V-I characteristics of IGBT. Mark and explain various operating regions and SOA of the IGBT.* **SPPU : April-19, Marks 4**
13. *Describe the concept of Safe operating areas of MOSFET and IGBT.*
SPPU : May-19, Marks 7
14. *Explain how the following devices can be operated as switch with necessary driving conditions : IGBT* **SPPU : April-19, Marks 3**

1.7 Performance Overview of Silicon, Silicon Carbide and GaN Based Power Devices

Silicon (Si) Power Devices : Silicon (Si) is used as a main semiconductor in manufacturing power devices such as thyristors, diodes, BJTs, MOSFETs and IGBTs.

Silicon Carbide (SiC) Power Devices : Silicon Carbide (SiC) is used as main semiconductor in manufacturing power devices. It has better characteristics compared to silicon.

Gallium Nitride (GaN) Power Devices : Gallium Nitride is very hard, mechanically stable, wide bandgap semiconductor. Hence it has higher breakdown strength, faster switching speed, higher thermal conductivity and lower on state resistance. Hence GaN based devices outperform silicon based devices.

- Si, SiC and GaN can be compared on the basis of bandgap, breakdown field strength, electron Nobility and thermal conductivity.

- GaN based devices have better switching performance and efficiencies.
- SiC power MOSFETs offer very high operating voltages from 900 V to 15 kV.
- SiC offers higher operational junction temperature and higher thermal conductivity.
- SiC based power devices offer higher voltage blocking capabilities and lower on state resistance.
- The SiC based power devices have lower inter-terminal capacitance, that allows higher switching frequencies.
- Thermal conductivity of GaN is lower than that of SiC. Hence SiC based power devices have better performance under high temperature conditions compared to GaN.
- GaN has better recovery characteristics compared to Si and SiC. Hence it has higher operating frequencies.
- GaN and SiC have high critical field compared to Si. Hence GaN and SiC based power devices can handle high voltages and lower leakage currents.
- GaN have highest electron mobility. SiC have electron mobility higher than Si, but lower than GaN. Hence GaN have highest operating frequency of all devices.
- SiC power device technology is more mature than GaN. Hence manufacturing of SiC based power devices is more economical.
- Production of SiC based power MOSFETs is easier than GaN.
- Availability of flawless manufacturing techniques for SiC and GaN based power devices are limiting their application in power converters.

1.8 Repetitive and Nonrepetitive Ratings of SCR, GTO, Power MOSFET and IGBT

1.8.1 SCR Ratings

SPPU : Dec.-2000,01,04,06,07,10, May-07,10,12, April-19

Every SCR is manufactured for particular voltage, current and switching frequencies. If these values are exceeded, then the SCR can be damaged. These are called ratings. The SCRs are to be protected when any of the voltage or current rating tries to exceed. In this section we will discuss these concepts.

Current Ratings of SCR

The current flow through the SCR increase the junction temperature. The excess current flow may exceed the permissible junction temperature and damage the device. Hence the current should not exceed the rated value. The various current ratings are discussed next :

i) **Average current rating (I_T)** : The average current rating is the maximum repetitive average current that can flow through the SCR. The power loss in the SCR depends upon average current flowing through it. If the SCR is operating at sufficiently high frequency, then switching loss will also be significant. Hence switching losses may be added to losses due to average current.

ii) **RMS current rating (I_{TR}) :** The RMS current rating is the maximum repetitive rms current that can flow through the SCR. The RMS current rating is same as average current rating for DC current. This rating is required to prevent excessive heating in metallic joints, leads and interfaces of SCRs.

iii) **Surge current rating (I_{TSM}) :** The surge current rating is the peak amplitude of the surge current that the SCR can withstand only limited number of times in its life cycle. The surge current is normally specified as number of cycles and peak amplitude. The SCR may be damaged when surge current rating and its number of cycles are exceeded.

iv) **$i^2 t$ rating :** The i^2t rating is the measure of thermal energy that the device can abosrb for a short period of time. Whenever fault occurs, the fast acting fuse clears such fault. Due to the fault, thermal energy is generated in the device also. The fuse should clear the fault and device should be protected. Hence $i^2 t$ rating is used to determine about how long the device can absorb the thermal energy. The fuse must clear the fault before the device is damaged due to exceeding $i^2 t$ rating.

v) **$\frac{di}{dt}$ rating :** The $\frac{di}{dt}$ rating specifies maximum allowable rate of change of current through the device. Due to rapid variations in anode current, the carriers doesnot spread across the junctions at the turn-on time. Hence they are concentrated in a small area of the device, creating local heating. This is called *hot-spot* created due to high current density in the restricted area of the junctions. Because of this, the junction temperature increases and the device may be damaged. The $\frac{di}{dt}$ rating specifies maximum allowable variations in anode current, so that the device will not be damaged. Normally it is specified in Amperes/microseconds and typical values are from 50 A/μs to 800 $A / \mu\, sec$.

Voltage Ratings of SCR

The SCR blocks the forward and reverse voltages. The voltage ratings mainly specify the maximum allowable voltages those the device can withstand without damaging the junctions.

i) **Peak repetitive forward blocking voltage (V_{DRM}) :** This is the maximum voltage that the SCR can block in the forward direction. It is specified with maximum allowable junction temperature and gate open circuited. If this rating is exceeded, the device turns on. Note that device is not damaged.

ii) **Peak repetitive reverse voltage (V_{RRM}) or peak inverse voltage (PIV) :** This is the maximum voltage that the device can withstand repetitively in the reverse blocking state. It is also specified at maximum allowable junction temperature. The device is damaged, when this rating is exceeded.

iii) **Non-repetitive peak reverse voltage (V_{RSM}) :** This the maximum transient voltage that the device can safely withstand in the reverse direction. This transient is not repetitive. The device is damaged if transient is exceeded or it occurs repetitively. This transient voltage can be increased by putting a diode of same current rating in series with the SCR. The total transient voltage capacity becomes due to SCR and diode.

iv) $\frac{dv}{dt}$ **rating :** The $\frac{dv}{dt}$ rating specifies maximum allowable rate of change of forward voltage that the device can withstand in forward direction. If the forward voltage variations exceed $\frac{dv}{dt}$ rating, then the device turns on. Such turn-on is false triggering and disturbs the operation of the controller.

The other ratings are : turn-on time (t_{on}), turn-off time (t_q), gate voltage (v_g), gate current (i_g), latching current (I_L) and holding current (I_H). These ratings we have discussed earlier.

1.8.2 GTO Ratings

i) **Maximum repetitive forward voltage (V_{DRM}) :** This is the maximum forward voltage that GTO can block assuming that supply voltage is sinusoidal. For this voltage to withstand, gate of GTO is reverse biased or connected to cathode through a low value resistance.

ii) **Repetitive reverse peak voltage (V_{RRM}) :** This is the maximum reverse voltage that the GTO can withstand. This voltage can be repeatedly applied without destroying the device.

iii) **RMS current rating (I_{TR}) :** This is the maximum RMS on state repetitive current that the GTO can withstand without damaging.

iv) **Average current rating (I_T) :** This is the maximum average current rating that the GTO can handle.

v) $\int i^2 dt$ **rating :** This is the maximum value of surge current integral for half cycle sine wave surge that the GTO can handle. The junction temperature is assumed to be at the maximum value before the surge.

vi) $\frac{di}{dt}$ **rating :** This is the maximum rate of change of forward current during turn on. GTO is damaged if this rating is exceeded.

vii) **Peak non-repetitive surge current (I_{TSM}) :** This is the maximum allowable value of half sinusoidal nonrepetitive surge current. This pulse is assumed to be applied when GTO is operating at its maximum junction temperature.

1.8.3 Power MOSFET Ratings

i) **Maximum Drain-Source Voltage (V_{DSS}) :** This is the maximum drain-source voltage of the MOSFET without causing avalanche break-down. It is assumed that the gate-source is short circuited and device is at 25 °C.

ii) **Continuous on State Drain Current (I_D) :** This is the maximum DC current that the MOSFET can handle in the forward direction. The device is assumed to be at 25 °C. This current depends upon maximum power dissipation, maximum on-state resistance and its temperature dependence.

iii) **Peak on State Drain Current (I_{DM}) :** This is the peak current of the MOSFET that can be handled at maximum junction temperature.

iv) **Break-down Voltage (BV_{DSS}) :** This is the maximum blocking voltage between the drain and the source at given drain current with gate shorted to the source. It has positive temperature coefficient.

v) **Threshold Gate Voltage ($V_{GS(th)}$) :** This is the gate-source voltage at which MOSFET turns-on and current starts flowing between drain to source. It has negative temperature coefficient.

vi) $\frac{dv}{dt}$ **rating :** This is the maximum permissible rate of rise of off-state voltage across the Drain-source of the MOSFET.

vii) **Maximum Gate-source Voltage (V_{GS}) :** This is the maximum gate to source voltage that can be applied. It depends upon the thickness and the characteristics of the gate oxide layer.

1.8.4 IGBT Ratings

i) **Collector Emitter Breakdown Voltage (BV_{CES}) :** This is the maximum collector emitter voltage that leads to breakdown of the IGBT. The gate-emitter are assumed to be shorted.

ii) **Maximum Average Forward Current (I_{CE}) :** This is the maximum average current from collector to emitter that the IGBT can handle in on state.

iii) **Repetitive Peak Collector Current ($I_{CE(peak)}$) :** This is the maximum value of peak current that can be allowed when the IGBT is in on state. The peak value is assumed to be half sine pulse.

iv) **Maximum Gate-emitter Voltage (V_{GES}) :** This is the maximum value of gate-emitter voltage with collector-emitter shorted.

v) $\int i^2 dt$ **rating :** This is the maximum allowable value of integration of over current so that IGBT doesnot destroy.

vi) Critical $\frac{di}{dt}$ **:** This is the critical rate of rise of collector current so that the IGBT is not damaged.

vii) Critical $\frac{dv}{dt}$ **:** This is the critical rate of rise of collector emitter voltage so that IGBT is not damaged.

viii) Junction Temperature (T_j) **:** This is the maximum chip temperature at which normal operation is possible. Exceeding this temperature may damage the IGBT.

ix) Maximum Power Dissipation (P_c) **:** This is the maximum allowable power dissipation of IGBT so that it is not damaged.

Review Questions

1. *Explain the following ratings :*
   (i) $i^2 t$ *rating* **SPPU : Dec.-01, Marks 8**
   (ii) $\frac{dv}{dt}$ *rating* **SPPU : May-12, Marks 8**
   (iii) $\frac{di}{dt}$ *rating* **SPPU : Dec.-2000, 06, 07, Marks 8, May-07, Marks 5**
   (iv) Surge current rating **SPPU : Dec.-01, Marks 8**
   (v) Average on state current **SPPU : May-10, Marks 8, Dec.-10, Marks 6**
2. *Write the short note on repetitive and non repetitive ratings of SCR.* **SPPU : Dec.-04, Marks 12**
3. *Explain following rating of SCR :* V_{RRM} **SPPU : April-19, Marks 2**

1.9 SCR Gate Characteristics

SPPU : May-01,11,19, Dec.-06

In the previous section we studied V-I characteristics of SCR. Now we will have a closer look towards gate characteristics of the SCR. Fig. 1.9.1 shows the gate trigger characteristics.

The gate voltage is plotted with respect to gate current in the above characteristics. $I_{g(\max)}$ is the maximum gate current that can flow through the SCR without damaging it. Similarly $v_{g(\max)}$ is the maximum gate voltage to be applied. Similarly $v_{g(\min)}$ and $I_{g(\min)}$ are minimum gate voltage and current, below which SCR will not be turned-on. Hence to turn-on the SCR successfully the gate current and voltage should be

$$I_{g(\min)} < I_g < I_{g(\max)}$$

and $$v_{g(\min)} < v_g < v_{g(\max)}$$

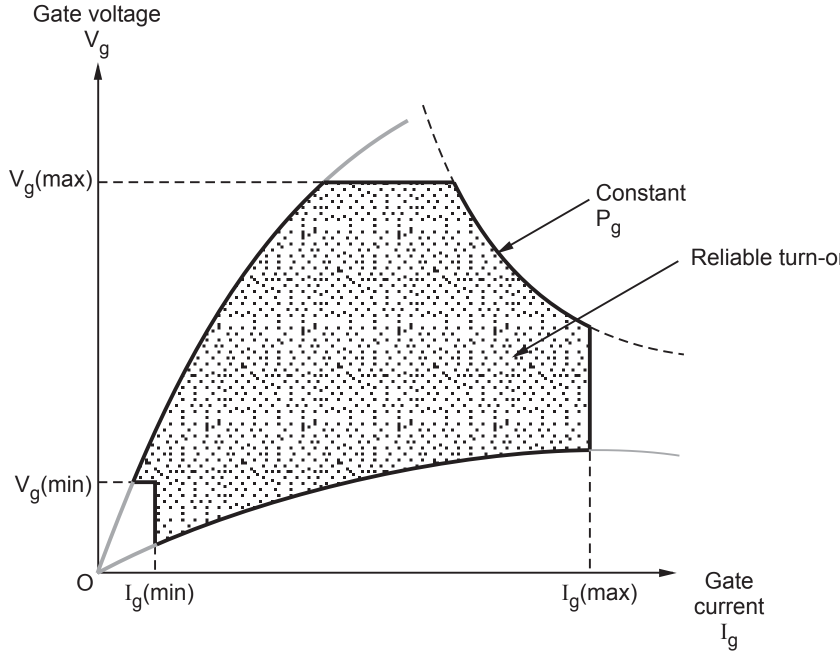


Fig. 1.9.1 Gate trigger characteristics

The characteristic of Fig. 1.9.1 also shows the curve for constant gate power (P_g). Thus for reliable turn-on, the (v_g, i_g) point must lie in the shaded area in Fig. 1.9.1. It turns-on SCR successfully. Note that any spurious voltage/current spikes at the gate must be less than $v_{g(\min)}$ and $I_{g(\min)}$ to avoid false triggering of the SCR. The gate characteristics shown in Fig. 1.9.1 are for DC values of gate voltage and current.

1.9.1 Pulsed Gate Drive

Instead of applying a continuous (DC) gate drive, the pulsed gate drive is used. The gate voltage and current are applied in the form of high frequency pulses. The frequency of these pulses is upto 10 kHz. Hence the width of the pulse can be upto 100 micro seconds. The pulsed gate drive is applied for following reasons (advantages) :

(i) The SCR has small turn-on time i.e. upto 5 microseconds. Hence a pulse of gate drive is sufficient to turn-on the SCR.

(ii) Once SCR turns-on, there is no need of gate drive. Hence gate drive in the form of pulses is suitable.

(iii) The DC gate voltage and current increases losses in the SCR. Pulsed gate drive has reduced losses.

(iv) The pulsed gate drive can be easily passed through isolation transformers to isolate SCR and trigger circuit.

1.9.2 Requirement of Gate Drive

The gate drive has to satisfy the following requirements :

(i) The maximum gate power should not be exceeded by gate drive, otherwise SCR will be damaged.

(ii) The gate voltage and current should be within the limits specified by gate characteristics (Fig. 1.9.1) for successful turn-on.

(iii) The gate drive should be preferably pulsed. In case of pulsed drive the following relation must be satisfied :

(Maximum gate power × pulse width) × (Pulse frequency) ≤ Allowable average gate power

(iv) The width of the pulse should be sufficient to turn-on the SCR successfully.

(v) The gate drive should be isolated electrically from the SCR. This avoids any damage to the trigger circuit if in case SCR is damaged.

(vi) The gate drive should not exceed permissible negative gate to cathode voltage, otherwise the SCR is damaged.

(vii) The gate drive circuit should not sink current out of the SCR after turn-on.

Example 1.9.1 *For an SCR gate cathode characteristics is given as $V_g = 1 + 10\ I_g$. Gate source voltage is a rectangular pulse of 15 V with 20 μs duration. For an average power dissipation of 0.3 watt and peak gate drive power of 5 watt, calculate :*

i) The value of R_g (series resistor in gate circuit)

ii) Triggering frequency

iii) Duty cycle of triggering pulse. **SPPU : May-11, Marks 6**

Solution : Given data :

$V_g = 1 + 10\ I_g$

$P_{g(av)} = 0.3$ W

$P_{g(peak)} = 5$ W

i) Value of R_g

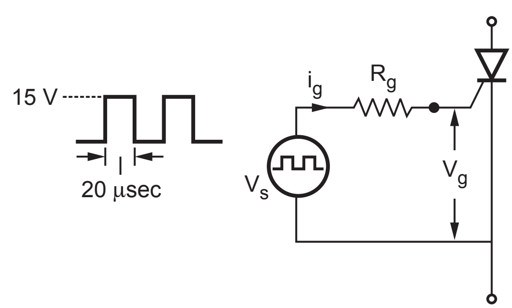


Fig. 1.9.2 Gate drive for SCR

When the gate pulse is applied, power dissipation in the gate will be peak value,

$$P_{g(peak)} = V_g \times I_g$$

Putting for $P_{g(peak)} = 5$ W and $V_g = 1 + 10\ I_g$,

$$5 = (1+10 I_g) \times I_g$$

$$-10 I_g^2 + I_g - 5 = 0$$

$$\therefore \qquad I_g = -0.759 \text{ or } 0.659 \text{ A}$$

Since I_g cannot be negative, we take I_g = 0.659 A.

During the on-pulse of gate drive,

$$V_s = I_g R_g + V_g$$

$$= I_g R_g + 1 + 10 I_g$$

Putting values of V_s = 15 V and I_g = 0.659 A,

$$15 = 0.659\ R_g + 1 + 10 \times 0.659$$

$$\Rightarrow \qquad R_g = 11.24\ \Omega$$

ii) Triggering frequency

$$\text{Duty cycle} = \frac{P_{g(av)}}{P_{g(peak)}} = \frac{0.3}{5} = 0.06$$

$$\therefore \quad \text{Duty cycle} = \frac{T_{on}}{T} = 0.06$$

$$\text{or} \quad \frac{20 \times 10^{-6}}{T} = 0.06 \quad \Rightarrow \quad \text{T} = 3.3333 \times 10^{-4} \text{ sec}$$

$$\text{Frequency,} \quad \text{f} = \frac{1}{T} = \frac{1}{3.3333 \times 10^{-4}} = 3000 \text{ Hz}$$

3) Duty cycle of triggering pulse

As obtained above,

$$\text{Duty cycle} = 0.06$$

Example 1.9.2 *The gate-cathode characteristic of a triac is given by $v_g = 2 + 5I_g$. A triggering pulse train with an amplitude of 10 V, ON period of 10 μsec is applied to the gate through a 10 Ω series register. Calculate :*

i) Peak gate power.

ii) Triggering frequency to obtain an average gate power of 0.5 W.

SPPU : Dec.-06, Marks 6

Solution : i) To obtain peak gate power

Fig. 1.9.3 shows the circuit diagram. From this diagram we can write,

$$10 \text{ V} = I_g \times \text{R} + V_g$$

$$10 \text{ V} = 10 I_g + 2 + 5 I_g$$

$$\therefore \qquad I_g = 0.533 \text{ A.}$$

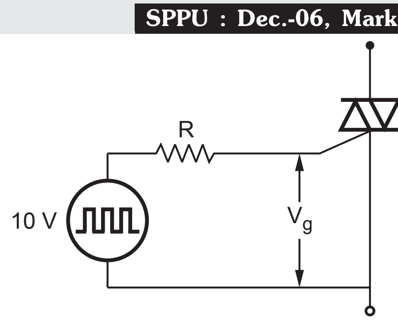


Fig. 1.9.3 Gate triggering circuit

Hence gate voltage can be obtained as,

$$V_g = 2+5\,I_g = 2+5\times 0.533 = 4.667$$

Here above V_g and I_g are calculated for peak amplitude of 10 V for the pulse train. Hence V_g and I_g indicate peak values.

$\therefore$ Peak gate power P_g (peak) $= V_g\,I_g = 4.667\times 0.533$

$= 2.48$ W.

ii) To obtain triggering frequency

$$\text{Duty cycle} = \frac{P_g(av)}{P_g(peak)} = \frac{0.5}{2.48} = 0.2$$

$$\text{Duty cycle} = \frac{T_{on}}{T} = T_{on}\times f$$

$$\therefore \quad f = \frac{Duty\,cycle}{T_{on}} = \frac{0.2}{10\times 10^{-6}} = 20 \text{ kHz.}$$

Review Questions

1. *Explain the SCR gate characteristics.*
2. *What are the requirements of gate drive ? What is pulse gate drive ?*
3. *Why high frequency pulse train is preferred for gating SCR ?* **SPPU : May-01, Marks 4**
4. *Explain the nature of gate characteristics and analyze the gate circuit requirements.* **SPPU : May-19, Marks 7**

1.10 R, RC and UJT Triggering of SCR

SPPU : Dec.-2000,01,03,06,08, May-2000,01,02,04,05, April-98,17, Oct.-98

Thyristor can be turned on by following :

i) Forward break-over voltage

ii) $\frac{dv}{dt}$ triggering

iii) Exceeding internal device temperature

iv) Focusing light beam on the junction

v) Gate triggering.

The gate triggering is the most widely used method of turning on the thyristor. In this section we will study various types of gate triggering circuits.

1.10.1 Features of Firing Circuits

The triggering circuits are called firing circuits. We have already discussed the requirements of gate trigger circuits. The following features or requirements must be fulfilled by the firing circuit in addition to those discussed earlier.

i) The firing circuit should produce the triggering pulses for every thyristor at appropriate instants.

ii) The triggering pulses generated by the control circuit need to be amplified and passed through the isolation circuit. The triggering pulses generated by the control circuit have very small power. Hence their power is increased by pulse amplifier. Fig. 1.10.1 shows the scheme. The firing circuit operates at low voltage levels (5 to 20 volts). And the thyristor operates at high voltage levels (greater than 250 volts). Hence there must be electrical isolation between firing circuit and thyristor. This isolation is provided by the pulse transformer or optocouplers.

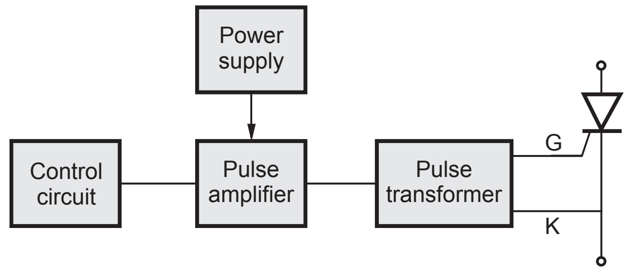


Fig. 1.10.1 Main blocks of firing circuit

1.10.2 R-Firing Circuit

Fig. 1.10.2 shows the simple R-firing circuit.

The resistance $R_{\min}$ is used to limit the gate current to its maximum value. If $I_{g(\max)}$ is maximum gate current and V_m is the peak supply voltage, then $R_{\min}$ will be,

$$R_{\min} \geq \frac{V_m}{I_{g(\max)}}$$

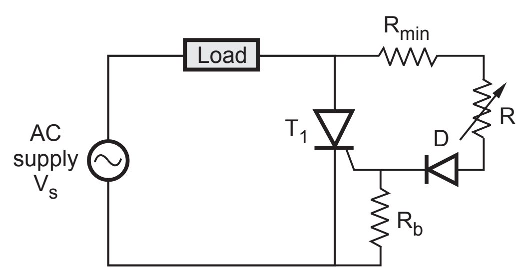


Fig. 1.10.2 R-firing circuit

The resistance R_b is the stabilizing resistance. The voltage across R_b should not exceed minimum gate voltage ($V_{g(\min)}$), otherwise thyristor will turn-on directly. Then the variable resistance R is used to trigger the thyristor T_1. When 'R' is zero, the triggering angle is minimum. The triggering angle increases as value of 'R' is increased. Fig. 1.10.3 shows the waveforms of this circuit.

The anode to cathode voltage and the gate current are in phase. Hence the triggering angle of T_1 cannot be delayed beyond 90°. In the above waveforms, observe that at points 'A' and 'B' gate voltage is same.

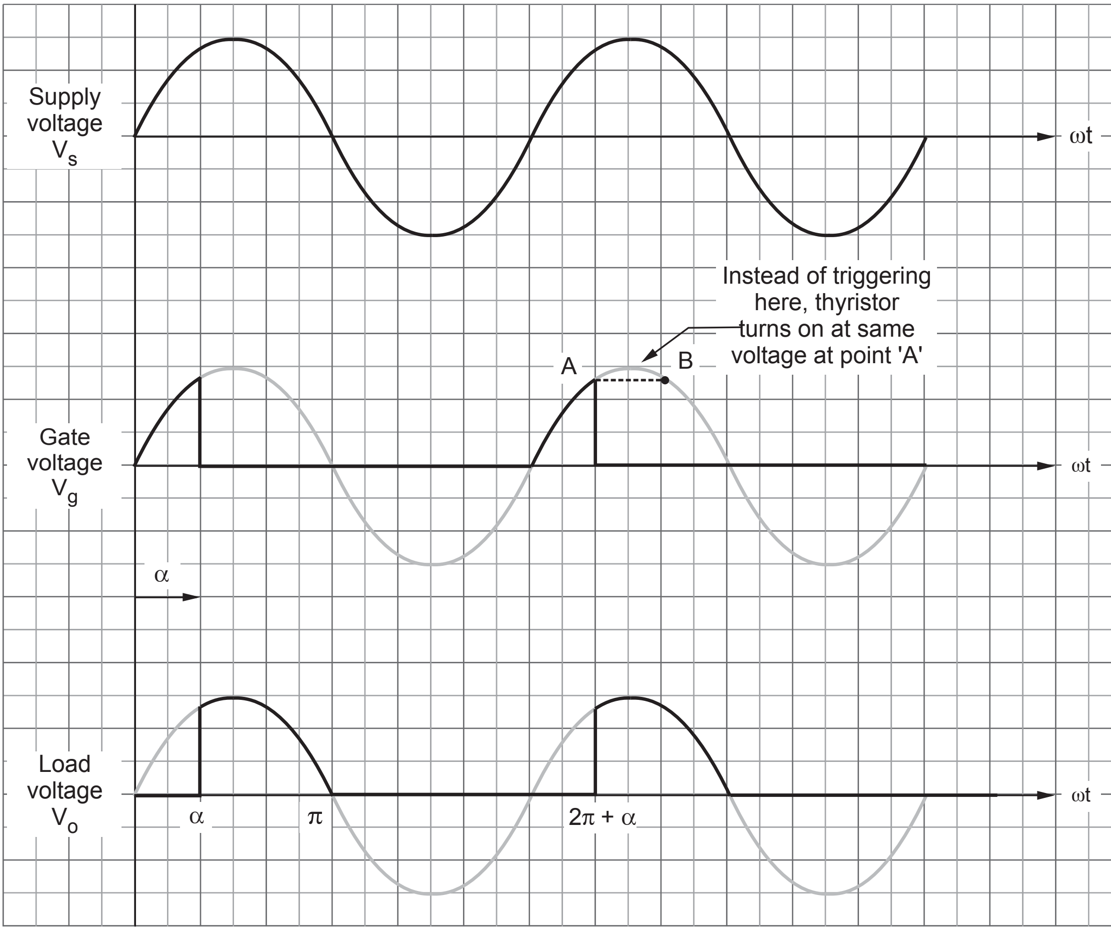


Fig. 1.10.3 Waveforms of R-firing circuit

If it is desired to trigger thyristor at point 'B', similar voltage appears at point 'A'. Hence thyristor will turn-on at point 'A' only. Hence maximum triggering angle will be 90°. This is because the gate current and anode voltage are in phase.

1.10.3 RC Firing Circuit

Fig. 1.10.4 shows the circuit diagram of RC-firing circuit. In the negative half cycle, the capacitor charges through diode D_2 to negative supply voltage. The capacitor charges to $-V_m$ (i.e. negative peak) of the supply. This is shown in waveforms of Fig. 1.10.5. The capacitor then discharges (i.e. charges towards positive) through resistance R during the positive half cycle of the

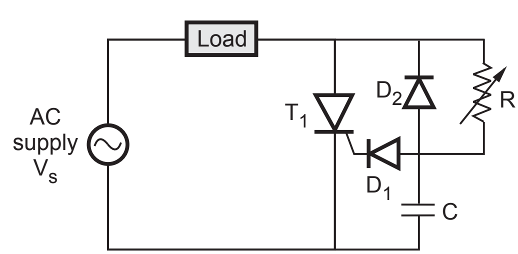


Fig. 1.10.4 RC half wave firing circuit

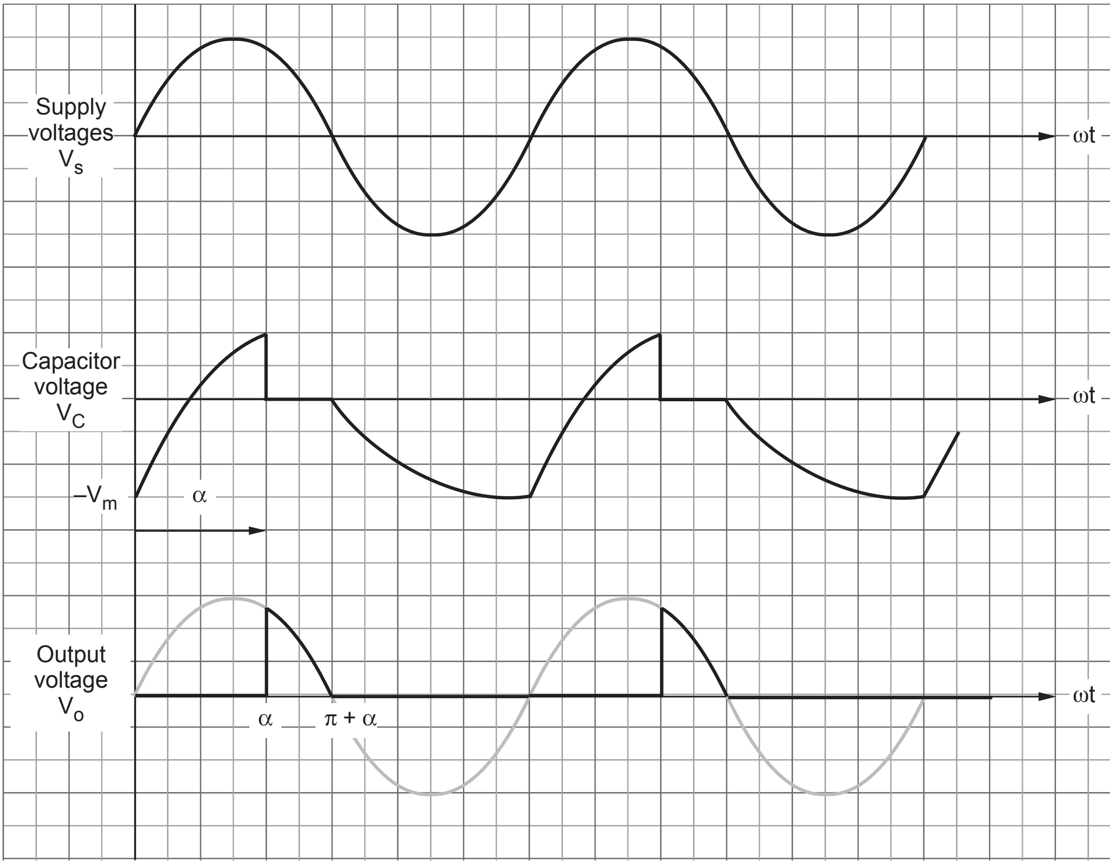


Fig. 1.10.5 Waveforms of half wave RC firing circuit

supply. The thyristor triggers when capacitor charges to value greater than $v_{g(\min)}$. Observe the capacitor voltage and load voltage waveforms in Fig. 1.10.5. The diode D_1 prevents the negative capacitor voltage appearing to gate of the thyristor. The triggering angle can be controlled from 0 to 180°. For zero output (i.e. maximum firing angle), the following relation holds :

$$RC \geq \frac{1.3}{2f} \qquad \text{... (1.10.1)}$$

Here f is the supply frequency. Since triggering is controlled only in one half cycle of the supply, this circuit is also called *half wave RC firing circuit.*

1.10.4 Full Wave RC-Firing Circuit

Fig. 1.10.6 shows the full wave RC-firing circuit. The supply to the thyristor is given through the uncontrolled rectifier. Hence both the half cycles are positive half cycles to the thyristor. The capacitor starts charging in every half cycle at the beginning.

Whenever the capacitor voltage reaches to the value greater than $v_{g(\min)}$, the thyristor turns-on. Fig. 1.10.7 shows the waveforms of this circuit. Once the thyristor turns-on, the capacitor voltage is clamped to zero, till next half cycle. The capacitor again starts charging from zero. The firing angle can be varied from 0 to 180°.

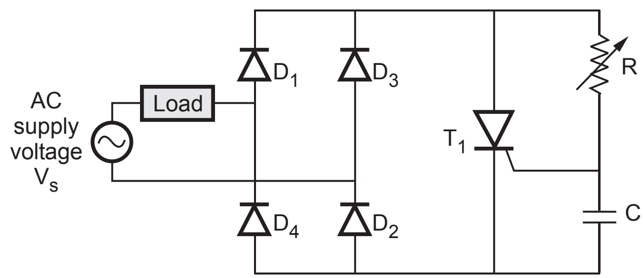


Fig. 1.10.6 Full wave RC firing circuit

The triggering is controlled in both the cycles. The following relation holds for maximum firing angle.

$$RC \geq \frac{0.157}{2\pi f} \qquad \text{... (1.10.2)}$$

Here f is the frequency of the supply.

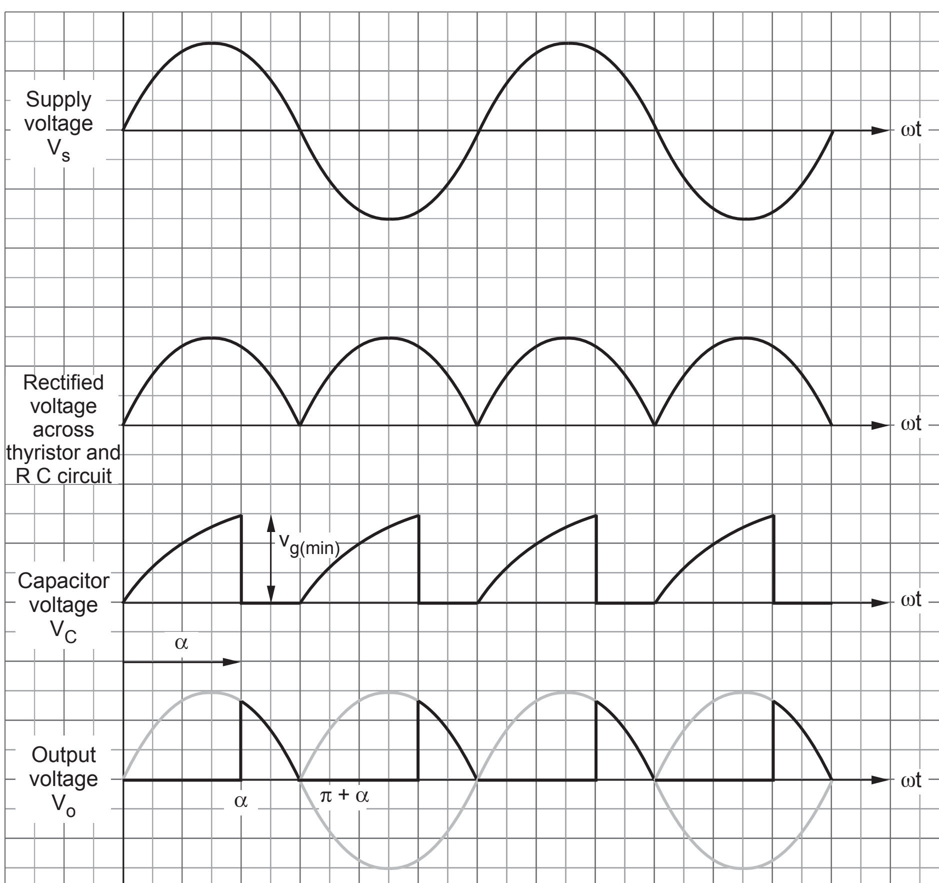


Fig. 1.10.7 Waveforms of full wave RC firing circuit

Examples for Understanding

Example 1.10.1 *Design a suitable RC triggering circuit for a thyristorized network operating on 220 V, 50 Hz supply. The specifications of the SCR are $V_{GT(\min)}$ = 5 V, $I_{GT(\max)}$ = 30 mA.*

Solution : Let us consider half wave RC firing circuit is used. This circuit is shown in Fig. 1.10.8. The given data is

V_s = 220 V, f = 50 Hz, $V_{GT(\min)}$ = 5 V,

$I_{GT(\max)}$ = 30 mA

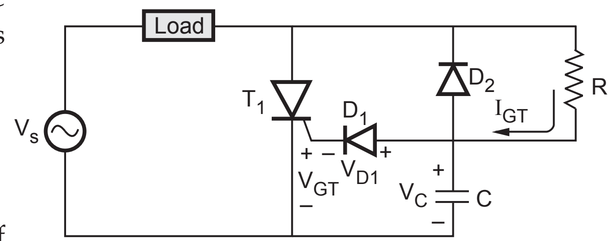


Fig. 1.10.8 RC half wave triggering circuit

The RC time constant of the half wave RC firing circuit is given by equation 1.10.1 as,

$$\text{RC} \;\geq\; \frac{1.3}{2f} \geq \frac{1.3}{2\times 50} \geq 0.013$$

The triggering circuit of Fig. 1.10.4 is reproduced above with various voltage drops.

The capacitor voltage is,

$$V_C \;=\; V_{GT} + V_{D1} \qquad \text{... (1)}$$

The SCR will turn-on when,

$$V_s \;\geq\; I_{GT}R + V_C \qquad \text{... (2)}$$

When above equation is satisfied, sufficient gate drive will be given to the SCR and it will turn-on. Putting expression for V_c from equation (1) in above equation,

$$V_s \;\geq\; I_{GT}R + V_{GT} + V_{D1}$$

$$\therefore \qquad \text{R} \;\leq\; \frac{V_s - V_{GT} - V_{D1}}{I_{GT}} \qquad \text{... (3)}$$

Here V_{GT} should be minimum and I_{GT} should be maximum to get maximum value of R. Putting values in above equation,

$$\text{R} \;\leq\; \frac{220-5-0.7}{30\times 10^{-3}} \qquad \text{Here } V_{D1} = 0.7 \text{ V}$$

$$\therefore \qquad \text{R} \;\leq\; 7143.33\ \Omega$$

$$\therefore \qquad \text{C} \;\geq\; \frac{0.013}{R} \geq \frac{0.013}{7143.33}$$

$$\therefore \qquad \text{C} \;\geq\; 1.82\ \mu F$$

1.10.5 UJT Triggering Circuit

The Unijunction transistor (UJT) triggering circuit is used in most of the applications. Fig. 1.10.9 shows the circuit diagram of UJT triggering circuit.

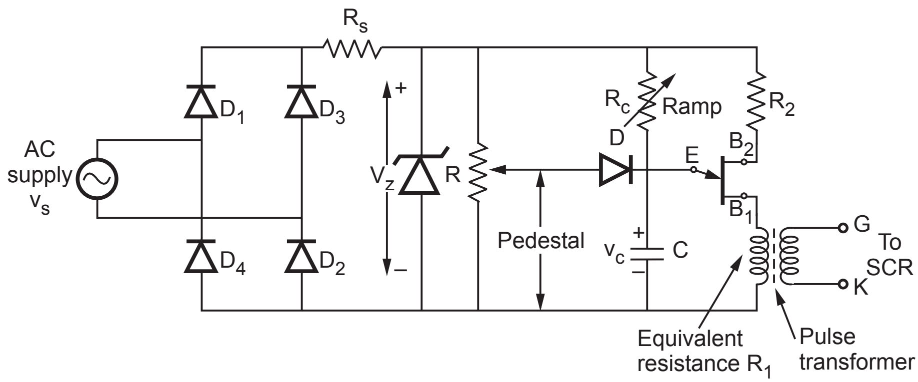


Fig. 1.10.9 UJT triggering circuit

Operation

- The supply voltage is rectified and given to the zener regulator. The voltage of zener diode is V_z. The zener diode clamps the rectified voltage to V_z as shown in the waveforms of Fig. 1.10.10. Hence voltage V_z is applied to the UJT circuit.
- The pedestal control indicates initial voltage level in the capacitor. It can be adjusted through resistance R. The ramp control indicates charging of capacitor from pedestal level. The waveforms of Fig. 1.10.10 shows these levels.
  i) The capacitor charges through resistance R_c. When the capacitor voltage becomes equal to V_p, the peak voltage of the UJT, it turns-on. The capacitor discharges through emitter (E), base (B_1) and primary of pulse transformer. The UJT is turned-on when the capacitor discharges. Since current flows through the primary of pulse transformer, a pulse is generated. This pulse as shown in Fig. 1.10.10 is the gate triggering pulse.

  ii) When the capacitor discharges to a voltage called valley voltage (V_v), the UJT turns-off and capacitor again starts charging from pedestal level. This mode of working of UJT is called *relaxation oscillator.*

  iii) The delay angle 'α' is the angle when first triggering pulse is generated in the half cycle. The charging of the capacitor can be varied by resistance R_c. Hence delay angle can also be varied. The UJT trigger circuit has the firing angle range from 0 to 180°.

The zener voltage acts as a supply voltage for UJT relaxation oscillator. This voltage becomes zero at 0, π, 2π, 3π, ...etc. The capacitor voltage also becomes zero at these

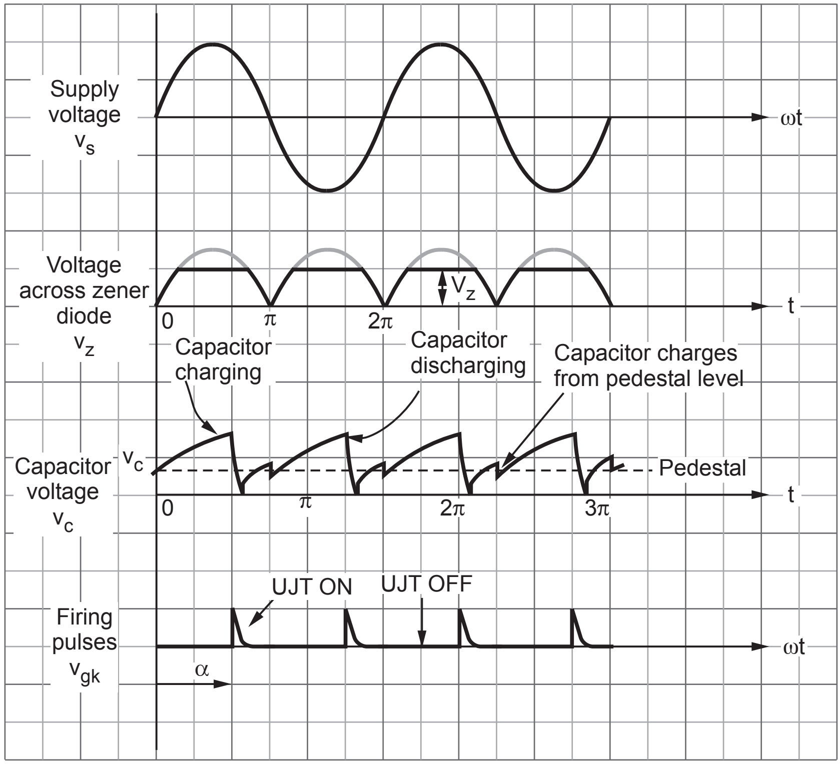


Fig. 1.10.10 Waveforms of UJT triggering circuit

instants. Thus synchronization with zero crossings is achieved. The UJT trigger circuit can be used to trigger SCRs in 1 ϕ converters, 1 ϕ AC regulators etc.

Mathematical analysis

The peak voltage at which UJT turns on is given as,

$$V_p = \eta V_{BB} + V_D \quad \text{... (1.10.3)}$$

Here V_p is the peak voltage

V_{BB} is the supply voltage of UJT circuit

V_D is forward drop of UJT

η is intrinsic standoff ratio.

The intrinsic standoff ratio (η) depends upon the UJT. The period of oscillation of the UJT relaxation oscillator is given as

$$\boxed{T = R_c\ C\ ln\left(\frac{1}{1-\eta}\right)} \quad \text{... (1.10.4)}$$

Fig. 1.10.11 shows the waveforms of free running UJT relaxation oscillator. The capacitor voltage waveform and UJT output are shown in the above figure. From Fig. 1.10.10, it is clear that triggering angle will be,

$$\alpha = \omega T$$

Hence from equation 1.10.4 we can write,

$$\boxed{\alpha = \omega\, R_c\, C\, ln\left(\frac{1}{1-\eta}\right)} \quad \text{... (1.10.5)}$$

This equation gives firing angle of UJT triggering circuit. Here $\omega = 2\,\pi\, f$ and f is the frequency of UJT oscillator. The resistance R_2 should be selected as follows :

$$\boxed{R_2 = \frac{0.7\left(R_{B2} + R_{B1}\right)}{\eta\, V_{BB}}} \quad \text{... (1.10.6)}$$

Here R_{B_2} and R_{B_1} are interbase resistance of the UJT. R_2 can also be calculated approximately as,

$$\boxed{R_2 = \frac{10^4}{\eta V_{BB}}} \quad \text{... (1.10.7)}$$

Note that this expression does not require R_{B_1} and R_{B_2}. Normally pulse transformer is connected at the base B_1 of UJT. Pulses are passed through pulse transformer. This provides isolation between SCR circuit and UJT triggering circuit. The resistance of pulse transformer primary can be denoted by R_1. This resistance controls width of the triggering pulse. From Fig. 1.10.11, this width is given as,

Width of triggering pulse, $\tau_2 = R_1 C$ ... (1.10.8)

More accurately this pulse width will be,

$$\tau_2 = (R_1 + R_{B_1})C \quad \text{... (1.10.9)}$$

Here we have considered the interbase resistance R_{B_1} also. If leakage current of UJT is given, then R_1 can be calculated using following equation,

$$V_{BB} = I_{leakage}(R_1 + R_2 + R_{B_1} + R_{B_2}) \quad \text{... (1.10.10)}$$

Here $I_{leakage}$ is the leakage current of UJT.

The maximum value of R_c is given as,

$$R_{c\,(\max)} = \frac{V_{BB} - V_p}{I_p} \quad \text{... (1.10.11)}$$

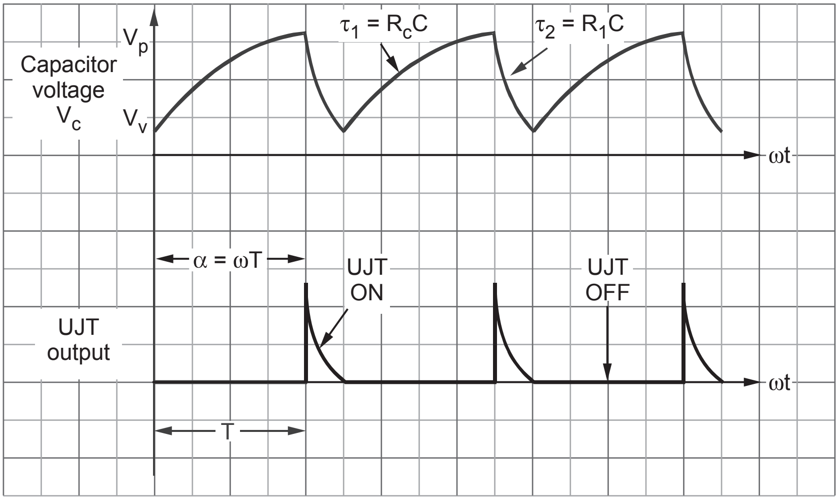


Fig. 1.10.11 Waveforms of free running UJT relaxation oscillator

and the minimum value of R_c is given as,

$$R_{c(\min)} = \frac{V_{BB} - V_v}{I_v} \quad \text{... (1.10.12)}$$

Here V_p is peak voltage

I_p is peak current

V_v is valley voltage

I_v is valley current

1.10.6 Pedestal Circuit with Cosine Modified Ramp

Fig. 1.10.12 shows the pedestal circuit having cosine modified ramp control.

- In the above circuit, the zener voltage is given to pedestal control and base of UJT.
- But the charging of capacitor C_1 takes place by rectified voltage.
- The pedestal voltage can be varied by resistance R_1.
- The charging of capacitor C_1 is cosine modified and its rate can be varied by resistance R_2.
- The firing angle can be controlled by controlling the pedestal voltage.

Advantages of cosine modified ramp control

(i) The control characteristics is linear.

(ii) Control gain is high.

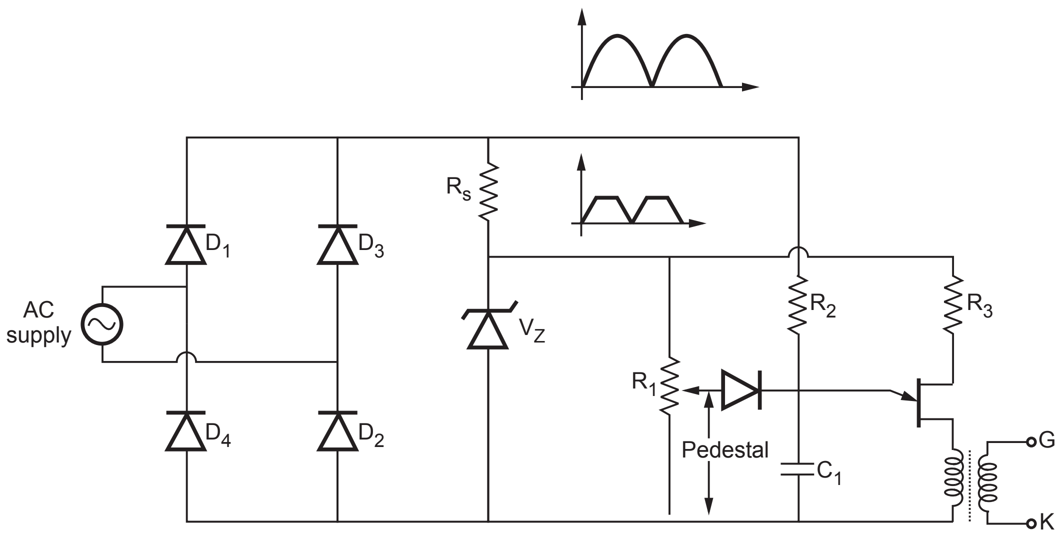


Fig. 1.10.12 Pedestal circuit with cosine modified ramp

Examples for Understanding

Example 1.10.2 *A UJT is used to trigger the thyristor whose minimum gate triggering voltage is 6.2 V. The UJT ratings are :*

$\eta = 0.66$, $I_p = 0.5\ mA$, $I_v = 3\ mA$,

$R_{B1} + R_{B2} = 5\ k\Omega$, *leakage current = 3.2 mA*

$V_p = 14\,V$ *and* V_v *= 1 V.*

Oscillator frequency is 2 kHz and capacitor $C = 0.04\ \mu F$. *Design the complete circuit.*

Solution : From equation 1.10.4,

$$T = R_c\, C\, ln\left(\frac{1}{1-\eta}\right)$$

Here $T = \frac{1}{f} = \frac{1}{2\times 10^3}$, since $f = 2$ kHz and putting other values,

$$\frac{1}{2\times 10^3} = R_c \times 0.04 \times 10^{-6}\, ln\left(\frac{1}{1-0.66}\right)$$

$$R_c = 11.6\ k\Omega$$

The peak voltage is given as,

$$V_p = \eta\, V_{BB} + V_D$$

Let V_D = 0.8, then putting other values,

$$14 = 0.66\, V_{BB} + 0.8$$

$$V_{BB} = 20\ \text{V}$$

The value of R_2 is given by equation 1.10.6 as,

$$R_2 = \frac{0.7\left(R_{B2}+R_{B1}\right)}{\eta\, V_{BB}} = \frac{0.7\left(5\times 10^3\right)}{0.66\times 20}$$

$$\therefore \qquad R_2 = 265\ \Omega$$

Value of R_1 can be calculated by equation (1.10.10) as,

$$V_{BB} = I_{leakage}\left(R_1+R_2+R_{B1}+R_{B2}\right)$$

$$20 = 3.2\times 10^{-3}\ \left(R_1+265+5000\right)$$

$$R_1 = 985\ \Omega$$

The value of $R_{c\,(\max)}$ is given by equation (1.10.11),

$$R_{c\,(\max)} = \frac{V_{BB}-V_p}{I_p} = \frac{20-14}{0.5\times 10^{-3}}$$

$$R_{c\,(\max)} = 12\ k\Omega$$

Similarly the value of $R_{c\,(\min)}$ is given by equation (1.10.12),

$$R_{c\,(\min)} = \frac{V_{BB}-V_v}{I_v} = \frac{20-1}{3\times 10^{-3}}$$

$$R_{c\,(\min)} = 6.33\ k\Omega$$

Fig. 1.10.13 shows the completely designed circuit.

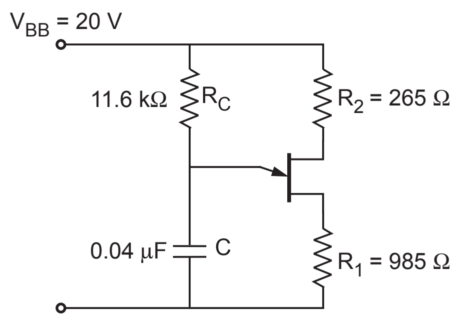


Fig. 1.10.13 UJT triggering circuit of example (1.10.2)

Example 1.10.3 *Design the UJT triggering circuit for SCR. Given - V_{BB} = 20 V, η = 0.6, $I_p = 10$ μA, $V_v = 2V$, I_v = 10 mA. The frequency of oscillation is 100 Hz. The triggering pulse width should be 50 μs.*

Solution : The frequency f = 100 Hz

$$\therefore \qquad T = \frac{1}{f} = \frac{1}{100}$$

From equation (1.10.4),

$$T = R_c C\, ln\left(\frac{1}{1-\eta}\right)$$

Putting values in above equation,

$$\frac{1}{100} = R_c C\, ln\left(\frac{1}{1-0.6}\right)$$

$$\therefore \qquad R_c C = 0.0109135$$

Let us select $C = 1\mu F$. Then R_c will be,

$$R_c = \frac{0.0109135}{1\times10^{-6}} = 10.91 \text{ k}\Omega$$

The peak voltage is given as,

$$V_p = \eta V_{BB} + V_D$$

Let V_D = 0.8 and putting other values,

$$V_p = 0.6\times20+0.8 = 12.8 \text{ V}$$

The minimum value of R_c can be calculated from equation (1.10.12) as,

$$R_{c(\min)} = \frac{V_{BB}-V_v}{I_v} = \frac{20-2}{10\times10^{-3}} = 1.8 \text{ k}\Omega$$

Value of R_2 can be calculated from equation (1.10.7) as,

$$R_2 = \frac{10^4}{\eta V_{BB}}$$

$$= \frac{10^4}{0.6\times20} = 833.33\ \Omega$$

Here the pulse width is given, i.e. 50 μ s.

Hence, value of R_1 will be,

$$\tau_2 = R_1 C \quad \text{from equation (1.10.8)}$$

The width τ_2= 50 μ sec and C = 1 μ F, hence above equation becomes,

$$50\times10^{-6} = R_1\times1\times10^{-6}$$

$$\therefore \quad R_1 = 50\ \Omega$$

Thus we obtained the values of components in UJT triggering circuit as,

$$R_1 = 50\ \Omega, \quad R_2 = 833.33\ \Omega$$

$$R_c = 10.91 \text{ k}\Omega, \quad C = 1\ \mu\text{F}.$$

Example 1.10.4 *A capacitor used in the UJT oscillator circuit is charged by a constant current source. The value of the capacitor is 0.5 μ F and that of the constant current is 1 mA. The sawtooth voltage of oscillator is found to have a crest value of 8.5 volts and valley level of 2.5 V. Calculate the frequency of the oscillator.*

Solution : Given data is,

$$C = 0.5\ \mu F$$

$$i_c = 1 \text{ mA constant current charging}$$

$$V_p = 8.5 \text{ V}, \quad V_v = 2.5 \text{ V}$$

The waveform of capacitor is sawtooth. Hence discharge period can be neglected. The voltage across capacitor is given as,

$$V_p = \frac{1}{C}\int_0^T i_c\, dt + V_v$$

As given by above equation, the capacitor charges to V_p at the end of period T. The residual voltage on capacitor is V_v. Putting values in above equation,

$$8.5 = \frac{1}{0.5\times 10^{-6}}\int_0^T 1\times 10^{-3}\, dt + 2.5$$

$$\therefore \quad 6 = \frac{1\times 10^{-3}}{0.5\times 10^{-6}}\int_0^T dt$$

$$\therefore \quad \int_0^T dt = 3\times 10^{-3}$$

$$\therefore \quad [t]_0^T = 3\times 10^{-3}$$

$$\therefore \quad T = 3\times 10^{-3}$$

$$\therefore \quad \text{Frequency, } f = \frac{1}{T} = \frac{1}{3\times 10^{-3}} = 333.33 \text{ Hz}$$

Example 1.10.5 *For an SCR, the gate cathode characteristic is given by a straight line with a gradients of 16 volts/ampere passing through the origin. The maximum turn-on time is* 4 μ sec *and the minimum gate current required to obtain this quick turn-on is 500 mA. If the gate source voltage is 15 V,*

a) Calculate the resistance to be connected in series with the SCR gate

b) Compute the gate power dissipation, given that pulse width is equal to turn-on time and average gate power dissipation is 0.3W. Also compute the maximum triggering frequency that will be possible when pulse firing is used.

SPPU : Dec.-09, Marks 6, May-12, Marks 10

Sol. : a) To calculate series resistance in gate

The gate-cathode characteristic has the gradient of 16 volts/Ampere. Hence gate cathode resistance is 16 Ω. Fig. 1.10.14 shows the equivalent gate-cathode circuit. In this circuit observe that gate-cathode is replaced by equivalent resistance of 16 Ω. The applied gate voltage is 15 V. A current of 500 mA passes through the circuit to trigger the SCR. By KVL to above circuit,

$$15 = (R+R_{GK})\times 500\times 10^{-3}$$

$$= (R+16)\times 500\times 10^{-3}$$

$$\therefore \quad R = 14\ \Omega$$

Thus a resistance of 14 Ω must be connected in series with the SCR gate.

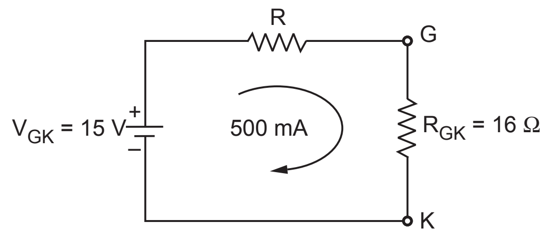


Fig. 1.10.14 Equivalent gate-cathode circuit

b) To compute gate power dissipation and maximum pulse frequency

In Fig. 1.10.14, observe that the gate current of 500 mA passes through the gate of 16 Ω resistance. The firing pulse of width 4 μs is applied to the gate. Hence the gate power dissipation is,

$$P_g = \int_0^{t_{on}} i^2(t)\, R_{GK}\, dt = \int_0^{4\mu s} (500\times 10^{-3})^2 \times 16\, dt$$

$$= 4\int_0^{4\mu s} dt = 16\ \mu W$$

The average gate power dissipation is 0.3 W. If we apply the multiple gate firing pulses, the gate power dissipation will increase. One pulse of 4 μs dissipates 16 μW. Hence average 0.3 W dissipation can be reached by,

$$f = \frac{0.3\times 1}{16\times 10^{-6}} = 18750$$

Thus the triggering frequency for pulse firing will be 18.75 kHz.

Examples with Solutions

Example 1.10.6 *A UJT is connected across a 20 V volts DC supply. The valley and peak point voltages are 1 V and 15 V. The period of UJT relaxation oscillator is 20 ms. Find the value of charging capacitor, if a charging resistor of 100 kΩ is used.*

Solution : The given data is,

$$V_{BB} = 220\ \text{V}$$

$$V_v = 1, \qquad V_p = 15\ \text{V}$$

$$\text{T} = 20\times 10^{-3}$$

$$R_C = 100\ \text{k}\Omega$$

The peak voltage of the UJT is given as,

$$V_p = \eta V_{BB} + V_D$$

Let $V_D = 0.8$

and putting values in above equation,

$$15 = \eta \times 20 + 0.8 \Rightarrow \eta = 0.71$$

From equation (1.10.4), $T = R_c C \ ln\left(\frac{1}{1-\eta}\right)$

Putting values in above equation,

$$20 \times 10^{-3} = 10 \times 10^3 \times C \ ln\left(\frac{1}{1-0.71}\right)$$

$$\therefore \quad C = 0.162 \ \mu F$$

Example 1.10.7 *Find the values of charging circuit components if the line synchronised UJT circuit can be operated to get delay angles of 20° to 160°. Assume suitable data if required.*

Solution : The given data is,

$$20° \leq \alpha \leq 60° \text{ i.e. } 0.349 \leq \alpha \leq 2.793$$

Let the operating frequency be f = 50 Hz.

$$\therefore \quad \omega = 2\pi f = 2\pi \times 50 = 100\ \pi$$

The firing angle is given by equation (1.10.5) as,

$$\alpha = \omega R_c C \ ln\left(\frac{1}{1-\eta}\right)$$

Let $\eta = 0.65$ and for $\alpha_1 = 0.349$,

$$0.349 = 100\pi \times R_{c1} C_1 ln\left(\frac{1}{1-0.65}\right)$$

$$\therefore \quad R_{c1} C_1 = 1.058 \times 10^{-3}$$

Similarly with $\alpha_2 = 2.793$,

$$2.793 = 100\pi \times R_{c2} C_2 ln\left(\frac{1}{1-0.65}\right)$$

$$\therefore \quad R_{c2} C_2 = 8.468 \times 10^{-3}$$

Let $C = C_1 = C_2 = 0.5\ \mu F$. Hence,

$$R_{c1} = \frac{1.058 \times 10^{-3}}{0.5 \times 10^{-6}} = 2.116 \ k\Omega$$

$$R_{c2} = \frac{8.468 \times 10^{-3}}{0.5 \times 10^{-6}} = 16.936 \text{ k}\Omega$$

Thus the resistance R_c should be varied from 2.116 kΩ to 16.936 kΩ. Hence a variable resistance of 20 kΩ can be used.

Example 1.10.8 *A line synchronized UJT relaxation oscillator, using a timing capacitor of 0.1 μF is to be designed for triggering a SCR in a 115 V, 60 Hz circuit. The UJT has the following data :*

$\eta = 0.63,\ V_p = 19.5\text{ V},\ I_p = 0.1\text{ mA},\ V_v = 1.5\text{ V},\ I_v = 5\text{ mA},$

$R_{BB} = 7K5,\ V_D = 0.5\text{ V}$, *normal leakage current with emitter open = 3 mA. Calculate*

i) Values of external resistance to be connected in base 1 and base 2 i.e. R_1 and R_2.

ii) Values of timing resistor if firing angle is to be varied from 20° to 160°.

SPPU : May-02, Marks 8

Solution : Given : C = 0.1 μF

$$\eta = 0.63,\ V_p = 19.5,\ I_p = 0.1\text{ mA}$$

$$V_v = 1.5\text{ V},\ I_v = 5\text{ mA}$$

$$R_{B1} + R_{B2} = 7.5\text{ k}\Omega$$

$$V_D = 0.5\text{ V},\quad I_{leakage} = 3\text{ mA}.$$

i) To calculate R_1 and R_2

$$V_p = \eta V_{BB} + V_D$$

$$V_{BB} = \frac{V_p - V_D}{\eta}$$

$$= \frac{19.5 - 0.5}{0.63} = 30.15\text{ V}$$

$$R_2 = \frac{0.7(R_{B2} + R_{B1})}{\eta V_{BB}}$$

$$= \frac{0.7 \times 7.5 \times 10^3}{0.63 \times 30.15} = 276.3\ \Omega$$

$$V_{BB} = I_{leakage}(R_1 + R_2 + R_{B1} + R_{B2})$$

$$30.15 = 3 \times 10^{-3}(R_1 + 276.3 + 7.5 \times 10^3)$$

$$\therefore \quad R_1 = 2390.3\ \Omega$$

ii) To obtain timing resistor

Here f = 60 Hz, therefore $\omega = 2\pi f = 2\pi \times 60 = 377$ rad/sec.

$$\alpha = \omega R_c C \ln\left(\frac{1}{1-\eta}\right)$$

For $\alpha = 20°$ i.e. 0.349 radians,

$$0.349 = 377 \times R_c \times 0.1 \times 10^{-6} \ln\left(\frac{1}{1-0.63}\right)$$

$$R_c = 9312.5\ \Omega$$

For $\alpha = 160°$ i.e. 2.792 radians,

$$2.792 = 377 \times R_c \times 0.1 \times 10^{-6} \ln\left(\frac{1}{1-0.63}\right)$$

$$R_c = 74.486\ \text{k}\Omega$$

Example 1.10.9 *An UJT triggering circuit is connected across a 20 V zener. The valley and peak point voltages are 1 V and 15 V respectively The intrinsic stand-off ratio is 0.75. It operates at a frequency of 1200 Hz. Find the charging capacitor if R = 5.6 kΩ.*

Solution : The given data is,

$$V_{BB} = 20\ \text{V}$$

$$V_v = 1, \quad V_p = 15$$

$$\eta = 0.75$$

$$f = 1200\ \text{Hz} \qquad \text{Hence T} = \frac{1}{f} = \frac{1}{1200}$$

$$R_c = 5.6\ \text{k}\Omega$$

The period of oscillation of UJT relaxation oscillator is given by equation 1.10.4 as

$$T = R_c C \ln\left(\frac{1}{1-\eta}\right)$$

Putting values in above equation,

$$\frac{1}{1200} = 5.6 \times 10^3 \times C \times \ln\left(\frac{1}{1-0.75}\right)$$

$$\therefore \quad C = 0.107\ \mu F$$

Examples for Practice

Example 1.10.10 : *A UJT trigger circuit is used to fire a PNPN device. It is supplied from a source across the SCR to be triggered through a 10 V zener. The valley and peak point voltages are found to be 1 V and 7 V respectively. Calculate the intrinsic stand-off ratio of UJT and frequency of relaxation oscillator if $R = 1\ k\Omega$ and $C = 1\ \mu F$.*

[Ans. : η = 0.62, f = 1033 Hz]

Example 1.10.11 : *An SCR is to be triggered using a relaxation oscillator, which has an UJT with $\eta = 0.7$, $I_p = 2\ \mu A$, $V_p = 16.5$ volts. Normal leakage current with emitter open is 3 mA, $V_v = 1$ volts, $I_v = 6$ mA, $R_{B_1 B_2} = 5.5\ k\Omega$. Triggering frequency is 100 Hz. With $C = 0.1\ \mu F$ design the UJT relaxation oscillator.*

[Ans. : $R_c = 83\ k\Omega$, $R_1 = 921.35\ \Omega$, $R_2 = 245.31\ \Omega$]

Example 1.10.12 : *An UJT used in a relaxation oscillator circuit is having $\eta = 0.7$, $V_v = 1V$ and the supply voltage to the circuit is 15 V. Design the suitable values of R and C given that the frequency of oscillation is 1 kHz. Peak current is 1 mA and valley current is 8 mA.*

[Hints and Ans. : $V_p = \eta V_{BB} + V_D = 11.3$ V, $T = R_c C \ ln\left(\frac{1}{1-\eta}\right) \Rightarrow R_c C = 8.3058 \times 10^{-4}$ sec

Let C = 0.3 μF, hence $R_C = 2.768\ k\Omega$, $R_{c(max)} = \frac{V_{BB} - V_p}{I_p} = 3700\Omega$, $R_{c(min)} = \frac{V_{BB} - V_V}{I_V} = 1750\Omega$ **]**

Review Questions

1. *Draw the circuit diagram of a line synchronized ramp and pedestal UJT triggering circuit for SCRs and explain its operation with the help of relevent waveforms.*
   SPPU : Dec.-03,06,13, May-01, Marks 8, Dec.-2000, 08,09, May-02, 17. Marks 10, Dec.-10, Marks 4, Dec.-11, Marks 5,
2. *State advantages of UJT triggering circuit.* **SPPU : Dec.-2000, Marks 10**
3. *Explain cosine modified controlled UJT triggering circuit for an SCR.*
   SPPU : Dec.-04, 05, Marks 4
4. *Draw and explain synchronized UJT triggering circuit for SCR with waveforms.*
   SPPU : April-17, Marks 6

1.11 Drive Circuit for MOSFET

SPPU : May-11, Dec.-18

The gate drive circuit for MOSFET should satisfy the following requirements :

i) The gate-source input capacitance should be charged quickly.

ii) MOSFET turns on when gate-source input capacitance is charged to sufficient level.

iii) To turn-off MOSFET quickly, the negative gate current should be sufficiently high to discharge gate-source input capacitance.

Fig. 1.11.1 shows the gate drive as per above requirements. The gate drive is applied across the terminals a-b. Initially the resistance R_1 is bypassed by C_1 and full drive voltage is applied to the gate. This charges the gate-source capacitance quickly. As the capacitor C_1 charges, the gate current reduces. Once the MOSFET is turned on required gate current is very small. When MOSFET is to be turned off, the voltage v_{a-b} is made zero. This applies capacitor voltage across gate-source in negative direction. Therefore charge on the gate-source capacitance is removed quickly. C_1 then discharges through R_1. The resistance R_2 provides additional discharge path for gate-source capacitance.

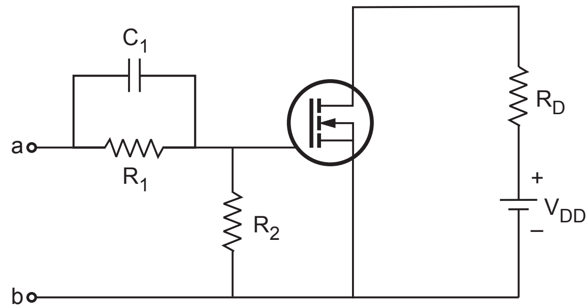


Fig. 1.11.1 Gate drive circuit

Review Questions

1. *Explain the typical gate drive circuit for MOSFET.* **SPPU : May-11, Marks 4**
2. *Draw the gate drive circuit for MOSFET.*
3. *Explain the gate drive circuit requirements for MOSFET and draw the sample drive circuit.* **SPPU : Dec.-18, Marks 6**

1.12 Driver Circuit for IGBT and MOSFET

SPPU : Dec.-2000,10, May-2000,13

Fig. 1.12.1 shows the driver circuit for IGBT which uses IR 2125 IC. (See Fig. 1.12.1 on next page).

- Here IR 2125 is the high voltage, fast switching MOS gate driver with single floating gate driver channel. This IC can be used to drive N-channel power MOSFET or IGBT.
- Over current flowing through the IGBT is detected through R_s and C_s terminal of the IC.
- The error pin of the IC indicates fault conditions.

Review Question

1. *Draw the typical driver circuit for the IGBT.* **SPPU : Dec.-2000, Marks 8; May-2000, Dec.-10 Marks 6; May-13, Marks 5**

1.13 Isolated Gate Drive Circuit

SPPU : May-11,12

1.13.1 Necessity of Isolation

We know that driver circuits operate at very low power levels. Normally the signal levels are 3 to 12 volts. Sometimes digital circuits and microprocessors are also used in the triggering circuits. The gate and base drives are connected to power devices which operate at high power levels. Fig. 1.13.1 shows this situation. Observe that drain of MOSFET can have voltages of 200 V. But base is connected to trigger circuit that have voltages of 5 V. If MOSFET is damaged and drain gate gets shorted, then high voltage

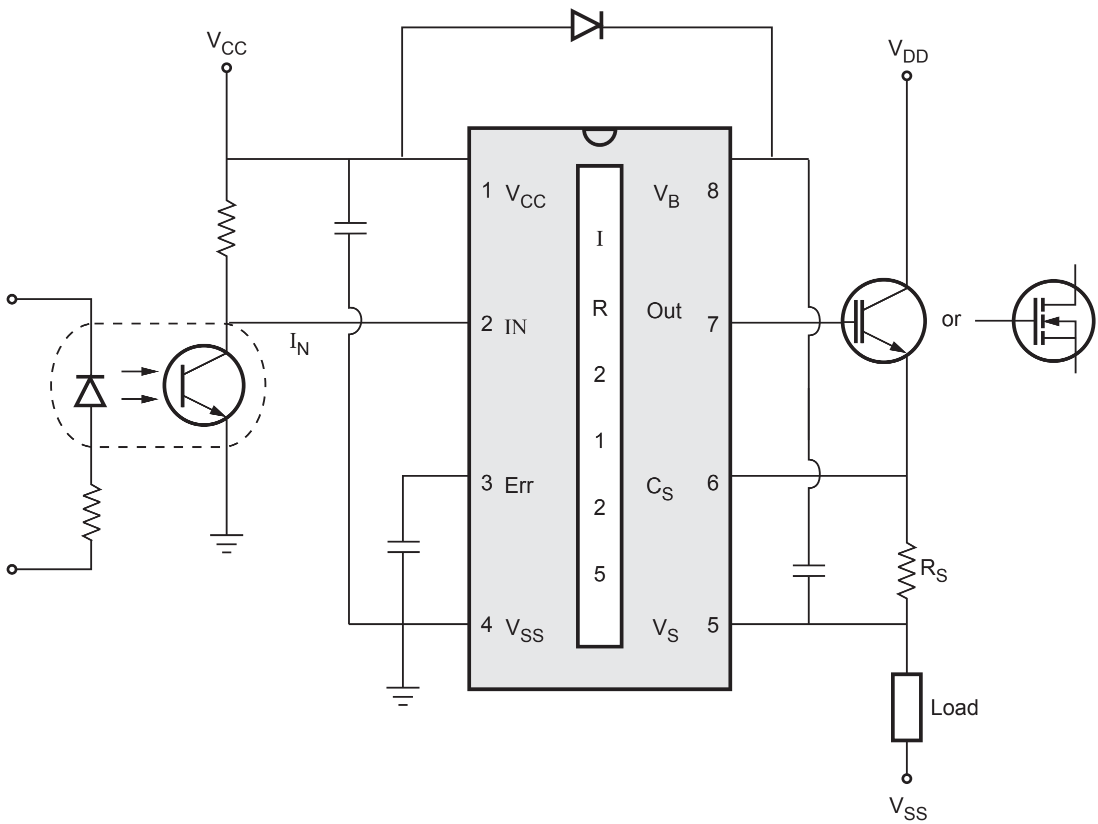


Fig. 1.12.1 Driver circuit for IGBT

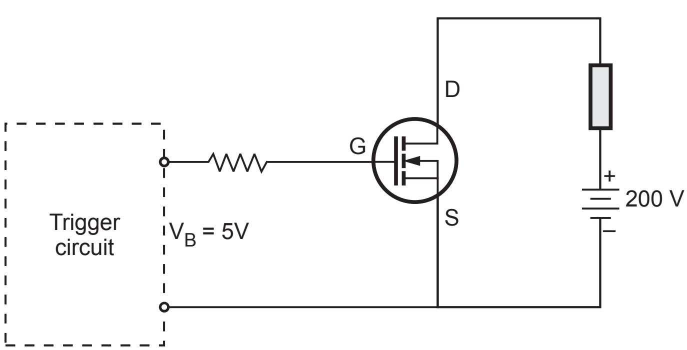


Fig. 1.13.1 Control / power levels

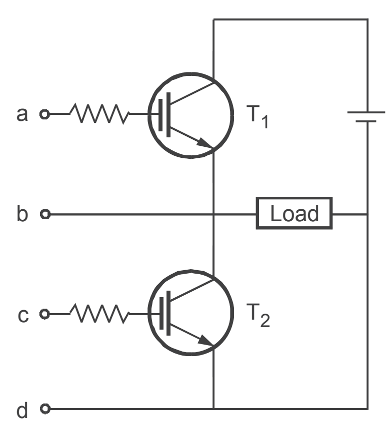


Fig. 1.13.2 Isolation of grounds

will get connected to trigger circuit. This will damage the trigger circuit also. This means trigger circuit is damage due to device damage. Therefore there must be some electric isolation between control and power circuit. There is one more reason for isolation.

Consider that the trigger circuit is deriving the two devices as shown in Fig. 1.13.2. Here observe that T_1 is given the drive between a-b. And T_2 is given the drive between c-d. The trigger circuit must isolate the two drives. If there is no electric isolation, the points 'b' and 'd' may be shorted due to common ground of the trigger circuit. Isolation can be obtained with the help of pulse transformers and optocouplers.

1.13.2 Isolation using Pulse Transformer

Pulse transformer has one primary and one or more secondary windings. It is normally used for pulsed mode of triggering Fig. 1.13.3 shows the isolation using pulse transformer.

In the above circuit, observe that triggering circuit is electrically isolated from IGBT. Hence if there is any electric damage to IGBT, there will be no effect on triggering circuit.

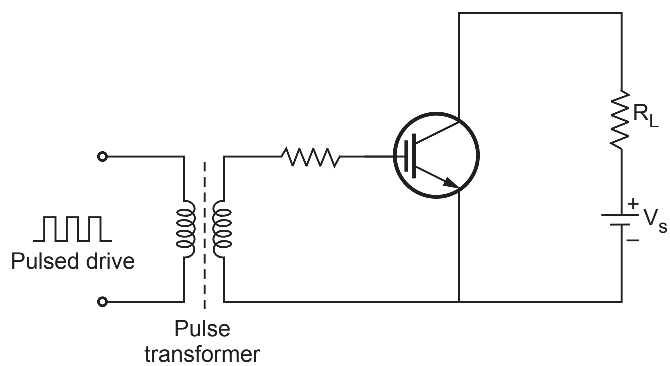


Fig. 1.13.3 Electric isolation using pulse transformer

Advantages

i) Pulse transformer does not need external power for its operation.

ii) It is very simple to use.

Disadvantages

i) Pulse transformer saturates at low frequencies hence it can be used only for high frequencies.

ii) Due to magnetic coupling, the signal is distorted.

1.13.3 Isolation using Optocouplers

Optocoupler consists of a pair of infrared LED and phototransistor Fig. 1.13.4 shows the symbol of optocoupler. When the signal is applied to the infrared LED, it turns on. It's light falls on phototransistor. Therefore phototransistor also starts conducting. There is no electric connection between LED and phototransistor.

Fig. 1.13.5 shows the triggering circuit that uses optocoupler. In this circuit the triggering pulses are given to the input (LED) of optocoupler. When 'V_g' is positive, LED turns-on. It's light falls on phototransistor. Hence it turns on. Therefore base of T_1 is connected to zero volts through phototransistor. Due to this, T_1 turns-on. Therefore the voltage V_{CC} is applied to gate of the MOSFET. Hence MOSFET turns on. When $V_g = 0$, the LED turns-off, therefore phototransistor also turn-off. Therefore base drive of T_1 goes to V_{CC} and it turn-off. When T_1 turns off, MOSFET gate voltage becomes zero. Therefore MOSFET turns-off. Thus gate drive circuit using optocoupler works.

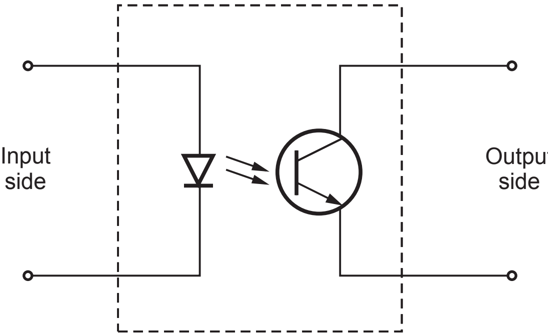


Fig. 1.13.4 Optocoupler

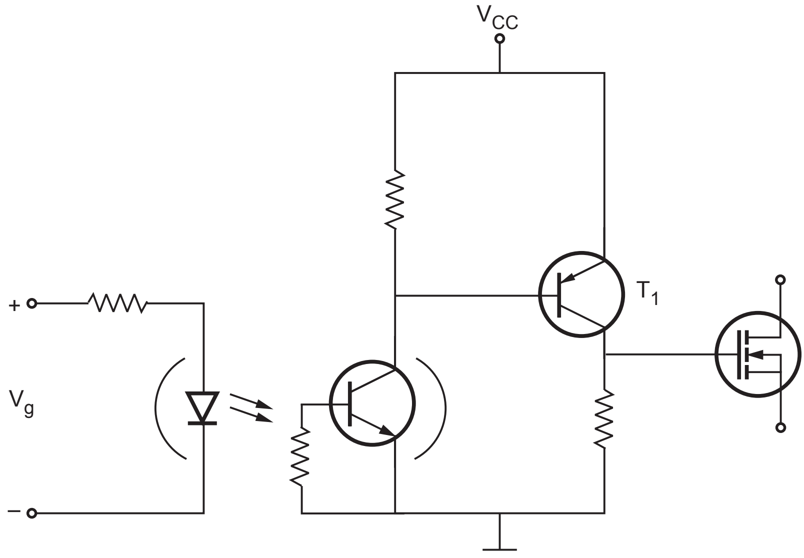


Fig. 1.13.5 MOSFET triggering circuit using optocoupler

Advantages

1) Very good response at low frequencies.

2) Compact and cheaper optocoupler devices are available.

Disadvantages

1) Optocoupler need, external biasing voltage for their operation.

2) High frequency response is poor.

Applications

Inverters, SMPS, Choppers, AC motor drives use optocouplers.

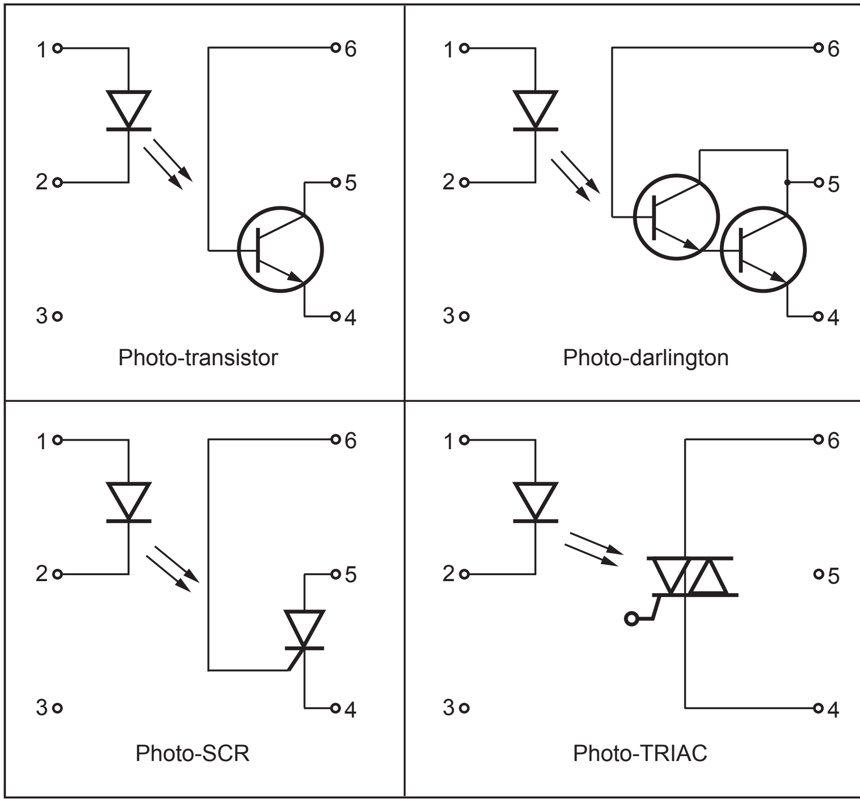


Fig. 1.13.6

1.13.4 Opto-Isolator Driving Circuits for SCR

What is an Opto-Isolator ?

Opto-isolator is also termed as an optical isolator or photo-coupler or Opto-coupler. It is one of electrical and electronics components used for transferring electrical signals from one circuit to another circuit (which are isolated) using light. In general, combination of LED (source) and phototransistor (sensor) is used in typical Opto-isolator IC packed in a single opaque package.

The rapidly changing voltages or other electrical parameters on one side of the circuit may cause damage to components on the other side of the circuit due to direct electrical contact. So, opto-isolator circuit can be used to isolate the high or rapidly changing voltages of one side of circuit.

Types of Opto-couplers : There are various types of opto-isolators which are classified based on various criteria such as number of channels, isolation voltage, type of packing, output voltage capacity, Current Transfer Ration (CTR), etc.

Opto-coupler circuit for SCR :

In opto-coupler isolation circuit, the low voltage gate drive circuit is optically isolated from the high voltage anode-cathode circuit as shown in above Fig. 1.13.7

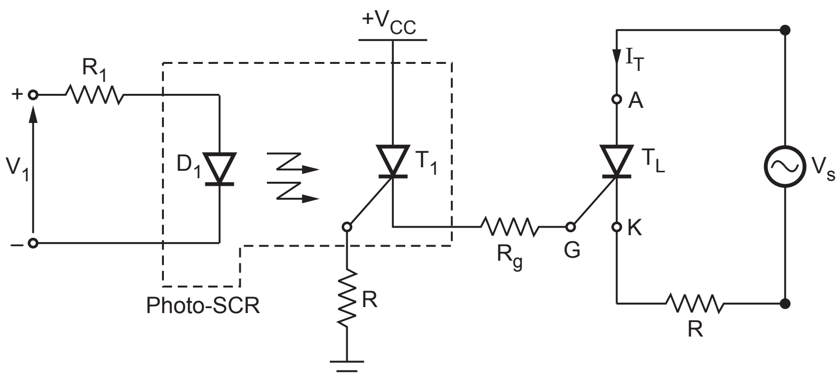


Fig. 1.13.7

In the above circuit, the gate drive circuit is connected to the light emitting diode D_1 through a current limiting resistor R_1. Pulses are sent to the light emitting diode D_1. These pulses turns on the photo SCR T_1 this in turn triggers the SCR T_L. Hence the gate drive circuit is optically isolated from the output circuit. Instead of using an opto-coupler, a pulse transformer can be used to magnetically isolate the gate drive circuit from the anode-cathode circuit.

Review Questions

1. *What is the necessity of isolation ? How it is implemented ?* **SPPU : May-11, Marks 6**
2. *Explain isolated gate drive circuit for MOSFET and explain its operation.* **SPPU : May-12, Marks 6**

1.14 Series and Parallel Operations of SCR's **SPPU : May-18**

The power-handling capabilities of power devices are generally limited by device operation, encapsulation, and cooling efficiency. Many high-power applications exist where a single device is insufficient and, in order to increase power capability, devices are connected in parallel to increase current carrying capability or connected in series to increase voltage ratings. Widely series connection of devices is utilized in HVDC transmission Thyristor and IGBT modules. Extensive parallel connections of IGBTs are most generally used in inverter applications. While connecting devices in series for high-voltage operation, both steady-state and transient voltages must be shared equally by each individual series device. When the power devices are connected in parallel to obtain higher current capability, the current sharing during both switching and conduction is achieved either by matching appropriate device electrical and thermal characteristics or external forced sharing techniques can be used.

Series Connection of SCR :

Necessity of SCR series connection : For some industrial applications, the demand for voltage and current ratings is so high that a single SCR cannot meet such requirements. In such cases, SCRs are connected in series in order to meet the high voltage demand and in parallel for meeting the high current demand.

- Series connection of power devices are often required to increase the overall voltage rating.
- For example we have to use SCR as a power switch in the power electronic circuit having voltage rating of 1000 volts.
- But we have a couple of power thyristors having voltage rating of 600 volts only.
- Then by connecting two thyristors in series we can implement the circuit.

Problems in SCR series operation

- When the thyristors are connected in series, they have small differences in their ratings. We know that in the world no two devices are having identical characteristics.
- Consider that two thyristors with same ratings are connected in series.
- The thyristor having highest internal resistance will have minimum leakage current.
- So high voltage will appear across it in off state.
- This creates voltage imbalance in the series connection.
- Hence equalization is necessary in the series connection.

Series configuration increases the voltage ratings of the thyristors while the current ratings remain the same. Thyristors of same type do not have same I-V and off state characteristics. Hence the voltage drop across the thyristors would be unequal. To solve this issue following parameters are set by default.

- Resistors are connected across each thyristor to avoid the unequal voltage sharing.
- The values of the resistors should be selected, such that equivalent resistance of thyristor and resistor would be same.
- To get best results following formula can be used to find out the value of resistor;

$$R = \frac{nv_{bm} - v_s}{(n-1)\Delta I_b}$$

Where, n = no. of SCR in the string

V_{bm} = Voltage blocked by the SCR having minimum leakage current.

ΔI_b = Difference between maximum and minimum leakage current flowing through SCRs.

V_s = Voltage across the string.

For SCR series operation, it should be ensured that each SCR rating is fully utilized and the system operation is satisfactory.

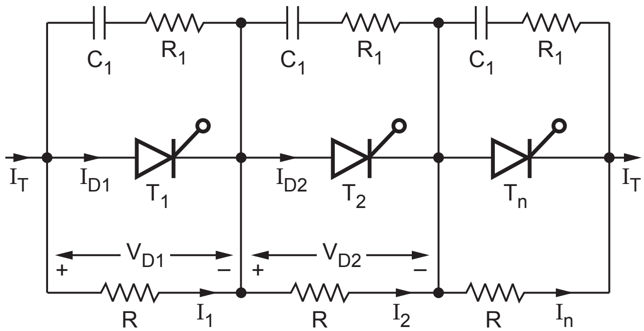


Fig. 1.14.1

String efficiency is a term that is used for measuring the degree of utilization of SCRs in a string.

The string efficiency of SCRs connected in series/parallel is defined as,

$$\text{String efficiency} = \frac{V_{oi} \text{ or actual current rating of the whole string}}{\text{nos of SCR in the string} \times V_{oi} \text{ or current rating of individual SCR}}$$

- In practice, this ratio is less than one.
- To get highest possible string efficiency, the SCRs connected in series string must have identical V-I characteristics.
- As a consequence, string efficiency can never be equal to one.
- However, unequal voltage/current sharing by the SCRs in a string can be minimized to a great extent by using external equalizing circuits.
- The measure of the reliability of string is given by a factor called derating factor DRF defined as

$$\text{DRF} = 1 - \text{String Efficiency}$$

Static Equalization :

- A uniform voltage distribution in steady state can be achieved by connecting a suitable resistance across each SCR such that each parallel combination has the same resistance.
- This shunt resistance R is called as static equalizing circuit.

- The series connected SCRs suffer from unequal voltage distribution across them during their turn-on and turn-off processes and also during their high frequency operation which means more frequent turning on and turning off of the devices.
- Thus a simple resistor used for static voltage equalization cannot maintain equal voltage distribution under transient condition.

Dynamic equalization

- During the turn-off process, due to the difference in junction capacitance, there is the differences in stored charge for the series connected SCRs.
- It will cause unequal reverse voltage sharing among the thyristors. This problem is solved by connecting capacitor across each thyristor.
- The value of capacitors should be large enough to swap the junction capacitance.
- A small resistance in series with this capacitance will limit the discharge current through the thyristor during turn-on process.
- The R_2 - C network will also act as a snubber network to limit the rate of rise of voltage across the thyristor at switch-on. The circuit arrangement for dynamic voltage equalization is shown in Fig. 1.14.1

Parallel operation of Thyristors :

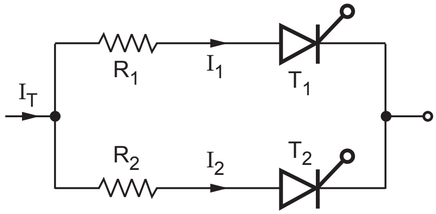
When the operating current is more than the individual current ratings of SCRs then more than one SCR is used in parallel. Due to different V-I characteristics SCRs of same rating there will be unequal current sharing in a string. Let a string consists of two SCRs in parallel and their current rating by 1 KA. From the V-I characteristics of the devices it can be seen that for operating volume V, current through SCR_1 is 1 KA and that through SCR_2 is 0.8 KA. Hence, SCR_2 is not fully utilized here. Though the string should withstand R KA theoretically it is only capable of handling 1.8 KA. So, the string efficiency is = 90 %.

Due to unequal current division when current through SCR increases, its temperature also increases which in turn decreases the resistance. Hence further increase in current takes place and this is a cumulative process. This is known as thermal 'run away' which can damage the device. To overcome this problem SCRs would be maintained at the same temperature. This is possible by mounting them on same heat sink. They should be mounted in symmetrical position as flux.

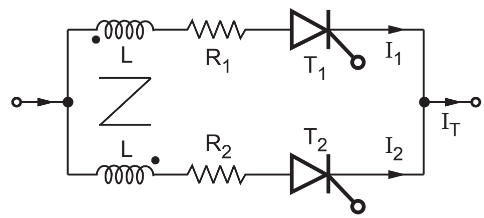
Static and Dynamic Current Sharing :

Resistors are used in case of static current sharing. When resistances are used in series, the losses may become high.

For dynamic current sharing, inductors are also used in addition to the resistors. In case of inductors (magnetically coupled), if current through the thyristor T_1 increases, an



(a) Static current sharing



(b) Dynamic current sharing

Fig 1.14.2

opposite polarity voltage would be induced (as of series coil of T_1) in the series coil of thyristor T_2 The current flow is increased through the thyristor, serving the purpose.

Review Question

1. *Discuss the needs of series operation of SCR and explain the static and dynamic equalizing circuit. State its advantages and limitations.* **SPPU : May-18, Marks 7**

1.15 Multiple Choice Questions

Q.1 A thyristor (SCR) is a ___________.

a P-N-P device
b N-P-N device
c P-N-P-N device
d P-N device

Q.2 Which terminal does not belong to the SCR?

a Anode
b Gate
c Base
d Cathode

Q.3 An SCR is a ___________

a four layer, four junction device
b four layer, three junction device
c four layer, two junction device
d three layer, single junction device

Q.4 Choose the false statement.

a SCR is a bidirectional device
b SCR is a controlled device
c In SCR the gate is the controlling terminal
d SCR are used for high-power applications

Q.5 In the SCR structure the gate terminal is located __________.

a near the anode terminal

b near the cathode terminal

c in between the anode and cathode terminal

d none of the mentioned

Q.6 The static V-I curve for the SCR is plotted for __________.

a Ia (anode current) vs Ig (gate current), Va (anode - cathode voltage) as a parameter

b Ia vs Va with Ig as a parameter

c Va vs Ig with Ia as a parameter

d Ig vs Vg with Ia as a parameter

Q.7 If the cathode of an SCR is made positive with respect to the anode and no gate current is applied then ____________________.

a all the junctions are reversed biased

b all the junctions are forward biased

c only the middle junction is forward biased

d only the middle junction is reversed biased

Q.8 For an SCR in the reverse blocking mode, (practically)

a leakage current does not flow

b leakage current flows from anode to cathode

c leakage current flows from cathode to anode

d leakage current flows from gate to anode

Q.9 With the anode positive with respect to the cathode and the gate circuit open, the SCR is said to be in the __________.

a reverse blocking mode

b reverse conduction mode

c forward blocking mode

d forward conduction mode

Q.10 For an SCR in the forward blocking mode (practically) __________.

a leakage current does not flow

b leakage current flows from anode to cathode

c leakage current flows from cathode to anode

d leakage current flows from gate to anode

Q.11 If you need a very efficient thyristor to control the speed of an AC fan motor. A good device to use would be __________.

a a 4-layer diode
b a PUT
c a triac
d a BJT

Q.12 The ________ can conduct current in either direction and is turned on when a break over voltage is exceeded.

a SCR
b diac
c SCS
d triac

Q.13 You need to design a relaxation oscillator circuit. The most likely device to use might be __________.

a an SCR
b a UJT
c a triac
d a 4-layer diode

Q.14 The ________ is like a diac with a gate terminal.

a triac
b SCR
c SCS
d none of the above

Q.15 The SCR can be triggered on by a pulse at the __________.

a gate
b anode
c cathode
d none of the above

Q.16 Thyristor that will enable you to turn it on with a pulse and also turn it off with a pulse. Which of the following should you recommend?

a an SCR
b an SCS
c a PUT
d a triac

Q.17 The minimum anode current that keeps a thyristor turned on is called the __________.

a holding current
b trigger current
c breakover current
d low-current drop out

Q.18 The triac is equivalent to ____________________.

a a four-layer diode

b two diacs in parallel

c a thyristor with a gate lead

d two SCRs in parallel

Q.19 The trigger voltage of an SCR is closest to __________.

a 0

b 0.7 V

c 4 V

d breakover voltage

Q.20 Exceeding the critical rate of rise produces ____________________.

a excessive power dissipation

b false triggering

c low-current drop out

d reverse-bias triggering

Q.21 Any thyristor can be turned off with __________.

a Breakover

b forward-bias triggering

c low-current drop out

d reverse-bias triggering

Explanations :

Q.1 Explanation : An SCR (silicon controlled rectifier) is a four layer p-n-p-n type device.

Q.2 Explanation : The SCR is having three terminals viz. anode, cathode and the gate.

Q.3 Explanation : SCR is a four layer p-n-p-n device which forms three p-n junctions.

Q.4 Explanation : It is a unidirectional device, current only flows from anode to cathode.

Q.5 Explanation : The gate is located near the cathode, because it allows fast turning on of the device when the gate signal is applied by forward biasing the second junction.

Q.6 Explanation : The curve is plotted for Ia vs Va for different values of gate current Ig.

Q.7 Explanation : The device is in the reverse blocking state (3rd quadrant) and only the middle junction is forward biased whereas other two are reversed biased.

Q.8 Explanation : In the reverse blocking mode, the gate current is zero and a reverse voltage is applied at the cathode-anode.

Q.9 Explanation : The SCR is in the forward blocking mode with its top and bottom junctions forward biased and the middle junction reversed biased.

Q.10 Explanation : In the forward blocking mode, the gate current is zero and only the middle J2 junction is reversed biased.

Answer Keys for Multiple Choice Questions :

Q.1	c	**Q.2**	c	**Q.3**	b	**Q.4**	a	**Q.5**	b
Q.6	b	**Q.7**	c	**Q.8**	c	**Q.9**	c	**Q.10**	b
Q.11	c	**Q.12**	b	**Q.13**	b	**Q.14**	a	**Q.15**	a
Q.16	b	**Q.17**	a	**Q.18**	d	**Q.19**	a	**Q.20**	b
Q.21	c								

❑❑❑

UNIT II

2 AC to DC Power Converters

Syllabus

Concept of line & forced commutation, Single phase Semi & Full converters using SCR for R and R-L loads and its performance analysis and numerical, Effect of source inductance, Significance of power factor and its improvement using PWM based techniques, Three phase Full converters using SCR for R load and its performance analysis, Single Phase PWM Rectifier using IGBT, Three Phase Controlled Rectifier Using IGBT, Difference between SCR based conventional rectifiers and IGBT based rectifiers.

Contents

2.1 Concept of Line and Forced Commutation

SPPU : Dec.-09,10, May-07,10,11, April-15,17

2.1.1 Principle of AC/DC Conversion (Controlled Rectifier)

- Controlled rectifiers are basically AC to DC converters. The power transferred to the load is controlled by controlling triggering angle of the devices. Fig. 2.1.1 shows this operation.
- The triggering angle 'α' of the devices is controlled by the control circuit.

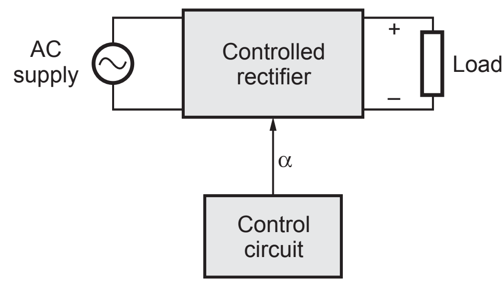


Fig. 2.1.1 Principle of operation of a controlled rectifier

- The input to the controlled rectifier is normally AC mains. The output of the controlled rectifier is adjustable DC voltage. Hence the power transferred across the load is regulated.

Applications :

The controlled rectifiers are used in battery chargers, DC drives, DC power supplies etc. The controlled rectifiers can be single phase or three phase depending upon the load power requirement.

2.1.2 Concept of Commutation

- **Definition :** Commutation is the collective operation, which turns of the conducting SCR.
- Commutation requires external conditions to be imposed in such a way that either current through SCR is reduced below holding current or voltage across it is reversed.

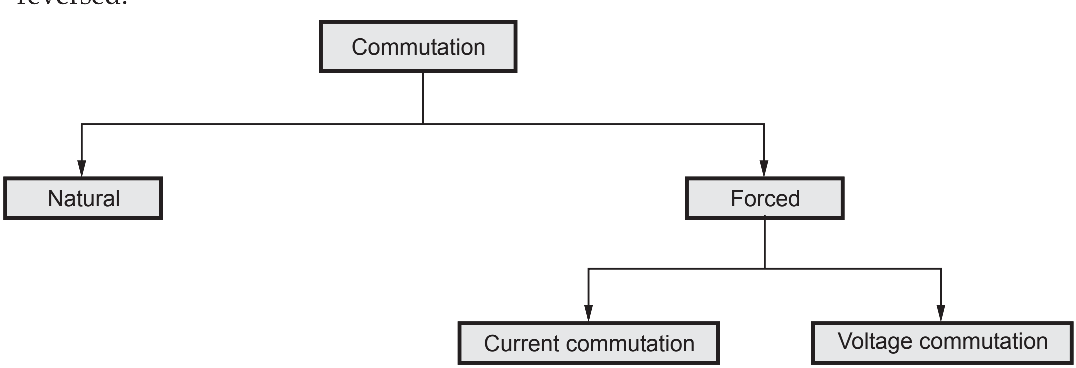


Fig. 2.1.2

- There are two types of commutation techniques.
- **Forced commutation :** It requires external components to store energy and it is used to apply reverse voltage across the SCR or reduce anode current below holding current of the SCR to turn it off.
- **Current commutation :** The SCR is turned off by reducing its anode current below holding current.
- **Voltage commutation :** The SCR is turned off by applying large reverse voltage across it.
- **Principle of line commutation**

The natural commutation does not need any external components. It uses supply (mains) voltage for turning off the SCR. Hence it is also called as line commutation.

- **Explanation**

Fig. 2.1.3 shows the circuit using natural commutation. It is basically half wave rectifier. The mains AC supply is applied to the input. The SCR is triggered in the positive half cycle at α. Since the SCR is forward biased, it starts conducting and load current i_o starts flowing. The waveforms of currents and voltages are shown in Fig. 2.1.4. Since the load is resistive,

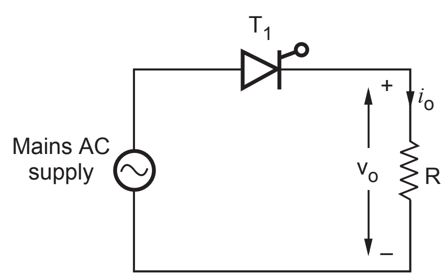


Fig. 2.1.3 A half wave rectifier uses natural commutation to turn off SCR

$$i_o = \frac{v_o}{R}$$

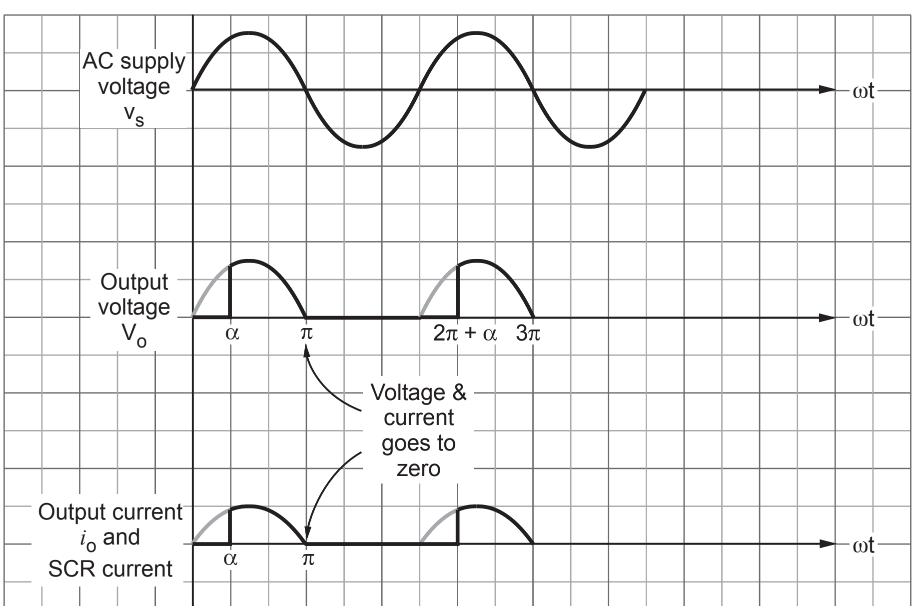


Fig. 2.1.4 Waveforms of half wave controlled rectifier to illustrate natural commutation

Hence the shape of the output current is same as output voltage. Observe that the output current is basically SCR current. At 'π' the supply voltage is zero. Hence current through SCR becomes zero. Therefore the SCR turns off. The supply voltage is then negative. This voltage appears across the SCRs and it does not conduct. Thus natural commutation takes place without any external components. Here note that natural commutation takes place only when the supply voltage is AC. Thus the controlled rectifiers use natural commutation.

Review Questions

1. *Define and explain the concept of commutation.* **SPPU : Dec.-10, Marks 2**
2. *Explain the principle of natural commutation. How it is used in controlled rectifiers ?* **SPPU : May-07,11, Marks 6**
3. *Explain the basic principle of phase controlled operation.* **SPPU : May-10, Marks 2**
4. *Compare line and forced commutation in SCR.* **SPPU : Dec.-09, Marks 2**
5. *What is commutation ? Explain natural commutation with forced commutation for SCR.* **SPPU : April-15, 17, Marks 3**

2.2 Single Phase Semiconverters (Half Bridge Converter)

SPPU : Nov.-07, Dec.-2000,03,04,06,08,09,10, April-15,16,17, May-03,06,07,08,10,12

The semiconverter is also called as half bridge converter.

2.2.1 Circuit Diagram

Fig. 2.2.1 shows the circuit diagram of single phase semiconverter. Observe that the semiconverter has two SCRs T_1 and T_2. There are two diodes D_1 and D_2. The input is 230 V_1 50 Hz AC supply. The output V_o of the semiconverter is DC. The load 'R' is connected across the output.

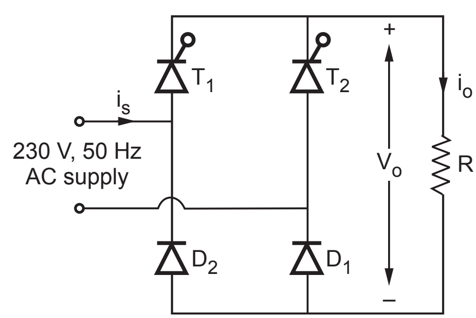


Fig. 2.2.1 Circuit diagram of 1 ϕ semiconverter

2.2.2 Working with Resistive Load

Let us consider the working of 1ϕ semiconverter having resistive load. In the positive half cycle of the supply, SCR T_1 and diode D_2 are forward biased. SCR T_1 is triggered at firing angle α. Current flows through the load. The equivalent circuit is shown below.

From the above figure, it is clear that, when $T_1 - D_1$ conducts,

$$V_o = V_s \quad \text{(i.e. supply voltage)} \qquad \text{... (2.2.1)}$$

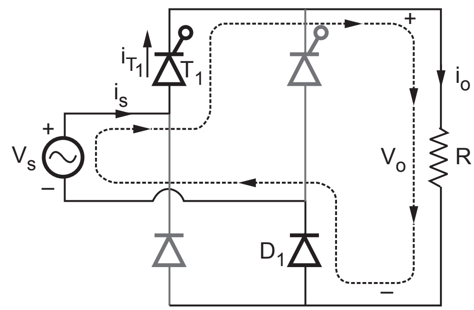


Fig. 2.2.2 Conduction of T_1 and D_1 in positive half cycle of the supply. Dotted line shows path of current flow

and $$i_o = \frac{V_o}{R} = \frac{V_s}{R} \qquad \text{... (2.2.2)}$$

Fig. 2.2.3 shows the waveforms of this circuit. The waveform of V_o is same as supply voltage V_s, when T_1 -D_1 conducts. Since the load is resistive, the output current waveform is same as voltage waveform. This is because,

$$i_o = \frac{V_o}{R}$$

Thus amplitude of V_o is only reduced by the factor 'R' to give i_o. But the shape of the current waveform does not change. In the Fig. 2.2.2 observe that i_{T1} is the SCR T_1 current, and i_s is the supply current. Basically i_o, i_{T1} and i_s is the same current. Hence,

$$i_o = i_s = i_{T1} \quad \text{(when } T_1 \text{ -} D_1 \text{ conducts)}$$

These currents are in the same direction and flow in the same loop. The waveforms of these currents are also shown in Fig. 2.2.3. (See Fig. 2.2.3 on next page.)

SCR T_1 and diode D_1 conduct till π. at π supply voltage is zero. Hence current through SCR T_1 drops to zero. Hence T_1 turns-off. After π, the supply voltage is negative and T_1 is reverse biased. Hence the output voltage V_o is also zero.

At $\pi + \alpha$, SCR T_2 is triggered. It starts conducting, since it is forward biased because of negative cycle of the supply. The current i_o flows through load, T_2 and D_2. Such equivalent circuit is shown in Fig. 2.2.4.

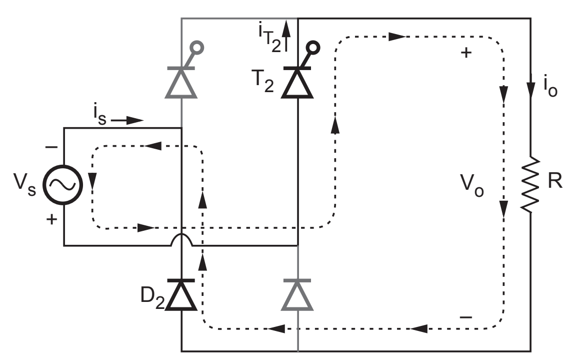


Fig. 2.2.4 Conduction of $T_2 - D_2$ in negative half cycle of the supply. Dotted line shows path of current flow

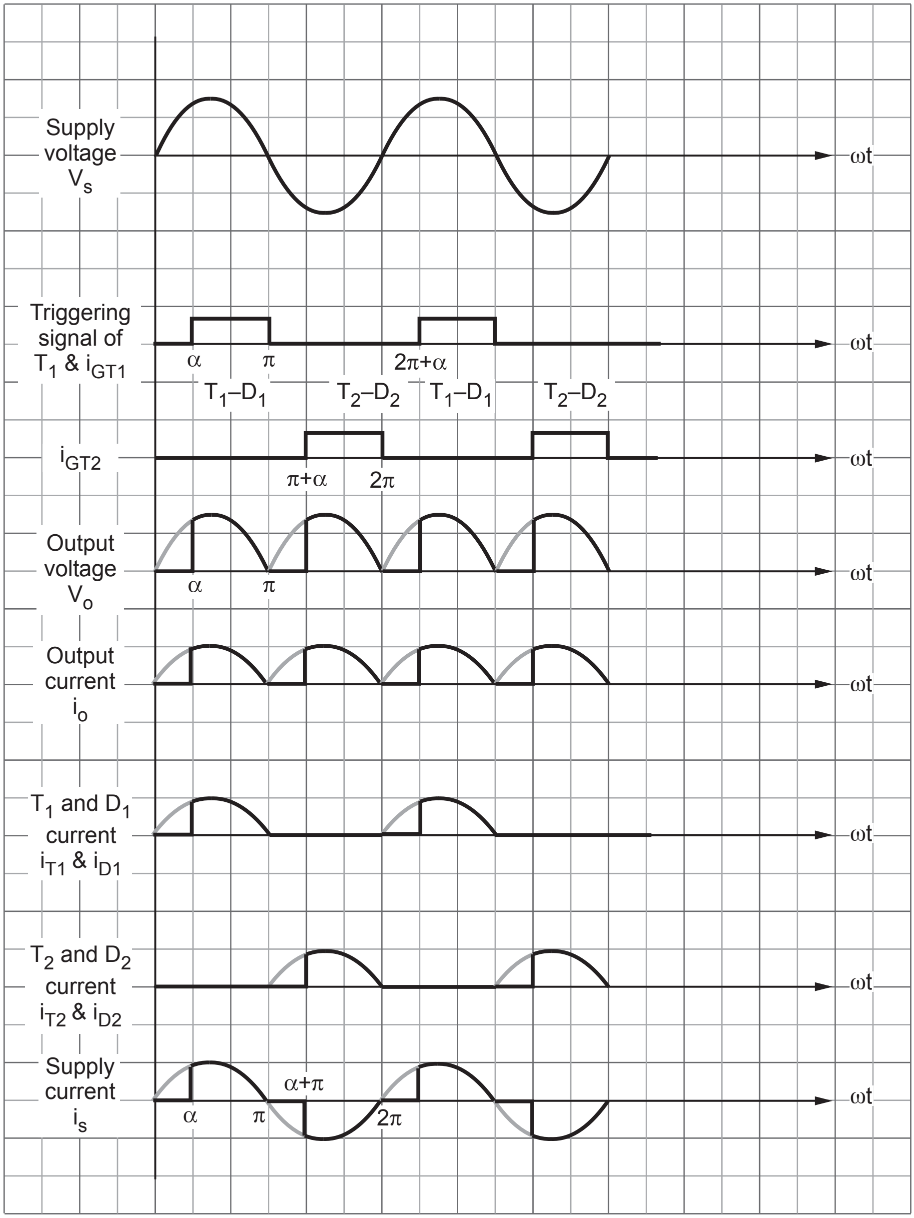


Fig. 2.2.3 Waveforms of semiconverter with R-load

From the above equivalent circuit observe that positive of V_s is connected to positive of V_o. Hence V_o remains positive even if supply polarity (i.e. negative cycle) is reversed. Hence we can write,

$$V_o = -V_s \qquad \text{... (2.2.3)}$$

and

$$i_o = \frac{V_o}{R} = -\frac{V_s}{R} \qquad \text{... (2.2.4)}$$

In Fig. 2.2.4 observe that current through T_2 flows in the same direction as i_o. Hence $i_{T2} = i_o$. Similarly i_o and i_s is the same current, but their directions are opposite as shown in Fig. 2.2.4. Hence,

$$i_s = -i_o$$

The waveforms of all the currents and voltages are shown in Fig. 2.3.3. At 2π, the supply voltage is zero. Hence T_2 turns off. After 2 π T_2 is reverse biased. Then T_1 is triggered again at $2\pi+\alpha$ and the complete cycle repeats.

Example 2.2.1 *For the 1ϕ semiconverter having resistive load of 'R' determine the following :*

i) Average output voltage $V_{o(av)}$ ii) RMS output voltage $V_{o(rms)}$

SPPU : May-10, Marks 4

Solution : i) Average output voltage :

The average output voltage is given as,

$$V_{o(av)} = \frac{1}{T}\int_0^T V_o(\omega t)\, d\,\omega t$$

Observe the waveform of output voltage in Fig. 2.2.3. It has a period π. Hence above equation can be written as,

$$V_{o(av)} = \frac{1}{\pi}\int_\alpha^\pi V_m \sin \omega t\; d\omega t$$

In the above equation $V_o(\omega t) = V_m\ sin\ \omega t$ from α to π . Solving the above integration we get,

$$\boxed{V_{o(av)} = \frac{V_m}{\pi}(1+cos\ \alpha)} \quad \text{... (2.2.5)}$$

ii) RMS output voltage :

RMS output voltage is given as,

$$V_{o(rms)} = \left[\frac{1}{T}\int_0^T V_0^2(\omega t)\, d\omega t\right]^{1/2}$$

Putting the values in above equation,

$$V_{o(rms)} = \left[\frac{1}{\pi}\int_\alpha^\pi V_m^2 \sin^2 \omega t\; d\omega t\right]^{\frac{1}{2}}$$

$$= \left\{ \frac{V_m^2}{\pi} \int_{\alpha}^{\pi} \left[\frac{1-\cos(2\omega t)}{2} \right] d\,\omega t \right\}^{\frac{1}{2}}$$

$$\therefore \qquad \boxed{V_{o(rms)} = \left\{ \frac{V_m^2}{2\pi} \left[\pi - \alpha + \frac{1}{2} \sin 2\alpha \right] \right\}^{\frac{1}{2}}} \qquad \text{... (2.2.6)}$$

This is the required derivation for rms value of output voltage.

Example 2.2.2 *A single phase half controlled bridge rectifier operates from the 115 V, 60 Hz mains and supplies a resistive load of 250 Ω. For firing angles of 45° and 135°, Calculate :*

i) Average output voltage *ii) rms output voltage*

iii) Load power *iv) rms supply current*

v) Peak supply current.

SPPU : Dec.-04, Marks 18

Solurion : Given : Half controlled bridge

$$V_{s(rms)} = 115 \text{ V}, \quad \text{therefore } V_m = \sqrt{2}\, V_{s(rms)}$$

$$= \sqrt{2} \times 115 = 162.6 \text{ V}$$

$$R = 250\ \Omega$$

$$\alpha_1 = 45° \text{ or } \frac{\pi}{4}$$

$$\alpha_2 = 135° \text{ or } \frac{3\pi}{4}$$

i) Average output voltage

For $\alpha = \frac{\pi}{4}$,

$$V_{o(av)} = \frac{V_m}{\pi}(1+\cos\alpha)$$

$$= \frac{162.6}{\pi}\left(1+\cos\frac{\pi}{4}\right) = 88.35 \text{ V}$$

For $\alpha = \frac{3\pi}{4}$,

$$V_{o(av)} = \frac{162.6}{\pi}\left(1+\cos\frac{3\pi}{4}\right) = 15.16 \text{ V}$$

ii) RMS output voltage

$$V_{o(rms)} = \left\{ \frac{V_m^2}{2\pi} \left[\pi - \alpha + \frac{1}{2}\sin 2\alpha \right] \right\}^{\frac{1}{2}}$$

For $\alpha = \frac{\pi}{4}$, $\quad V_{o(rms)} = \left\{\frac{162.6^2}{2\pi}\left[\pi - \frac{\pi}{4} + \frac{1}{2}\sin\left(2 \cdot \frac{\pi}{4}\right)\right]\right\}^{\frac{1}{2}}$

$$= 109.63 \text{ V}$$

For $\alpha = \frac{3\pi}{4}$, $\quad V_{o(rms)} = \left\{\frac{162.6^2}{2\pi}\left[\pi - \frac{3\pi}{4} + \frac{1}{2}\sin\left(2 \cdot \frac{3\pi}{4}\right)\right]\right\}^{\frac{1}{2}}$

$$= 34.65 \text{ V}$$

iii) Load power

$$P_o = \frac{V_{o(av)}^2}{R}$$

For $\alpha = \frac{\pi}{4}$, $\quad P_o = \frac{(88.35)^2}{250} = 31.22$ Watt

For $\alpha = \frac{3\pi}{4}$, $\quad P_o = \frac{(15.16)^2}{250} = 0.919$ Watt

iv) RMS supply current

For 1 ϕ half bridge inverter with resistive load,

$$I_{s(rms)} = I_{o(rms)} = \frac{V_{o(rms)}}{R}$$

For $\alpha = \frac{\pi}{4}$, $\quad I_{s(rms)} = \frac{109.63}{250} = 0.438$ A

For $\alpha = \frac{3\pi}{4}$, $\quad I_{s(rms)} = \frac{34.65}{250} = 0.1386$ A

v) Peak supply current

- The supply current will be maximum, when output current is maximum. i.e. $I_{s(\max)} = I_{o(\max)}$.
- Now the output current will be maximum when output voltage is maximum.
- For $\alpha = \frac{\pi}{4}$, peak value of output voltage is V_m Hence,

$$I_{s(peak)} = \frac{V_m}{R} = \frac{162.6}{250} = 0.65 \text{ A}$$

- For $\alpha = \frac{3\pi}{4}$, peak value of output voltage is $V_m \sin\frac{3\pi}{4}$ Hence,

$$I_{s(peak)} = \frac{V_m \sin\frac{3\pi}{4}}{R} = \frac{162.6\times 0.7071}{250} = 0.46 \text{ A}$$

Example 2.2.3 *A single phase HCB operated from the 230 V, 50 Hz mains feeds a resistive load of 100 Ω. If the firing angle is 60°, calculate,*

i) Average output voltage *ii) RMS output voltage*

iii) Total output power *iv) DC output power*

v) Load current at instant of turn-on i.e. $\omega t = \alpha$.

iv) Peak load current. **SPPU : May-03, April-15, Marks 12**

Solution : Given : 1ϕ HCB

$$V_s = 230 \text{ V}, \quad V_m = \sqrt{2}V_s = \sqrt{2}\times 230 = 325.27 \text{ V}$$

$$R = 100\ \Omega, \quad \alpha = 60° \text{ or } \frac{\pi}{3}$$

i) Average output voltage

$$V_{o(av)} = \frac{V_m}{\pi}(1+\cos\alpha) = \frac{325.27}{p}\left(1+\cos\frac{\pi}{3}\right) = 155.3 \text{ V}$$

ii) RMS output voltage

$$V_{o\,(rms)} = \left\{\frac{V_m^2}{2\pi}\left[\pi-\alpha+\frac{1}{2}\sin 2\alpha\right]\right\}^{\frac{1}{2}}$$

$$= \left\{\frac{(325.27)^2}{2\pi}\left[\pi-\frac{\pi}{3}+\frac{1}{2}\sin\left(2\cdot\frac{\pi}{3}\right)\right]\right\}^{\frac{1}{2}}$$

$$= 206.3 \text{ V}$$

iii) Total output power

$$P_{o(total)} = \frac{V_{o(rms)}^2}{R} = \frac{(206.3)^2}{100} = 426 \text{ Watt}$$

iv) DC output power

$$P_{o(DC)} = \frac{V_{o(av)}^2}{R} = \frac{(155.3)^2}{100} = 241.18 \text{ Watt}$$

v) Load current at the instant of turn-on

$$i_o = \frac{v_o(\omega t)}{R} = \frac{V_m \sin\omega t}{R}$$

$$= \frac{325.27 \sin \frac{\pi}{3}}{100} \quad \text{by putting } \omega t = \alpha = \frac{\pi}{3}$$

$$= 2.816 \text{ A}$$

vi) Peak load current

Since SCRs are triggered at $\alpha = \frac{\pi}{3}$, the supply peak voltage occurs at $\alpha = \frac{\pi}{2}$. Therefore load current will be at its peak when $\omega t = \frac{\pi}{2}$. i.e.,

$$I_{o(peak)} = \frac{V_{o(peak)}}{R} = \frac{V_m \sin \omega t}{R} = \frac{325.27 \sin \frac{p}{2}}{100} = 3.25 \text{ A}$$

2.2.3 Working with Inductive (R-L) Load

Normally the semiconverters are used to drive the DC motors. These motors are basically inductive (R-L) load. Hence it is necessary to consider the working of semiconverter with R-L load also. With the inductive load, the three modes are possible :

i) Continuous load current. ii) Discontinuous load current.

iii) Continuous and ripple free current for large inductive load.

2.2.3.1 Continuous Current Mode

In this mode, the current flows continuously in the load because of inductive effect. The waveforms of load current and load voltage are shown in Fig. 2.2.5. In these waveforms observe that SCR T_1 and diode D_1 conducts from α to π. Since the load is inductive current keeps on increasing (saturating) and it is maximum at π. (See Fig. 2.2.5 on next page)

Freewheeling action : At π, even though the supply voltage is zero, current doesnot go to zero. This is because load inductance opposes this sudden change of current. The load inductance generates a large voltage so as to maintain load current. This current flows through T_1 and D_2. The equivalent circuit of this operation is shown in Fig. 2.2.6. The SCR T_1 conducts even after π, since it is forward biased due to voltage induced in the load inductance i.e. $L\frac{di}{dt}$. Diode D_2 is also forward biased

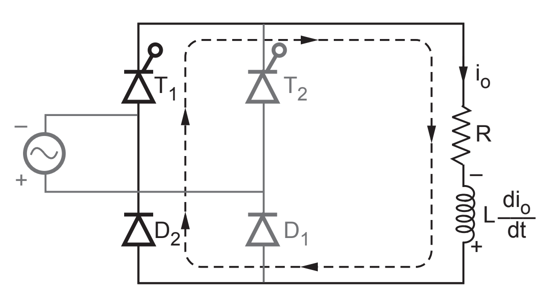


Fig. 2.2.6 Freewheeling action takes place through T_1 - D_2

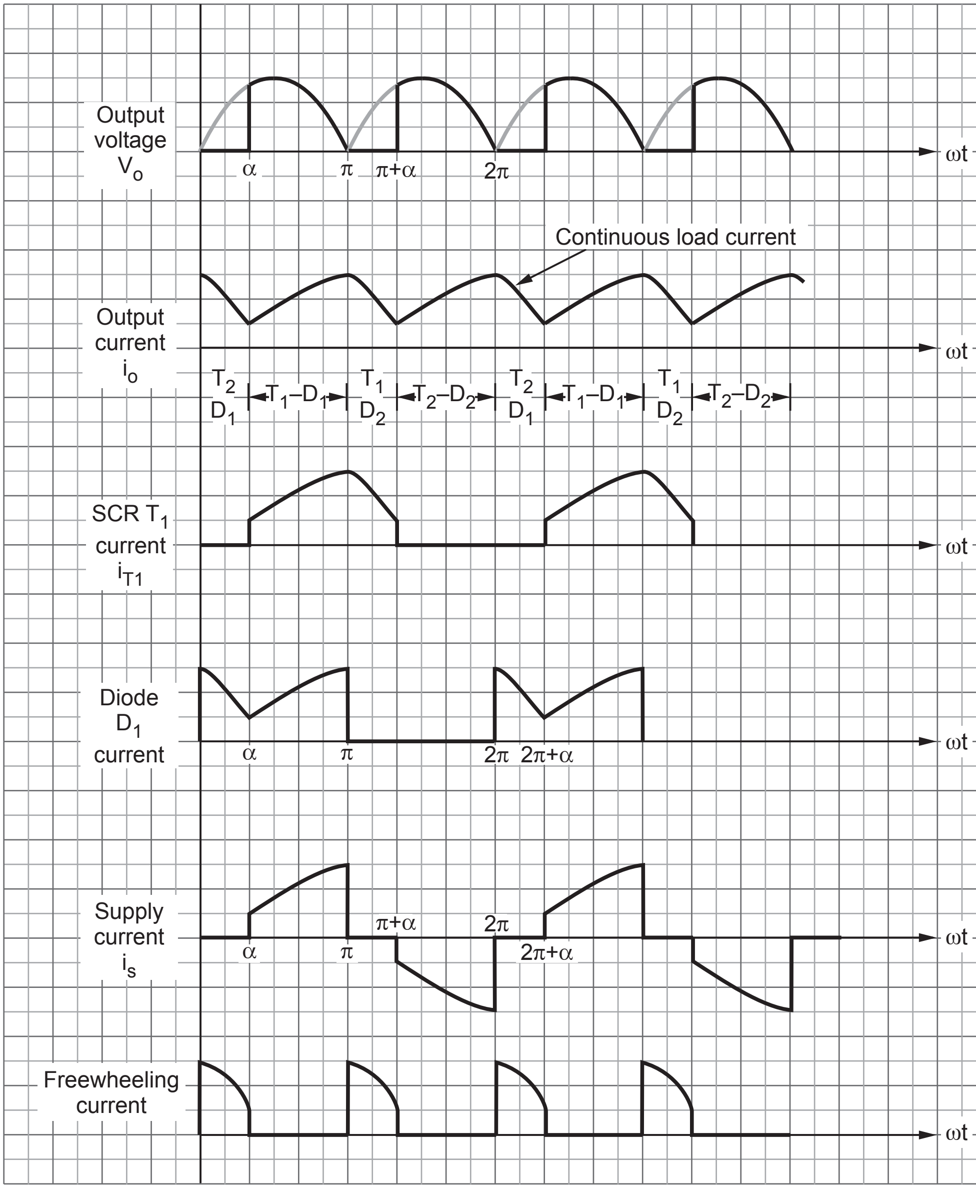


Fig. 2.2.5 Waveforms of 1φ semiconverter for continuous load current

due to this voltage. Hence current does not flow through supply i.e. i_s when freewheeling action takes place. Thus the energy stored in the load inductance is fedback to load itself in freewheeling action.

SCR T_2 is triggered at $\pi+\alpha$ and the output current starts increasing. Since the current i_o is continuous, it is called continuous current mode of semiconverter. The similar operation takes place when T_2 and D_2 conducts in negative half cycle of the supply.

Fig. 2.2.5 shows supply current (i_s), freewheeling current and other waveforms for inductive load. Note that the output voltage waveform remains same. If there is freewheeling diode in semiconverter, then freewheeling current flows through this diode.

Average value of output voltage with inductive load

Compare the output voltage waveforms of Fig. 2.2.3 (resistive load) and Fig. 2.2.5 (inductive load). The voltage waveforms are same. Hence average and RMS values of output voltage are also same. i.e. for inductive load,

From equation (2.2.5) $$\boxed{V_{o\,(av)} = \frac{V_m}{\pi}(1+\cos\alpha)} \quad \text{... (2.2.7)}$$

From equation (2.2.6) $$\boxed{V_{o(rms)} = \left\{\frac{V_m^2}{2\pi}\left[\pi-\alpha+\frac{1}{2}\sin 2\alpha\right]\right\}^{\frac{1}{2}}} \quad \text{... (2.2.8)}$$

Difference between freewheeling and feedback diodes **SPPU : April-17**

Sr. No.	Freewheeling diodes	Feedback diodes
1.	Load energy is utilized in load itself through freewheeling diodes.	Load energy is feedback to the source through feedback diodes.
2.	Freewheeling diodes have to carry full load current.	Feedback diodes carry full load current some times.
3.	Freewheeling diodes are slower.	Feedback diodes should be fast.

2.2.3.2 Discontinuous Current Mode

In this mode, the current through the load becomes zero for some duration. Hence it is called discontinuous current mode. Fig. 2.2.7 shows the waveforms of discontinuous current mode of semiconverter.

As shown in above waveforms, T_1 -D_1 conducts from α to π and the load current i_o goes on increasing. At π supply voltage is zero. But because of inductance, i_o does not go to zero. The load inductance induces a large voltage $L\frac{di_o}{dt}$ to maintain current in the same direction. Hence i_o continuous to flow and it goes to zero at β. Since next SCR T_2 is triggered at $\pi+\alpha$ (see Fig. 2.2.7), output current is discontinuous. Freewheeling takes place from π to β. The freewheeling current flows through T_1 and D_2. Similar operation repeats in next half cycle.

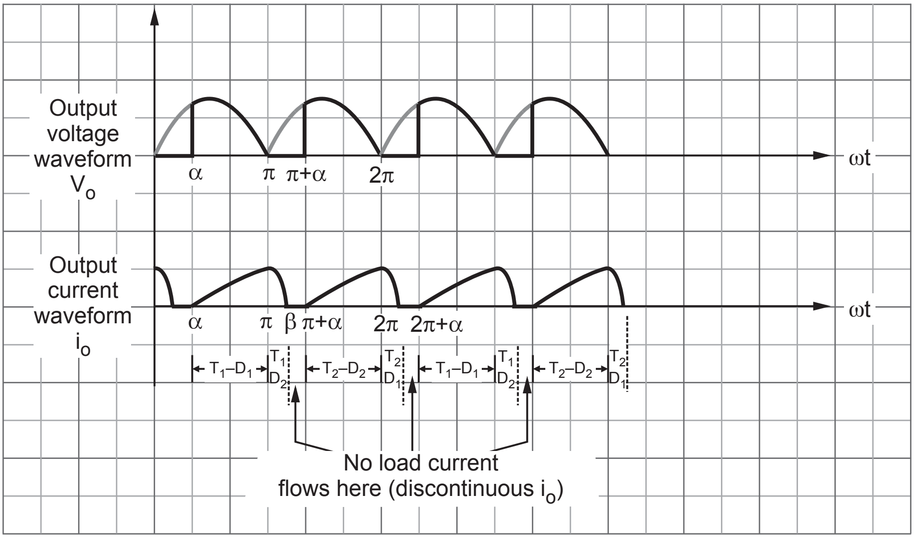


Fig. 2.2.7 Discontinuous mode of single phase semiconverter

Observe that the voltage waveform remains same in discontinuous mode also. Hence $V_{o(av)}$ and $V_{o(RMS)}$ are same as that of resistive load.

2.2.3.3 Continuous and Ripple Free Current for Large Inductive Load

As the load inductance increases, the ripple in i_o reduces. When the load inductance is very large, the ripple in i_o will be negligible. And i_o can be treated as continuous and ripple free. Fig. 2.2.8 shows the waveforms of 1ϕ semiconverter for large inductive load. (See Fig. 2.2.8 on next page). The load current is continuous and ripple free. Observe that the output voltage waveform is same as resistive load. But the current waveforms are different.

The output current is constant DC of amplitude $I_{o(av)}$. The SCRs conduct for π radians. Hence SCR current is square wave. The supply current has the amplitudes of $\pm I_{o(av)}$. The supply current is zero whenever freewheeling action takes place.

Example 2.2.4 *Derive an expression for output current for RLE load driven by 1ϕ semiconverter. Assume continuous conduction.*

Solution : Fig. 2.2.9 shows the circuit diagram of 1 ϕ semiconverter for RLE load. (See Fig. 2.2.9 on next page.)

Normally, the RLE load is motor load. L is the inductance of the motor and R isthe resistance of the inductance. E is an induced emf in the motor. The waveforms of this circuit will be similar to those shown in Fig. 2.2.5. From α to π, $T_1 - D_1$ conducts and supply voltage v_s is applied to the load. Hence an equivalent circuit will be as shown below :

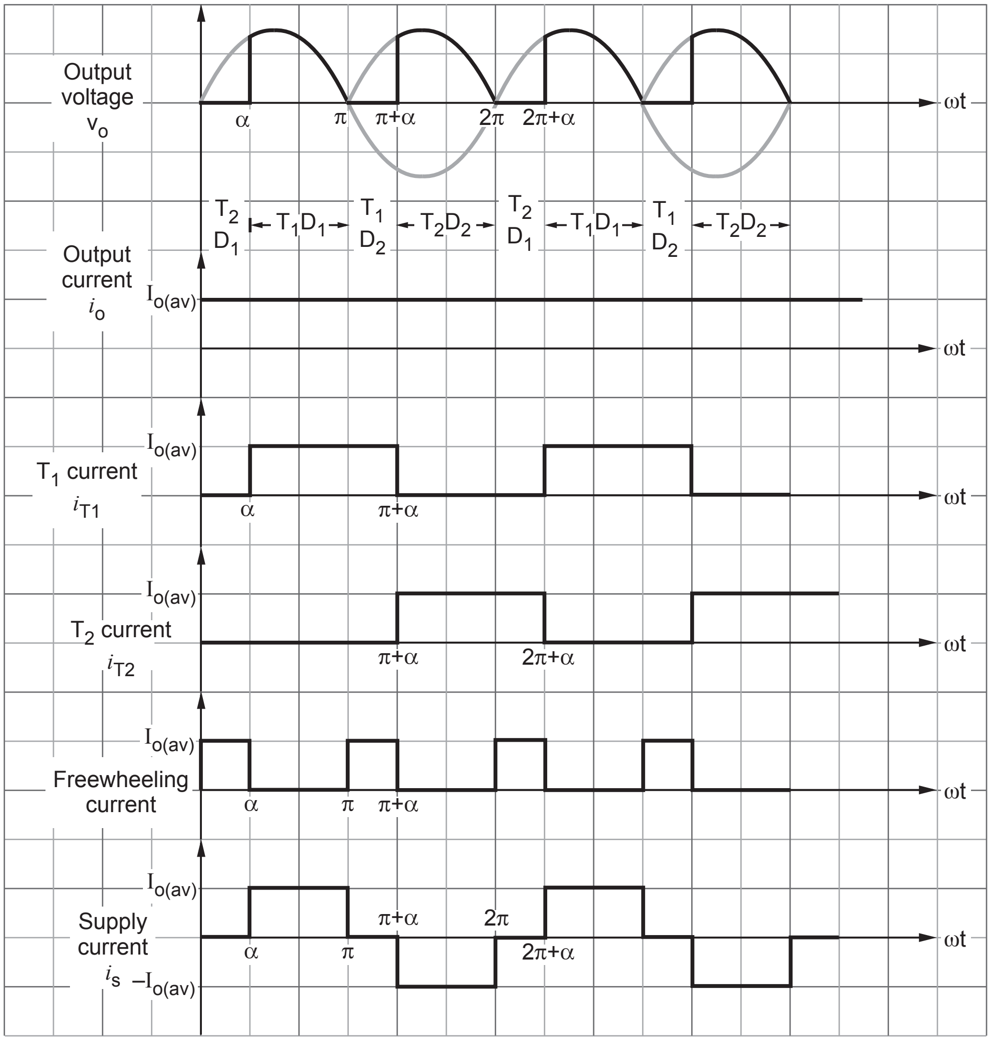


Fig. 2.2.8 Waveforms of 1ϕ semiconverter for highly inductive load

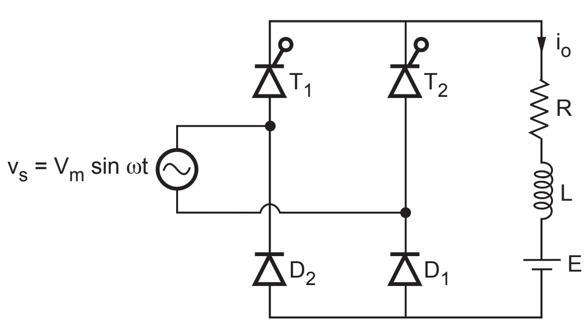


Fig. 2.2.9 A 1ϕ semiconverter driving RLE load

By KVL in above circuit we get,

$$V_m \sin \omega t = R\, i_{o1}(\omega t) + L \frac{d\, i_{o1}(\omega t)}{dt} + E$$

This equation can be solved using Laplace transform. The solution is,

$$i_{o1}(\omega t) = \frac{V_m}{Z} \sin(\omega t - \theta) + i_{o1}(0)\, e^{-t\frac{R}{L}} - \frac{E}{R} \qquad \text{... (2.2.9)}$$

Here $\quad Z = \sqrt{R^2 (\omega L)^2}$

$$\theta = \tan^{-1}\left(\frac{\omega L}{R}\right)$$

$i_{o1}(0)$ is initial current at $\omega t = \alpha$.

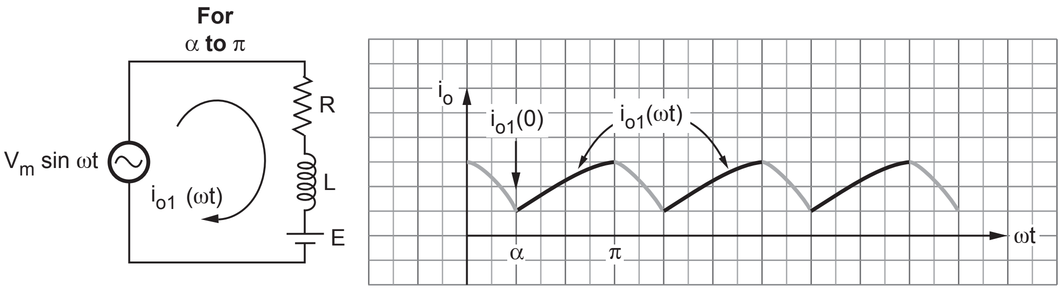


Fig. 2.2.10 Equivalent circuit when T_1-D_1 or T_2-D_2 conduct

From π to $\pi + \alpha$ freewheeling takes place. $T_1 D_2$ conduct in this duration. The equivalent circuit is shown in Fig. 2.2.11.

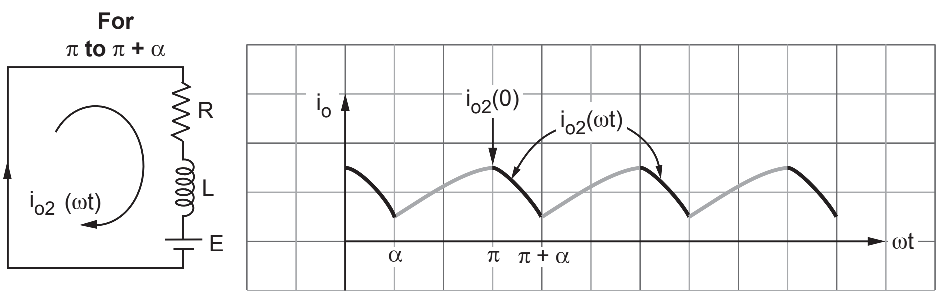


Fig. 2.2.11 Freewheeling action in $T_1 D_2$ or $T_2 D_1$

By KVL to this circuit we can write,

$$R\, i_{o2}(\omega t) + L \frac{d\, i_{o2}(\omega t)}{dt} + E = 0$$

This equation can be solved using Laplace transform. The solution is,

$$i_{o2}(\omega t) = i_{o2}(0) e^{-t\frac{R}{L}} - \frac{E}{R}(1 - e^{-t\frac{R}{L}}) \qquad \text{... (2.2.10)}$$

Here $i_{o2}(0)$ is the initial current at $\omega t = \pi$. In the waveforms of Fig. 2.3.10 and Fig. 2.2.11 observe that,

$$\left.\begin{aligned} & i_{o2}(0) = i_{o1}(\omega t = \pi) \\ \text{and} \quad & i_{o1}(0) = i_{o2}(\omega t = \alpha) \end{aligned}\right\} \quad \text{... (2.2.11)}$$

Putting the above two conditions in equations (2.2.9) and (2.2.10) we can get the initial values. Then two currents $i_{o1}(\omega t)$ and $i_{o2}(\omega t)$ are separately expressed for semiconverter.

Example 2.2.5 *For a 1φ half bridge converter having highly inductive load, derive the following :*

i) Fourier series for supply current. *ii) n^{th} harmonic of supply current.*

iii) Fundamental component of supply current. *iv) RMS value of supply current.*

SPPU : Nov.-07, Marks 8, May-06,08, Marks 6

Solution : i) To determine Fourier series

The general expression for Fourier series is given as,

$$i_s(\omega t) = I_{s(av)} + \sum_{n=1}^{\infty} c_n \sin(n\omega t + \phi_n)$$

where $$c_n = \sqrt{a_n^2 + b_n^2}$$

and $$\phi_n = \tan^{-1}\left(\frac{a_n}{b_n}\right)$$

Here $$a_n = \frac{2}{T}\int_0^T i_s(\omega t)\cos n\omega t \; d\omega t = \frac{2}{2\pi}\int_0^{2\pi} i_s(\omega t)\cos n\omega t \; d\omega t$$

From the supply current waveform of Fig. 2.2.8 we can write,

$$a_n = \frac{2}{2\pi}\left[\int_{\alpha}^{\pi} I_{o(av)}\cos n\omega t \; d\omega t + \int_{\pi+\alpha}^{2\pi}(-I_{o(av)})\cos n\omega t \; d\omega t\right]$$

$$= \frac{I_{o(av)}}{\pi}\left[\int_{\alpha}^{\pi}\cos n\omega t \; d\omega t - \int_{\pi+\alpha}^{2\pi}\cos n\omega t \; d\omega t\right] = -\frac{I_{o(av)}}{n\pi}\sin n\alpha(1-\cos n\pi)$$

$$\therefore \quad a_n = \begin{cases} \dfrac{-2I_{o(av)}}{n\pi}\sin n\alpha & \text{for } n = 1, 3, 5, \ldots\ldots \\ 0 & \text{for } n = 2, 4, 6, \ldots\ldots \end{cases} \quad \text{... (2.2.12)}$$

The above equation shows that a_n is zero for even harmonics of supply current.

b_n is given as,

$$b_n = \frac{2}{T}\int_0^T i_s(\omega t)\sin n\omega t\ d\omega t$$

Putting values of $T = 2\pi$ and $i_s(\omega t)$ from supply current waveform of Fig. 2.2.8,

$$b_n = \frac{2}{2\pi}\left[\int_\alpha^\pi I_{o(av)}\sin n\omega t\ d\omega t + \int_{\pi+\alpha}^{2\pi}(-I_{o(av)})\sin n\omega t\ d\omega t\right]$$

$$= \frac{I_{o(av)}}{\pi}\left[\int_\alpha^\pi \sin n\omega t\ d\omega t - \int_{\pi+\alpha}^{2\pi}\sin n\omega t\ d\omega t\right] = \frac{I_{o(av)}}{n\pi}(1+\cos n\alpha)(1-\cos n\pi)$$

$$\therefore \quad b_n = \begin{cases} \dfrac{2I_{o(av)}}{n\pi}(1+\cos n\alpha) & \text{for } n = 1, 3, 5, \ldots \\ 0 & \text{for } n = 2, 4, 6, \ldots \end{cases} \qquad \ldots (2.2.13)$$

The above equation shows that b_n is zero for even harmonics of supply current.

Hence $$c_n = \sqrt{a_n^2 + b_n^2}$$

$$= \left\{\left[-\frac{2I_{o(av)}}{n\pi}\sin n\alpha\right]^2 + \left[\frac{2I_{o(av)}}{n\pi}(1+\cos n\alpha)\right]^2\right\}^{\frac{1}{2}}$$

$$= \frac{4\,I_o(av)}{n\pi}\cos\frac{n\alpha}{2} \qquad \text{for n = 1, 3, 5, ...} \qquad \ldots (2.2.14)$$

This equation gives peak value of n^{th} harmonic of supply current. And ϕ_n can be calculated as,

$$\phi_n = \tan^{-1}\frac{a_n}{b_n} = \tan^{-1}\left\{\frac{\dfrac{-2I_{o(av)}}{n\pi}\sin n\alpha}{\dfrac{2I_{o(av)}}{n\pi}(1+\cos n\alpha)}\right\}$$

$$= -\tan^{-1}\left\{\tan\frac{n\alpha}{2}\right\} = -\frac{n\alpha}{2} \qquad \ldots (2.2.15)$$

Observe the supply current waveform of Fig. 2.2.8. It has symmetric positive and negative half cycles. Hence its average value is zero. This can also be verified mathematically as follows.

$$I_{s\,(av)} = \frac{1}{T}\int_0^T i_s(\omega t)\ d\omega t$$

Here $\quad T = 2\pi$ and putting values of $i_s(\omega t)$ from Fig. 2.2.8,

$$I_{s(av)} = \frac{1}{2\pi}\left[\int_{\alpha}^{T} I_{o(av)}\, d\omega t + \int_{\pi+\alpha}^{2\pi} -I_{o(av)}\, d\omega t\right]$$

$$= \frac{I_{o(av)}}{2\pi}\left[\int_{\alpha}^{\pi} d\omega t - \int_{\pi+\alpha}^{2\pi} d\omega t\right] = \frac{I_{o(av)}}{2\pi}\left\{[\omega t]_{\alpha}^{\pi} - [\omega t]_{\pi+\alpha}^{2\pi}\right\}$$

$$= \frac{I_{o(av)}}{2\pi}\{\pi+\alpha-2\pi-(\pi+\alpha)\} = 0$$

Thus the average value of symmetric waveform is zero.

Thus the Fourier series can be written as,

$$i_s(\omega t) = \sum_{n=1,3,5,\ldots\ldots}^{\infty} \frac{4I_{o(av)}}{n\pi}\cos\frac{n\alpha}{2}\sin\left(n\omega t-\frac{n\alpha}{2}\right) \qquad \ldots (2.2.16)$$

ii) nth harmonic of supply current

$$I_{sn} = \frac{c_n}{\sqrt{2}} = \frac{\frac{4I_{o(av)}}{n\pi}\cos\frac{n\alpha}{2}}{\sqrt{2}} = \frac{2\sqrt{2}\, I_{o(av)}}{n\pi}\cos\frac{n\alpha}{2},\; n = 1, 3, 5, \ldots$$

iii) Fundamental component of supply current

Putting for n = 1 in above equation,

$$I_{s_1} = \frac{2\sqrt{2}\, I_{o(av)}}{\pi}\cos\frac{\alpha}{2} \qquad \ldots (2.2.17)$$

iv) To obtain rms value of supply current

The rms value is given as,

$$I_{s(rms)} = \left[\frac{1}{T}\int_{0}^{T} i_s^2(\omega t)\, d\omega t\right]^{\frac{1}{2}}$$

With $T = 2\pi$ and putting for $i_s(\omega t)$ from supply current waveform of Fig. 2.2.8,

$$I_{s(rms)} = \left\{\frac{1}{2\pi}\left[\int_{\alpha}^{\pi} I_{o(av)}^2\, d\omega t + \int_{\pi+\alpha}^{2\pi} (-I_{o(av)})^2\, d\omega t\right]\right\}^{\frac{1}{2}}$$

$$= \left\{\frac{I_{o(av)}^2}{2\pi}\left[\int_{\alpha}^{\pi} d\omega t + \int_{\pi+\alpha}^{2\pi} d\omega t\right]\right\}^{\frac{1}{2}} = I_{o(av)}\sqrt{\frac{\pi-\alpha}{\pi}} \qquad \ldots (2.2.18)$$

The above equation shows that rms value of supply current depends on α.

Example 2.2.6 *For a 1ϕ half controlled converter having highly inductive load, derive the following :*

i) Displacement factor (DF) *ii) Supply power factor (PF)*

iii) Harmonic factor (HF) *iv) Current distortion factor (CDF).*

Solution : i) Displacement factor (DF)

The displacement factor is given as,

$$DF = \cos\phi_1$$

From equation (2.2.15), $\phi_n = -\frac{n\alpha}{2}$; Hence $\phi_1 = -\frac{\alpha}{2}$.

$$\therefore \quad DF = \cos\left(-\frac{\alpha}{2}\right)$$

$$\therefore \quad \boxed{DF = \cos\frac{\alpha}{2}} \quad \text{... (2.2.19)}$$

ii) Supply power factor (PF)

The supply power factor is given as,

$$PF = \frac{I_{s1}}{I_{s(rms)}}\cos\phi_1$$

Putting the values of I_{s1} (equation 2.2.17), $I_{s(rms)}$ (equation 2.2.19) from previous example and ϕ_1 above we get,

$$PF = \frac{\frac{2\sqrt{2}\,I_{o(av)}}{\pi}\cos\frac{\alpha}{2}}{I_{o(av)}\sqrt{\frac{\pi-\alpha}{\pi}}}\cos\frac{\alpha}{2}$$

$$\therefore \quad \boxed{PF = \sqrt{\frac{8}{\pi(\pi-\alpha)}}\cos^2\frac{\alpha}{2}} \quad \text{... (2.2.20)}$$

iii) Harmonic factor (HF)

The Harmonic Factor (HF) is given as,

$$HF = \sqrt{\frac{I_{s(rms)}^2}{I_{s1}^2} - 1}$$

Putting values in above equation,

$$= \left\{ \frac{I_{o(av)}^2 \left(\frac{\pi - \alpha}{\pi} \right)}{\frac{8 I_{o(av)}^2}{\pi^2} \cos^2 \frac{\alpha}{2}} - 1 \right\}^{\frac{1}{2}}$$

$$\therefore \quad \boxed{HF = \sqrt{\frac{\pi(\pi - \alpha)}{8 \cos^2 \frac{\alpha}{2}} - 1}} \qquad \text{... (2.3.21)}$$

This is an expression for harmonic factor of supply current.

iv) Current distortion factor (CDF)

The current distortion factor (CDF) is given as,

$$CDF = \frac{I_{s1}}{I_{s(rms)}} = \frac{\frac{2\sqrt{2}\, I_{o(av)}}{\pi} \cos \frac{\alpha}{2}}{I_{o(av)} \sqrt{\frac{\pi - \alpha}{\pi}}}$$

$$= \frac{2\sqrt{2}\, \cos \frac{\alpha}{2}}{\sqrt{\pi(\pi - \alpha)}} \qquad \text{...(2.2.22)}$$

Example 2.2.7 *For a 1 ϕ half controlled bridge having continuous and ripple free current, obtain, i) Active power and ii) Reactive power.*

Solution : i) Active power

Active power is given as,

$$P_{active} = V_s\, I_{s1} \cos \phi_1$$

$$= V_s \cdot \frac{2\sqrt{2}\, I_{o(av)}}{\pi} \cos \frac{\alpha}{2} \cos\left(-\frac{\alpha}{2}\right) \qquad \text{since } \phi_1 = -\frac{\alpha}{2}$$

$$= \frac{\sqrt{2}\, V_s\, I_{o(av)}}{\pi} 2 \cos^2 \frac{\alpha}{2}$$

$$= \frac{V_m I_{o(av)}}{\pi} (1 + \cos \alpha) \qquad \text{...(2.2.23)}$$

ii) Reactive power

Reactive power is given as,

$$P_{reactive} = V_s\, I_{s1} \sin \phi_1$$

$$= V_s \cdot \frac{2\sqrt{2}\, I_{o(av)}}{\pi} \cos\frac{\alpha}{2} \sin\left(-\frac{\alpha}{2}\right)$$

$$= -\frac{\sqrt{2}\, V_s\, I_{o(av)}}{\pi} 2\sin\frac{\alpha}{2} \cos\frac{\alpha}{2}$$

$$= -\frac{V_m I_{o(av)}}{\pi} \sin\alpha \qquad \ldots(2.2.24)$$

The negative sign indicates that power is reactive.

Comments

i) Active power is consumed by the load.

ii) Reactive power is not consumed by the load. Hence its sign is negative.

iii) Reactive power fluctuates between load and source.

iv) Total power includes active as well as reactive power.

Example 2.2.8 *A single phase half controlled bridge rectifier supplies a ripple free load current of 10 A and operates from the 110 V, 60 Hz mains. If the average output voltage is 75 V calculate : i) Firing angle ii) RMS output voltage iii) RMS supply current iv) RMS 7^{th} harmonic supply current v) Supply power factor.* **SPPU : Dec.-03, Marks 16**

Solution : Given : $I_{o(av)} = 10$ A ripple free

$V_s = 110$ V, A $V_m = \sqrt{2}\, V_s = \sqrt{2} \times 110 = 155.56$ V

$V_{o(av)} = 75$ V

i) Firing angle $V_{o(av)} = \dfrac{V_m}{\pi}(1+\cos\alpha)$

$$75 = \frac{155.56}{\pi}(1+\cos\alpha)$$

$\therefore \quad \alpha = 1.03$ radians or 59°

ii) RMS output voltage

$$V_{o(rms)} = \left\{\frac{V_m^2}{2\pi}\left[\pi - \alpha + \frac{1}{2}\sin 2\alpha\right]\right\}^{\frac{1}{2}}$$

$$= \left\{\frac{(155.56)^2}{2\pi}\left[\pi - 1.03 + \frac{1}{2}\sin(2\times 1.03)\right]\right\}^{\frac{1}{2}}$$

$$= 99.15 \text{ V}$$

iii) RMS supply current

$$I_{s(rms)} = I_{o(av)}\sqrt{\frac{\pi-\alpha}{\pi}} = 10\sqrt{\frac{\pi-1.03}{\pi}} = 8.198\ \text{A}$$

iv) RMS 7th harmonic supply current

$$I_{s7} = \frac{c_7}{\sqrt{2}} = \frac{\dfrac{4\,I_{o(av)}}{7\pi}\cos\dfrac{7\alpha}{2}}{\sqrt{2}}$$

$$= \frac{\dfrac{4\times 10}{7\pi}\cos\dfrac{(7\times 1.03)}{2}}{\sqrt{2}} = -\ 1.15\ \text{A}$$

Here negative sign can be dropped since it is rms value.

v) Supply power factor

$$PF = \sqrt{\frac{8}{\pi(\pi-\alpha)}}\cos^2\frac{\alpha}{2} \qquad \text{... By equation (2.2.20)}$$

$$= \sqrt{\frac{8}{\pi(\pi-1.03)}}\cos^2\left(\frac{1.03}{2}\right) = 0.83$$

Example 2.2.9 *A single phase semiconverter operates with 230 V, 50 Hz ac input and supplies level load current of 10 A, operated at firing angle of 60°. Calculate :*

i) RMS supply current ii) Output voltage

iii) Supply power factor iv) RMS value of third harmonic input current.

SPPU : Dec.-2000, Marks 8; Dec.-06, April-17, Marks 10

Solution : Given : 1ϕ HCB

$$V_s = 230\ \text{V},\ V_m = \sqrt{2}\,V_s = \sqrt{2}\times 230 = 325.27\ \text{V}$$

$$I_{o(av)} = 10\ \text{A},\quad \alpha = 60° \text{ or } \frac{\pi}{3}$$

i) RMS supply current

$$I_{s(rms)} = I_{o(av)}\sqrt{\frac{\pi-\alpha}{\pi}} = 10\sqrt{\frac{\pi-\dfrac{\pi}{3}}{\pi}} = 8.165\ \text{A}$$

ii) Output voltage

$$V_{o(av)} = \frac{V_m}{\pi}(1+\cos\alpha) = \frac{325.27}{\pi}\left(1+\cos\frac{\pi}{3}\right)$$

$$= 155.3\ \text{V}$$

iii) Supply power factor

$$PF = \sqrt{\frac{8}{\pi(\pi-\alpha)}}\cos^2\frac{\alpha}{2}$$

$$= \sqrt{\frac{8}{\pi\left(\pi-\frac{\pi}{3}\right)}}\cos^2\left(\frac{\pi/3}{2}\right) = 0.8269$$

iv) RMS value of 3rd harmonic input current

$$I_{sn} = \frac{C_n}{\sqrt{2}} = \frac{\frac{4I_{o(av)}}{n\pi}\cos\frac{n\alpha}{2}}{\sqrt{2}}$$

$$\therefore \quad I_{s3} = \frac{2\sqrt{2}\,I_{o(av)}}{3\pi}\cos\left(\frac{3\times\frac{\pi}{3}}{2}\right) = 0$$

Example 2.2.10 *A single phase semiconverter is operated from 120 V, 50 Hz, AC supply. The load resistance is 10 Ω. If the average output voltage is 25 % of the maximum possible average output voltage, determine :*

i) Firing angle ii) RMS and average output current

iii) RMS and average thyristor current. **SPPU : Dec.-09, April-16, Marks 6**

Solution : $V_s = 120\ V$, hence $V_m = \sqrt{2}\ V_s = \sqrt{2}\times 120\ V$

$R = 10\ \Omega$

i) To obtain firing angle

For semiconverter average output voltage is given as,

$$V_{o(av)} = \frac{V_m}{\pi}(1+\cos\alpha) \quad \text{... (2.2.25)}$$

Here $V_{o(av)}$ will be maximum when $\cos\alpha = 1$

i.e. $V_{o(av)\ \max} = \frac{2\ V_m}{\pi}$

We have to obtain firing angle for $V_{o(av)} = 0.25\ V_{o(av)\ \max}$

i.e., $V_{o(av)} = 0.25\times\frac{2V_m}{\pi} = \frac{0.5V_m}{\pi}$

Putting this value of $V_{o(av)}$ in equation (2.2.25)

$$\frac{0.5V_m}{\pi} = \frac{V_m}{\pi}(1+\cos\alpha)$$

$$\therefore \quad \alpha = 120° \text{ or } 2.09435 \text{ radians}$$

ii) To obtain rms and average output currents

Average output voltage is given as,

$$V_{o(av)} = \frac{V_m}{\pi}(1+\cos\alpha)$$

Putting for $\alpha = 120°$ and $V_m = \sqrt{2}\times 120$ V,

$$V_{o(av)} = \frac{\sqrt{2}\times 120}{\pi}(1 + \cos 120°) = 27 \text{ V}$$

And the rms value of output voltage is given as,

$$V_{o(rms)} = \left\{\frac{V_m^2}{2\pi}\left[\pi - \alpha + \frac{1}{2}\sin 2\alpha\right]\right\}^{\frac{1}{2}}$$

Putting values and α in radians,

$$V_{o(rms)} = \left\{\frac{\left(\sqrt{2}\times 120\right)^2}{2\pi}\left[\pi - 2.09435 + \frac{1}{2}\sin(2\times 120°)\right]\right\}^{\frac{1}{2}}$$

$$= 53 \text{ V}$$

$\therefore$ RMS output current, $I_{o\ (rms)} = \frac{V_{o(rms)}}{R} = \frac{53}{10} = 5.3\text{A}$

Average output current, $I_{o\ (av)} = \frac{V_{o(av)}}{R} = \frac{27}{10} = 2.7\text{A}$

iii) To obtain rms and average thyristor currents

Average thyristor (SCR) currents $\left(I_{T(av)}\right)$

The average value of the current is given as,

$$I_{T(av)} = \frac{1}{T}\int_0^T i_T(\omega t)\, d\omega t$$

Here the cycle period is 2π and the SCR conducts for α to π. The output current flows through the SCR. Hence $i_T(\omega t) = i_o(\omega t) = \frac{v_o(\omega t)}{R}$. Putting these values in above equation,

$$I_{T(av)} = \frac{1}{2\pi}\int_\alpha^\pi \frac{v_o(\omega t)}{R}\, d\omega t$$

We know that $v_o(\omega t) = V_m \sin \omega t$. Then above equation becomes,

$$I_{T(av)} = \frac{1}{2\pi} \int_{\alpha}^{\pi} \frac{1}{R} \left[V_m \sin \omega t \right] d\omega t$$

$$= \frac{1}{2R} \left[\frac{1}{\pi} \int_{\alpha}^{\pi} \mathrm{V_m} \sin \omega t \; d\omega t \right]$$

In the above equation the quantity inside the brackets is $V_{o(av)}$. i.e.,

$$I_{T(av)} = \frac{1}{2} \cdot \frac{V_{o(av)}}{R}$$

$$= \frac{I_{o(av)}}{2}, \text{ since } I_{o(av)} = \frac{V_{o(av)}}{2}$$

$$= \frac{2.7}{2} = 1.35 \text{ A}$$

RMS thyristor (SCR) current ($I_{T(rms)}$)

The rms value of the current is given as,

$$I_{T(rms)} = \left[\frac{1}{T} \int_{0}^{T} i_T^2 (\omega t) \; d\omega t \right]^{\frac{1}{2}}$$

We know that $i_T(\omega t) = \dfrac{v_o(\omega t)}{R}$. The cycle period is $T = 2\pi$ and SCR conducts from α to π . Then above equation will be,

$$I_{T(rms)} = \left[\frac{1}{2\pi} \int_{\alpha}^{\pi} \left(\frac{v_o(\omega t)}{R} \right)^2 d\omega t \right]^{\frac{1}{2}}$$

$$= \left[\frac{1}{2\pi} \int_{\alpha}^{\pi} \left(\frac{V_m^2 \sin^2 \omega t}{R^2} \quad d\omega t \right)^2 \right]^{\frac{1}{2}}, \qquad \text{since } V_o(\omega t) = V_m \sin \omega t$$

$$= \frac{1}{\sqrt{2}R} \left[\frac{1}{\pi} \int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \; d\omega t \right]^{\frac{1}{2}}$$

Here the term inside the brackets with square root is $V_{o(rms)}$. Hence,

$$I_{T(rms)} = \frac{1}{\sqrt{2}} \cdot \frac{V_{o(rms)}}{R}$$

$$= \frac{I_{o\,(rms)}}{\sqrt{2}}, \text{ since } I_{o\,(rms)} = \frac{V_{o\,(rms)}}{R}$$

$$= \frac{5.3}{\sqrt{2}} = 3.747 \text{ A}$$

Examples for Practice

Ex. 2.2.11 : *Single phase semiconverter is operated from 120 V, 60 Hz supply. The load current with an average value of I_a is continuous with negligible ripple content. Turns ratio of transformer is unity. The delay angle $\alpha = \frac{\pi}{3}$.*

Calculate - a) Harmonic factor of input current
b) The displacement factor c) Input power factor.

[Ans. : HF = 31.08 %, DF = 0.866, PF = 0.827 (lagging)]

Review Questions

1. *Draw the circuit diagram, voltage and current waveforms for α = 60°, RL load of semi-converter.* **SPPU : Dec.-10, Marks 6**
2. *Draw the circuit diagram of single phase semi-converter for 'R' load. Explain the operation with the help of voltage and current waveforms.* **SPPU : May-12, Marks 8**
3. *With the help of circuit diagram and relevant waveforms, explain the operation of single phase half controlled bridge feeding a continuous ripple free constant current.* **SPPU : May-06,10, Marks 10, Dec.-10, Marks 6**
4. *Draw the circuit diagram, voltage and current waveform for $\alpha = 60°$, RL load of semi-converter.* **SPPU : May-07, Marks 8**
5. *How freewheeling is present inherently in the semiconverters ?*
6. *Compare freewheeling diodes and feedback diodes.* **SPPU : Dec.-06,08, April-17, Marks 3**

2.3 Single Phase Full Converters

SPPU : April-15,16,17,19, May-2000,01,02,03,06,07,08,10,12,15,17,18,19, Nov.-07, Dec.-2000,01,04,06,08,09,10,11,13,15,18

Fig. 2.3.1 shows the block diagram of 1ϕ full bridge converter. It contains four SCRs T_1, T_2, T_3 and T_4. The conduction of all these SCRs is controlled. Hence this is called full converter. The input to this converter is 1ϕ AC supply. The output is controllable DC. The full bridge converter is mainly used for speed control of DC motors.

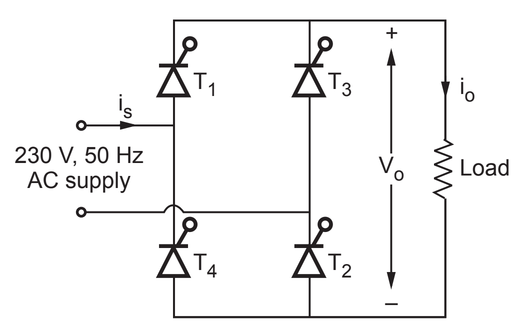


Fig. 2.3.1 Circuit diagram of 1ϕ full converter

2.3.1 Working with Resistive Load

Let us consider the working of 1ϕ bridge (Full) converter with resistive load. In the positive half cycle of the supply SCRs T_1 and T_2 are triggered at firing angle α. Hence current starts flowing through the load. The equivalent circuit for this operation is shown in Fig. 2.3.2.

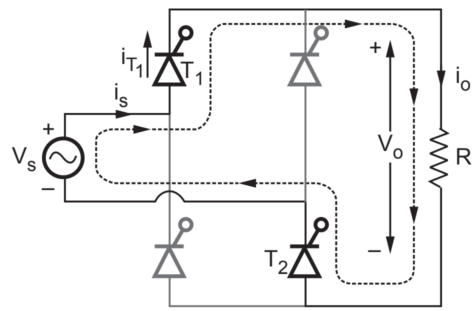


Fig. 2.3.2 Conduction of T_1 and T_2 in positive half cycle of the supply. Dotted line shows path of current flow

It is clear from Fig. 2.3.2 that, when T_1 and T_2 conducts,

$$V_o = V_s \quad \text{(i.e. supply voltage)} \qquad \text{... (2.3.1)}$$

and,

$$i_o = \frac{V_o}{R} = \frac{V_s}{R} \qquad \text{... (2.3.2)}$$

Fig. 2.3.3 shows the waveforms of this circuit. (See Fig. 2.3.3 on next page). Observe that load voltage is same as supply voltage from α to π. Since the load is resistive, waveforms of V_o and i_o are same. The supply current i_s and i_o are in the same direction hence $i_s = i_o$. T_1 and T_2 turn off when supply voltage becomes zero at π. In the negative half cycle T_3 and T_4 are triggered at $\pi + \alpha$. Fig. 2.3.4 shows the equivalent circuit when T_3 and T_4 conduct.

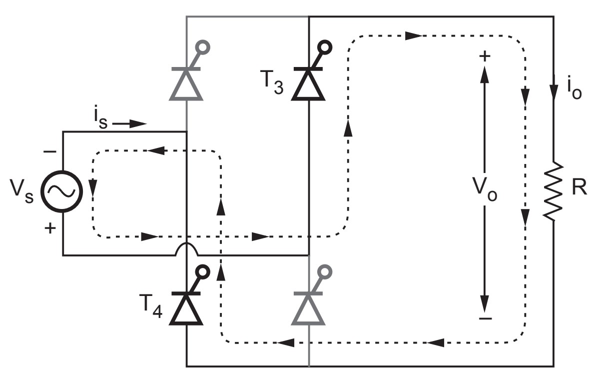


Fig. 2.3.4 Conduction of T_3 - T_4 in negative half cycle of the supply. Dotted line shows current path

In the adjacent figure observe that supply current i_s and load current i_o flow through the same loop. But directions of i_s and i_o are opposite hence

$$i_s = -i_o$$

The supply current waveform is also shown in Fig. 2.3.3. T_3 and T_4 turn off when supply voltage becomes zero at 2π. At $2\pi + \alpha$, T_1 and T_2 are triggered again and the cycle repeats.

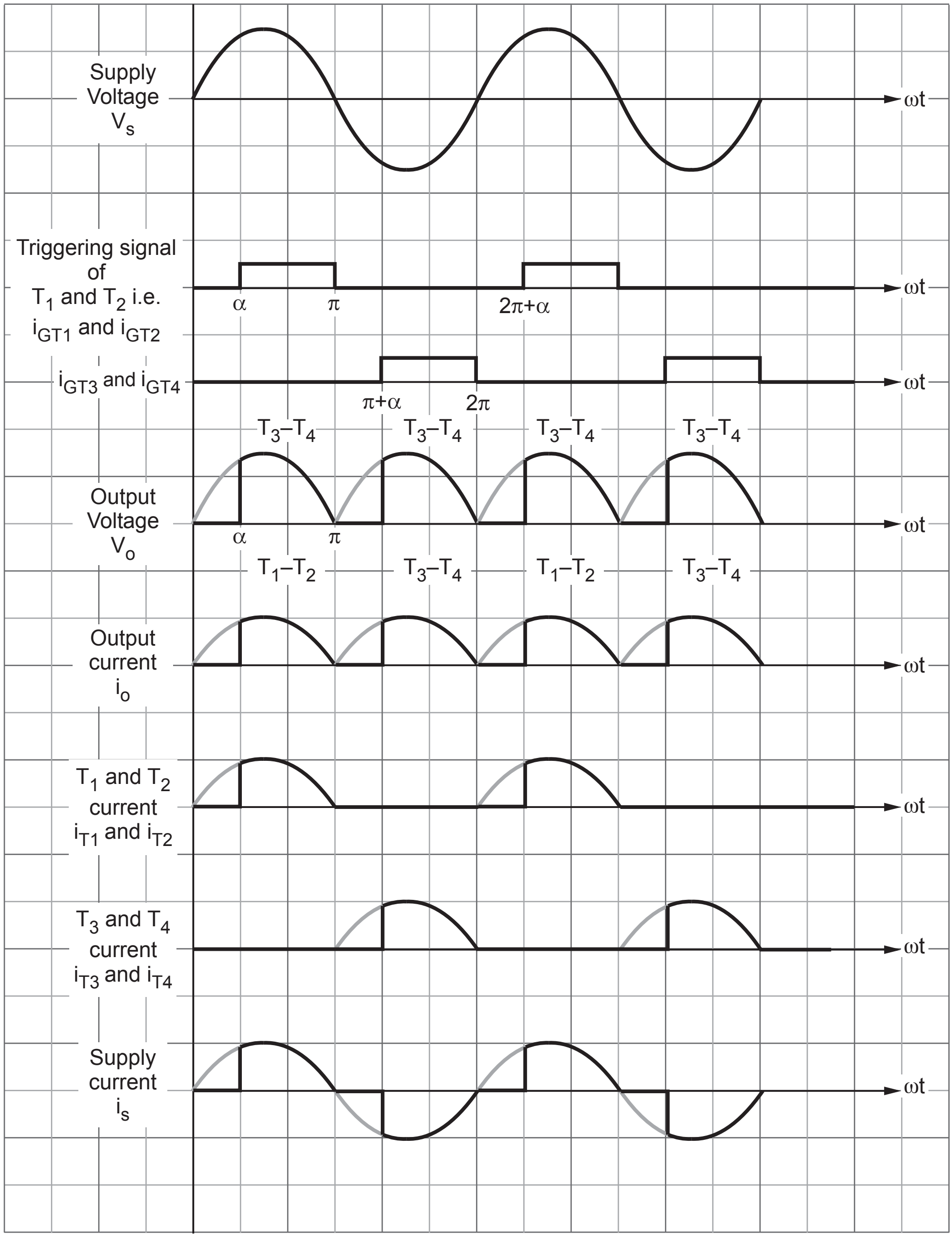


Fig. 2.3.3 Waveforms of full bridge converter for resistive load

Example 2.3.1 *For the 1 φ fully controlled bridge converter having load of 'R' determine the following : i) Average output voltage $V_{o(av)}$ ii) RMS output voltage $V_{o(rms)}$*

If supply voltage is 230 V, 50 Hz and firing angle is 60°, determine average output voltage. **SPPU : May-19, End Sem, Marks 7**

Solution : Compare the waveforms of 1ϕ semiconverter given in Fig. 2.2.3 and that of 1ϕ full converter given in Fig. 2.2.3. The waveforms are exactly same. Thus the operation of semiconverter and full converter is exactly same for resistive load. Hence their average and RMS output voltages are also same. Hence from equation (2.2.5), the average output voltage of full converter is,

$$\boxed{V_{o(av)} = \frac{V_m}{\pi}(1+\cos\alpha)} \quad \text{... (2.3.3)}$$

The supply voltage is 230 V. Hence,

$$V_s = 230 \text{ V} \qquad \therefore \quad V_m = 230\sqrt{2}$$

$$\text{and} \quad \alpha = 60°$$

Putting values in equation (2.3.3),

$$V_{o(av)} = \frac{230\sqrt{2}}{\pi}(1+\cos 60°) = 155.3 \text{ V}$$

From equation (2.3.6), RMS output voltage of full converter is,

$$\boxed{V_{o(rms)} = \frac{V_m^2}{2\pi}\left[\pi-\alpha+\frac{1}{2}\sin 2\alpha\right]^{\frac{1}{2}}} \quad \text{... (2.3.4)}$$

Example 2.3.2 *For the circuit shown in Fig. 2.3.5, find the current through 100 Ω load, if the SCRs are triggered at 30° delay. Supply voltage is 200 V, 50 Hz.*

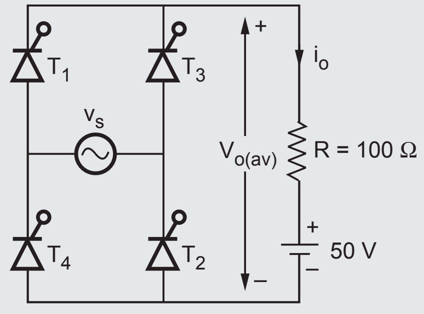


Fig. 2.3.5 Circuit diagram for example 2.3.2

Solution : This is a fully controlled bridge with resistive load of 100 Ω in series with the battery of 50 V. Hence output voltage of the converter appears across resistance of 100 Ω and battery of 50 V. Hence let us first calculate average value of output voltage. The given data is,

$$\alpha = 30°$$

$$V_s = 220 \text{ V}$$

$$\therefore \quad V_m = 220\sqrt{2}$$

The average output voltage for resistive load is given by equation (2.3.4) as,

$$V_{o(av)} = \frac{V_m}{\pi}(1+\cos\alpha)$$

$$= \frac{230\sqrt{2}}{\pi}(1+\cos 30°)$$

$$= 184.8 \text{ V}$$

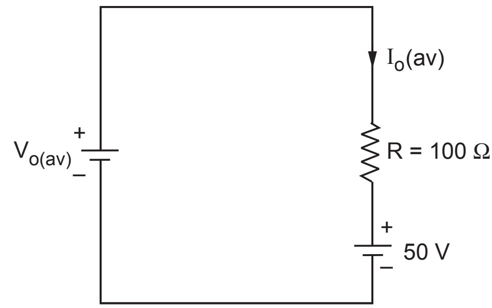


Fig. 2.3.6 Equivalent load circuit

This voltage is applied to the load. Fig. 2.3.6 shows the equivalent circuit.

By applying KVL to above circuit,

$$V_{o(av)} = I_{o(av)}R + 50$$

$$\therefore \quad 184.8 = I_{o(av)} \times 100 + 50$$

$$I_{o(av)} = 1.348 \text{ A}$$

Thus the current through the load is 1.348 A

2.3.2 Working with Inductive Load

The inductive load means resistance and inductance in the load. Such loads are DC motors. Because of the inductive (R-L) load, the load current shape is changed. Hence operation of the full bridge converter can be discussed into three modes :

i) Continuous load current.

ii) Continuous and ripple free current for large inductive load.

iii) Discontinuous load current.

2.3.2.1 Continuous Load Current

In the continuous load current, the load or output current i_o flows continuously. The waveforms are shown in Fig. 2.3.7.

As shown in the waveforms of Fig. 2.3.7, T_1 and T_2 conduct from α to π . The nature of the load current depends upon values of R and L in the inductive load. Because of the inductance, i_o keeps on increasing and becomes maximum at π. At π, the supply voltage reverses but SCRs T_1 and T_2 does not turn off. This is because, the load inductance does not allow the current i_o to go to zero instantly. The load inductance generates a large voltage $L\,\frac{di_o}{dt}$.

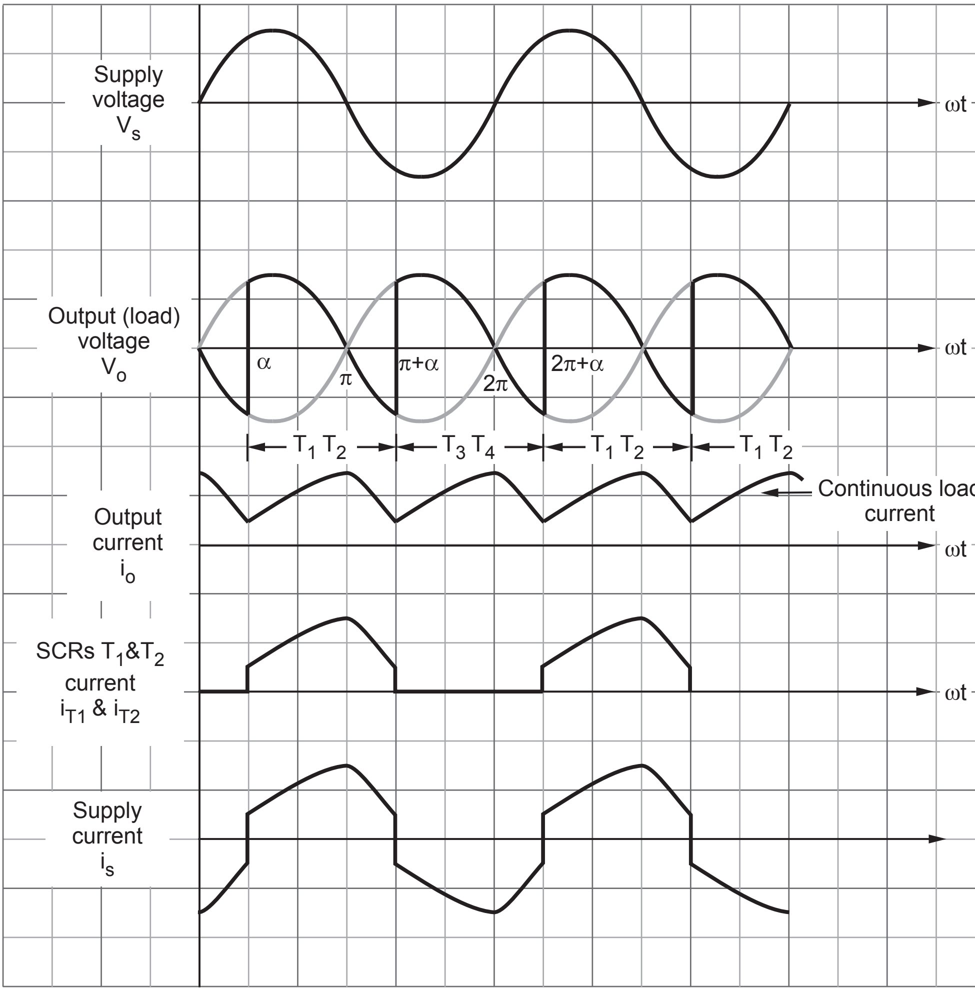


Fig. 2.3.7 Waveforms of 1ϕ full converter for inductive load having continuous load current

This voltage forward biases T_1 and T_2 as shown in Fig. 2.3.8. In this figure observe that the load current flows against the supply voltage. The energy stored in the load inductance is supplied partially to the mains supply and to the load itself. Hence this is also called as *feedback* operation. The output voltage is negative from π to $\pi + \alpha$ since supply voltage is negative. But the load current keeps on reducing.

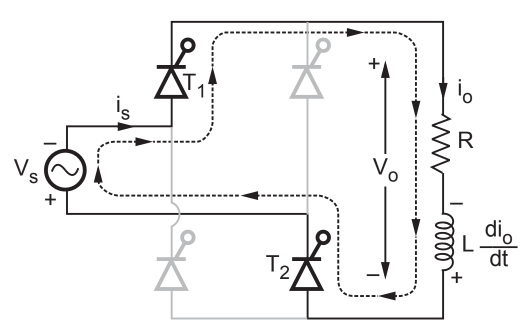


Fig. 2.3.8 Conduction of T_1 and T_2 from π to $\pi + \alpha$ due to inductance voltage

At $\pi+\alpha$, SCRs T_3 and T_4 are triggered. The load current starts increasing. The load current remains continuous in the load. The similar operation repeats. The ripple in the load current reduces as the load inductance is increased.

2.3.2.2 Continuous and Ripplefree Current for Large Inductive Load

Now let us consider the case when there is large inductance in the load. Because of the large inductance, the ripple in the load current is very small and it can be neglected. Hence load current will be totally DC as shown in Fig. 2.3.9.

In the waveforms shown in Fig. 2.3.9, there is no effect on output voltage waveform for large inductive load. The supply current waveform (i_s) is square wave for large inductive load.

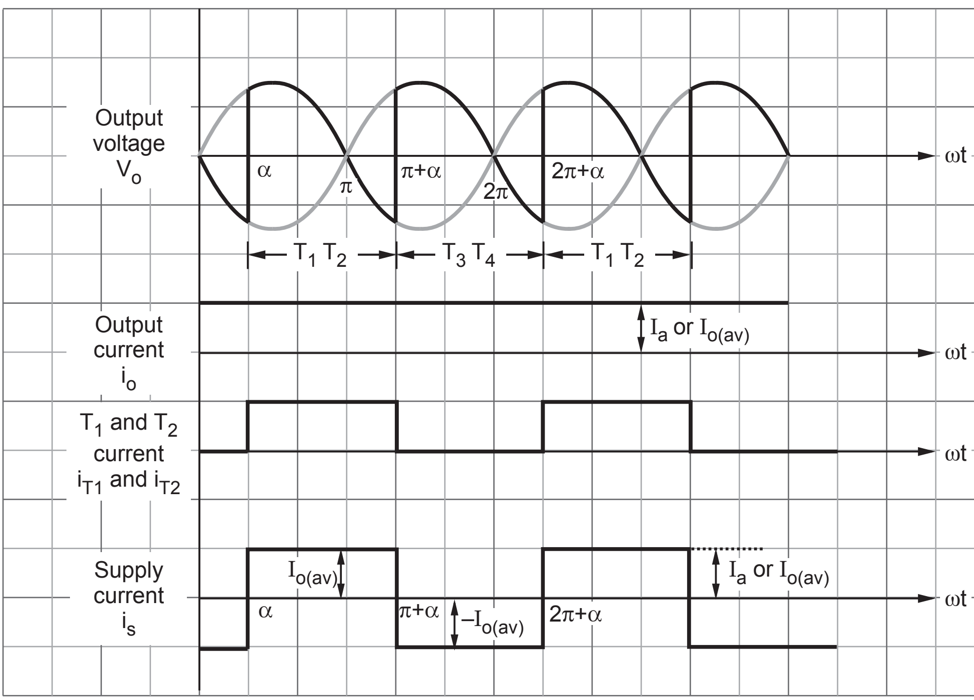


Fig. 2.3.9 Waveforms of 1ϕ full converter for continuous and ripplefree load current in case of large inductive load

Example 2.3.3 *For the 1ϕ full converter having inductive load and continuous load current, obtain the following : i) Average output voltage $V_{o(av)}$ ii) RMS output voltage $V_{o(rms)}$.*

SPPU : Dec.-04, Marks 3, Dec.-11,13, May-10, Marks 4, Dec.-09, Marks 8

Solution : i) Average output voltage for inductive load

The average output voltage is given as,

$$V_{o(av)} = \frac{1}{T}\int_0^T v_o(\omega t)\, d\omega t$$

Observe the waveforms of 1ϕ full converter for inductive load given in Fig. 2.3.7 and Fig. 2.3.9. The output voltage waveform has a period from α to $\pi+\alpha$; i.e. π. And $v_o(\omega t) = V_m \sin \omega t$ during this period. Hence above equation becomes,

$$V_{o(av)} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin \omega t \; d\omega t$$

$$= \frac{V_m}{\pi}\left[-\cos \omega t\right]_{\alpha}^{\pi+\alpha}$$

$$\therefore \quad \boxed{V_{o(av)} = \frac{2 V_m}{\pi} \cos\alpha} \qquad \text{... (2.3.5)}$$

This is the expression for average load voltage of 1ϕ full converter for inductive load.

Plot of $V_{o(av)}$ versus firing angle (α)

Following table lists the values of $V_{o(av)}$ with firing angle (α)

α	$V_{o(av)} = \frac{2V_m}{\pi}\cos\alpha$
0	$\frac{2V_m}{\pi} = 0.637\ V_m$
30°	$0.55\ V_m$
60°	$0.318\ V_m$
90°	0
120°	$-0.318\ V_m$
150°	$-0.55\ V_m$
180°	$-0.637\ V_m$

Table 2.3.1 $V_{o(av)}$ with respect to α

Observe that $V_{o\,(av)}$ is positive for $\alpha < 90°$. Hence it is called rectification. For $\alpha > 0$, $V_{o\,(av)}$ is negative. Hence it is called inverting mode of operation. In inverting mode, output energy is fedback to the source.

ii) RMS value of output voltage for inductive load

The rms value is given as,

$$V_{o(rms)} = \left[\frac{1}{T}\int_0^T v_o^2(\omega t)\, d\omega t\right]^{\frac{1}{2}}$$

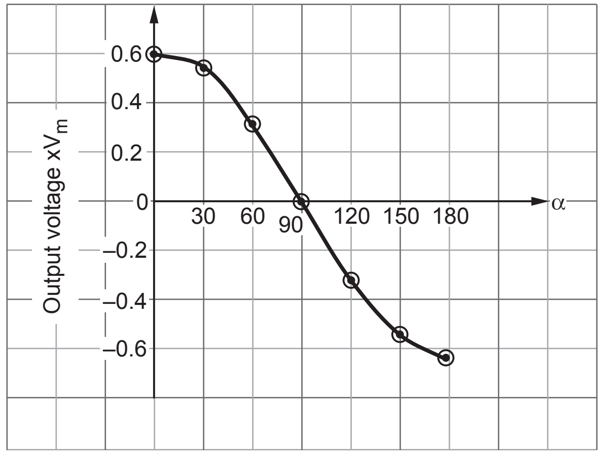


Fig. 2.3.10 Variation of $V_{o\,(av)}$ with respect to α

$$= \left[\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m^2 \sin^2 \omega t \, d\,\omega t\right]^{\frac{1}{2}}$$

$$= \left[\frac{V_m^2}{\pi}\int_{\alpha}^{\pi+\alpha} \frac{1-\cos 2\omega t}{2}\, d\,\omega t\right]^{\frac{1}{2}} = \left[\frac{V_m^2}{2}\right]^{\frac{1}{2}}$$

$$\therefore \qquad \boxed{V_{o\,(rms)} = \frac{V_m}{\sqrt{2}} = V_s} \qquad \text{... (2.3.6)}$$

Thus the rms value of load voltage is same as rms value of the AC supply voltage.

Example 2.3.4 *Draw the circuit arrangement of a single phase full converter feeding a general load comprising of R, L and E. Sketch the AC supply voltage o/p voltage and the load current waveforms. Assuming continuous load current operation, derive an expression for DC output voltage. A single phase full converter feeding an RLE load is fed by 230 V, 50 Hz mains.*

If R = 0.5 Ω, L = 8 mH and E = 50 volts, assuming that conduction is continuous and firing angle is 40°, find average value of load current.

Solution : Circuit diagram and waveforms

Fig. 2.3.11 shows the circuit diagram of full converter supplying RLE load.

The RLE load is normally motor load. 'R' is the resistance and 'L' is an inductance of armature winding of the motor. 'E' is the induced emf of the motor. When the load current is continuous, then waveforms of this circuit will be similar to that of RL load. Hence with small ripple in output current, the waveforms of this circuit will be similar to those shown in Fig. 2.3.7. Note that 'E' is not reflected in the waveforms as long as output current (i_o) is continuous.

If output current (i_o) is constant and ripple free, then the waveforms will be similar to those shown in Fig. 2.3.9.

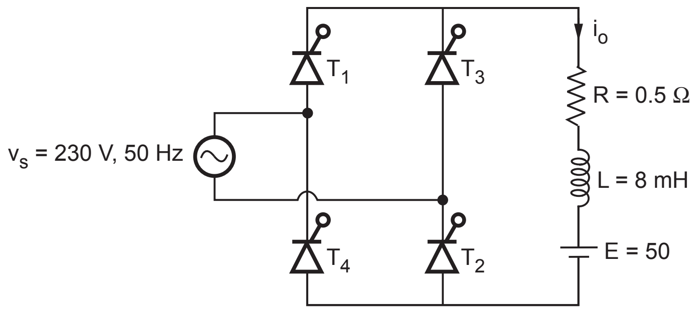


Fig. 2.3.11 1φ full converter feeding RLE load

RMS and average output voltage

The output voltage waveform remains same with RL load and RLE load when i_o is continuous. Therefore the rms and average values of output voltage will be same as those derived in previous example for RL load. i.e.,

$$V_{o(av)} = \frac{2V_m}{\pi}\cos\alpha$$

$$V_{o(rms)} = \frac{V_m}{\sqrt{2}} = V_s$$

Second part : To obtain average load current

The ripple in the load current (i_o) depends upon values of R, L and E. If load inductance is small, then i_o can become discontinuous. In Fig. 2.3.7, observe that i_o repeats at the intervals of π. The waveform of i_o remains same whenever T_1-T_2 or T_3-T_4 conducts. Hence in any interval (i.e. $\alpha \le \omega t \le \pi+\alpha$ or $\pi+\alpha \le \omega t \le 2\pi+\alpha$) the equivalent circuit will be as shown below.

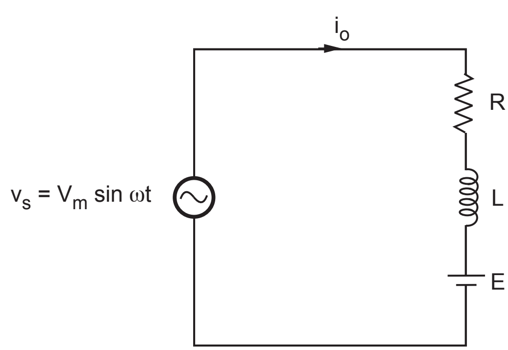


Fig. 2.3.12 Equivalent circuit when T_1-T_2 or T_3-T_4 conduct

By applying KVL to above circuit,

$$V_m \sin\omega t = Ri_o + L\frac{di_o}{dt} + E$$

This equation can be solved using Laplace transform. The solution of above equation is,

$$i_o(\omega t) = \frac{V_m}{Z}\sin(\omega t-\theta)-\frac{E}{R}+\left\{i_o(0)+\frac{E}{R}-\frac{V_m}{Z}\sin(\alpha-\theta)\right\}e^{\frac{R}{\omega L}(\alpha-\omega t)} \quad \text{... (2.3.7)}$$

Here $Z = \sqrt{R^2+(\omega L)^2}$ and $\theta = \tan^{-1}\left(\frac{\omega L}{R}\right)$

$i_o(0)$ is the initial value of the output current. This value is same at $\alpha,\ \pi+\alpha,\ 2\pi+\alpha,\ldots\ldots.$ and so on.

Hence $i_o(\omega t=\alpha) = i_o(0)$

or $i_o(\omega t=\pi+\alpha) = i_o(0)$

Putting this value in equation (2.3.7) and solving for $i_o(0)$ we get,

$$i_o(0) = -\frac{V_m}{Z}\sin(\alpha-\theta)\left[\frac{1+e^{-\frac{\pi R}{\omega L}}}{1-e^{-\frac{\pi R}{\omega L}}}\right]-\frac{E}{R} \quad \text{.... (2.3.8)}$$

The given data is,

$V_s = 230$ $\therefore$ $V_m = \sqrt{2}\times 230 = 325.27$ V

$f = 50$ Hz $\therefore$ $\omega = 2\pi f = 2\pi\times 50 = 314.159$

$R = 0.5\ \Omega$, $L = 8$ mH, $E = 50\ V$, $\alpha = 40°$

$$\therefore \quad \omega L = 314.154\times 8\times 10^{-3} = 2.513$$

$$\frac{\pi R}{\omega L} = \frac{\pi\times 0.5}{2.513} = 0.625$$

$$\therefore \quad e^{-\frac{\pi R}{\omega L}} = e^{-0.625} = 0.5352$$

$$\theta = \tan^{-1}\left(\frac{\omega L}{R}\right) = \tan^{-1}\left(\frac{2.513}{0.5}\right) = 1.3744$$

$$\alpha = 40° = 0.698 \text{ radians}$$

and $$Z = \sqrt{R^2+(\omega L)^2} = \sqrt{(0.5)^2+(2.513)^2} = 2.5622$$

Putting values in equation (2.3.8) we get $i_o(0)$ as

$$i_o(0) = -\frac{325.27}{2.5622}\sin(0.698-1.3744)\left[\frac{1+0.5352}{1-0.5352}\right]-\frac{50}{0.5} = 162.48 \text{ A}$$

This is the minimum value of output current. If this value becomes negative, then it indicates discontinuous operation.

Putting values in equation (2.3.7) we get equation for $i_o(\omega t)$. i.e.,

$$i_o(\omega t) = \frac{325.27}{2.5622}\sin(\omega t - 1.3744) - \frac{50}{0.5} +$$

$$\left\{162.48 + \frac{50}{0.5} - \frac{325.27}{2.5622}\sin(0.698 - 1.3744)\right\} e^{\frac{0.5}{2.513}(0.698-\omega t)}$$

$$= 126.95 \sin(\omega t - 1.3744) - 100 + 392.89\, e^{-0.1989\,\omega t} \qquad \dots (2.3.9)$$

This is the equation for output current from α to $\pi+\alpha$. This waveform has period of π and it repeats at $\pi+\alpha$. Hence average value of i_o will be given as,

$$I_{o(av)} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} i_o(\omega t)\, d\omega\, t$$

$$= \frac{1}{\pi}\int_{0.698}^{\pi+0.698} [126.95\sin(\omega t - 1.3744) - 100 + 392.89 e^{-0.1989\,\omega t}]\, d\omega t$$

$$= \frac{126.95}{\pi}\int_{0.698}^{3.839} \sin(\omega t - 1.3744)\, d\omega t - \frac{100}{\pi}\int_{0.698}^{3.839} d\omega t + \frac{392.89}{\pi}\int_{0.698}^{3.839} e^{-0.1989\omega t}\, d\omega t$$

$$= 217.28 \text{ A}$$

This is the average value of output current.

Example 2.3.5 *If a freewheeling diode is added across the highly inductive load in 1ϕ full converter, derive an expression for average load voltage.*

Solution : We know that freewheeling action does not take place in 1ϕ full converter inherently. In the positive half cycle, T_1 and T_2 conduct from α to π as usual. But from π to $\pi+\alpha$ freewheeling diode starts conducting. This is shown in Fig. 2.3.13. The freewheeling diode is more forward biased compared to T_1 and T_2. Hence freewheeling diode conducts. The freewheeling diode is connected across the output V_o. Hence $V_o = 0$ during freewheeling. The energy stored in the load inductance is circulated back in the load itself. Fig. 2.3.14 shows the waveforms of this operation. The output voltage

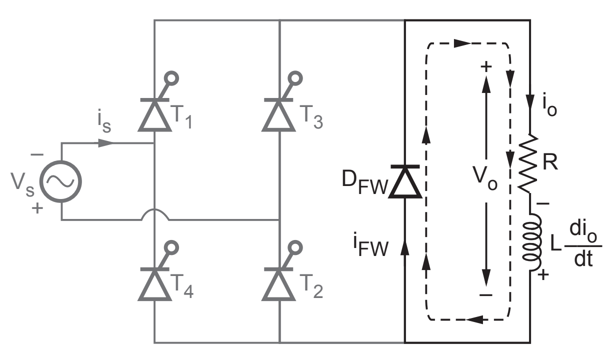


Fig. 2.3.13 Freewheeling diode conducts from π to $\pi+\alpha$ due to inductive load

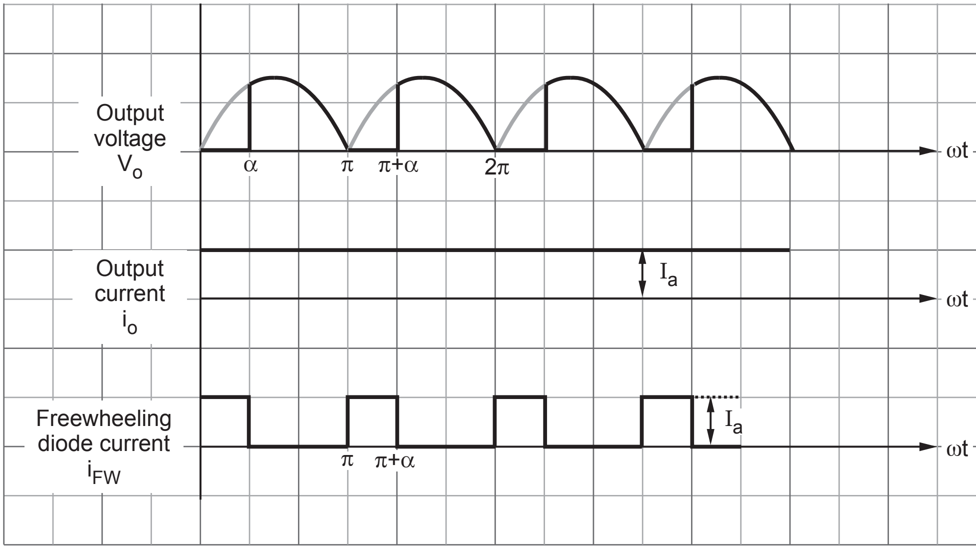


Fig. 2.3.14 Waveforms of 1ϕ full converter for highly inductive load and freewheeling diode across the load

becomes zero in the freewheeling periods. Compare the load voltage waveform of Fig. 2.2.13 with that of 1ϕ full converter with resistive load Fig. 2.3.3. They are same. Hence the average load voltage can be obtained from equation (2.3.3). i.e.,

$$V_{o(av)} = \frac{V_m}{\pi}(1+\cos\alpha) \qquad \text{... (2.3.10)}$$

Example 2.3.6 *A single phase fully controlled bridge rectifier is fed from 230 V - 50 Hz supply. The load is highly inductive. Find the average load voltage and current if the load resistance is 10 Ω and firing angle is 45°. Draw the supply current waveform.*

SPPU : Dec.-13, April-16, Marks 8

Solution : The rms value of the supply voltage is,

$$V_{s(rms)} = 230 \text{ V}$$

Hence peak value of supply voltage is,

$$V_m = V_{s(rms)}\sqrt{2} = 230\sqrt{2}$$

Since the load is highly inductive, the load current can be considered continuous and ripple free as shown in Fig. 2.3.9. For such operation, the average load voltage is given by equation (2.3.5) as,

$$V_{o(av)} = \frac{2V_m}{\pi}\cos\alpha$$

The firing angle $\alpha = 45°$. Hence above equation becomes

$$V_{o\,(av)} = \frac{2 \times 230\,\sqrt{2}}{\pi}\; cos\; 45° = 146.42 \text{ volts}$$

The average load current $I_{o(av)}$ or I_a is given as,

$$I_{o\,(av)} = \frac{V_{o\,(av)}}{R}$$

Putting the values of $R = 10\ \Omega$ and $V_{o\,(av)} = 146.42$ volts,

$$I_{o\,(av)} = \frac{146.42}{10} = 14.64 \text{ A}$$

The supply current waveform will be a square wave as shown in Fig. 2.3.9. The amplitude of the square wave will be $I_{o\,(av)}$ i.e. 14.64 A.

Example 2.3.7 *For a 1ϕ full converter having highly inductive load derive the following :*
i) Fourier series for supply current. ii) Fundamental component of supply current.
iii) RMS value of supply current. **SPPU : Dec.-04, Marks 6**

Solution : i) To determine Fourier series

The general expression for Fourier series is given as,

$$i_s\,(\omega\, t) = I_{s\,(av)} + \sum_{n=1}^{\infty} c_n \,\sin\,(n\omega\, t + \phi_n)$$

where $$c_n = \sqrt{a_n^2 + b_n^2}$$

and $$\phi_n = \tan^{-1}\left(\frac{a_n}{b_n}\right)$$

Here, $$a_n = \frac{2}{T}\int_0^T i_s(\omega\, t)\,\cos\, n\omega\, t\, d\,\omega\, t = \frac{2}{2\pi}\int_0^{2\pi} i_s(\omega\, t)\,\cos\, n\omega\, t\;\; d\,\omega\, t$$

From the supply current waveform of Fig. 2.3.9 we can write,

$$a_n = \frac{2}{2\pi}\left[\int_{\alpha}^{\pi+\alpha} I_{o(av)} \cos n\omega\, t\; d\,\omega\, t + \int_{\pi+\alpha}^{2\pi+\alpha}\left(-I_{o(av)}\right)\cos n\omega\, t\; d\,\omega\, t\right]$$

$$= \frac{I_{o(av)}}{\pi}\left[\int_{\alpha}^{\pi+\alpha}\cos\; n\omega\, t\; d\,\omega\, t - \int_{\pi+\alpha}^{2\pi+\alpha}\cos\; n\omega\, t\; d\,\omega\, t\right]$$

$$= \frac{2\, I_{o\,(av)}}{n\,\pi}\,\sin n\,\alpha\;\left[\cos\; n\,\pi - 1\right]$$

$$= \begin{cases} \dfrac{-4\, I_{o(av)}}{n\,\pi} \sin n\,\alpha & \text{for} \quad n = 1,3,5,\ldots\ldots \\ 0 & \text{for} \quad n = 0,2,4,\ldots\ldots \end{cases} \qquad \ldots (2.3.11)$$

Similarly, $b_n = \dfrac{2}{T} \displaystyle\int_0^T i_s\,(\omega\, t)\, \sin\; n\omega\, t\;\; d\,\omega\, t = \dfrac{2}{2\pi} \int_0^{2\pi} i_s\,(\omega\, t)\, \sin\; n\omega\, t\;\; d\omega\, t$

From supply current of Fig. 2.3.9,

$$b_n = \frac{2}{2\pi} \left[\int_{\alpha}^{\pi+\alpha} I_{o(av)} \sin n\omega\, t\, d\,\omega\, t + \int_{\pi+\alpha}^{2\pi+\alpha} \left(-I_{o(av)} \sin\; n\omega\, t\; d\,\omega\, t \right) \right]$$

$$= \frac{I_{o(av)}}{\pi} \left[\int_{\alpha}^{\pi+\alpha} \sin n\omega\, t\, d\,\omega\, t - \int_{\pi+\alpha}^{2\pi+\alpha} \sin\; n\omega\, t\, d\,\omega\, t \right]$$

$$= \frac{2\, I_{o(av)}}{n\pi} \cos n\alpha\, [1 - \cos\, n\,\pi]$$

$$= \begin{cases} \dfrac{4\, I_{o(av)}}{n\pi} \cos\, n\,\alpha & \text{for} \quad n = 1, 3, 5, \ldots\ldots \\ 0 & \text{for} \quad n = 0, 2, 4, 6, \ldots\ldots \end{cases} \qquad \ldots (2.3.12)$$

Hence $c_n = \sqrt{a_n^2 + b_n^2} = \left\{ \left(\dfrac{4\, I_{o(av)}}{n\,\pi} \right)^2 \left[\sin^2 n\,\alpha + \cos^2 n\,\alpha \right] \right\}^{\frac{1}{2}}$

$$= \frac{4\, I_{o(av)}}{n\,\pi} \quad \text{for} \quad n = 1,\ 3,\ 5,\ \ldots\ldots \qquad \ldots (2.3.13)$$

And $\phi_n = \tan^{-1} \dfrac{a_n}{b_n} = -n\,\alpha$ from equation (2.3.11) and equation (2.3.12)

Thus $\phi_n = -n\,\alpha$ ... (2.3.14)

The average value of supply current is zero. i.e. $I_{s(av)} = 0$. This is clear from Fig. 2.3.9.

Therefore Fourier series is,

$$i_s\,(\omega\, t) = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4\, I_{o(av)}}{n\pi} \sin\,(n\omega\, t - n\,\alpha) \qquad \ldots (2.3.15)$$

ii) Fundamental component of the supply current

RMS value of the n^{th} component is given as,

$$I_{sn} = \frac{c_n}{\sqrt{2}} = \frac{4I_0(av)/n\pi}{\sqrt{2}} = \frac{2\sqrt{2}I_{0(av)}}{n\pi}$$

The fundamental component of the supply current is given as,

$$I_{s1} = \frac{c_1}{\sqrt{2}}$$

From equation (2.3.13), $c_1 = \dfrac{4\,I_{o(av)}}{\pi}$ with $n=1$. Hence above equation will be,

$$\boxed{I_{s1} = \frac{4\,I_{o(av)}}{\pi} \times \frac{1}{\sqrt{2}} = \frac{2\sqrt{2}\;I_{o(av)}}{\pi}} \quad \text{... (2.3.16)}$$

iii) To obtain rms value of supply current

The rms value is given as,

$$I_{s(rms)} = \left[\frac{1}{T}\int_0^T I_s^2\,(\omega\, t)\; d\,\omega\, t\right]^{1/2}$$

From supply current waveform of Fig. 2.3.9,

$$I_{s(rms)} = \left\{\frac{1}{2\pi}\left[\int_{\alpha}^{\pi+\alpha} I_{o(av)}^2\; d\,\omega\, t + \int_{\pi+\alpha}^{2\pi+\alpha}\left(-I_{o(av)}\right)^2\, d\,\omega\, t\right]\right\}^{\frac{1}{2}}$$

$$\therefore \quad \boxed{I_{s(rms)} = I_{o(av)}} \quad \text{... (2.3.17)}$$

Example 2.3.8 *For a 1ϕ full converter having highly inductive load, derive the following :*

i) Displacement factor (DF) ii) Supply power factor (PF)

iii) Harmonic factor (HF) iv) Current distortion factor (CDF)

SPPU : Dec.-18, End Sem, Marks 6

Solution : i) Displacement Factor (DF)

The displacement factor (DF) is given as,

$$\text{DF} = \cos\phi_1 \quad \text{... (2.3.18)}$$

From equation (2.3.14) $\phi_n = -n\,\alpha$; Hence $\phi_1 = -\alpha$.

$$\therefore \quad \text{DF} = \cos(-\alpha)$$

$$\therefore \quad \boxed{\text{DF} = \cos\alpha} \quad \text{... (2.3.19)}$$

ii) Supply Power Factor (PF)

The supply power factor is given as,

$$PF = \frac{I_{s1}}{I_{s(rms)}} \cos \phi_1$$

From result of previous example and equation (2.3.18),

$$PF = \frac{\frac{2\sqrt{2}\, I_{o(av)}}{\pi}}{I_{o(av)}} \cos \alpha$$

$$\therefore \qquad \boxed{PF = \frac{2\sqrt{2}}{\pi} \cos \alpha} \qquad \text{... (2.3.20)}$$

iii) Harmonic Factor (HF)

The harmonic factor (HF) is given as,

$$HF = \sqrt{\left(\frac{I_{s(rms)}}{I_{s1}}\right)^2 - 1}$$

$$= \left[\frac{I_{o(av)}^2}{\left(\frac{2\sqrt{2}\, I_{o(av)}}{\pi}\right)^2} - 1\right]^{\frac{1}{2}}$$

$$\therefore \qquad \boxed{HF = 0.4834 \quad \text{or} \quad 48.34\ \%} \qquad \text{... (2.3.21)}$$

Thus the harmonic factor of supply current is fixed to 0.4834, irrespective of triggering angle.

iv) Current Distortion Factor (CDF)

The current distortion factor (CDF) is given as,

$$CDF = \frac{I_{s1}}{I_{s(rms)}} = \frac{\frac{2\sqrt{2}\, I_{o(av)}}{\pi}}{I_{o(av)}}$$

$$= \frac{2\sqrt{2}}{\pi} = 0.9 \qquad \text{...(2.3.22)}$$

Example 2.3.9 *Show that reactive power input reduces to half due to semiconverter as compared to full controlled bridge for same firing angle α, feeding a continuous ripple free constant current load.* **SPPU : Dec.-2000, Marks 10**

Solution :

a) Reactive power of semiconverter

$$P_{(reactive)} = V_s I_{s1} \sin \phi_1$$

$$= V_s \cdot \frac{2\sqrt{2}\, I_{o(av)}}{\pi} \cos\frac{\alpha}{2} \sin\left(-\frac{\alpha}{2}\right)$$

$$= -V_s \cdot \frac{\sqrt{2}\, I_{o(av)}}{\pi} 2 \sin\frac{\alpha}{2} \cos\frac{\alpha}{2}$$

$$= -\frac{\sqrt{2}\, V_s I_{o(av)}}{\pi} \sin\alpha \qquad \text{since } 2\sin\frac{\alpha}{2}\cos\frac{\alpha}{2} = \sin\alpha$$

$$= \frac{V_m\, I_{o(av)}}{\pi} \sin\alpha \qquad \text{since } \sqrt{2}\, V_s = V_m$$

b) Reactive power of full converter

$$P_{(reactive)} = V_s I_{s1} \sin \phi_1 = V_s \cdot \frac{2\sqrt{2}\, I_{o(av)}}{\pi} \sin(-\alpha)$$

$$= -\frac{2\sqrt{2}\, V_s\, I_{o(av)}}{\pi} \sin\alpha$$

$$= -\frac{2 V_m\, I_{o(av)}}{\pi} \sin\alpha \qquad \text{since } \sqrt{2}\, V_s = V_m$$

Result : From the reactive powers of semiconverter and full converter, observe that reactive power of semiconverter is half of full converter.

Example 2.3.10 *A single phase full converter operates with 220 V, 50 Hz ac input and supplies output load consisting of R-L load with very high inductance drawing level load current 10 A and operated at firing angle of 30°. Find -*

i) RMS supply current.

ii) Fundamental component of input current.

iii) Input displacement factor.

iv) Harmonic factor

v) Power factor vi) Output voltage. **SPPU : May-2000, Marks 10**

Solution : **Given :** 1 ϕ FCB

$$V_s = 220 \text{ V} \quad \therefore \; V_m = 220\sqrt{2} = 311.12 \text{ V}$$

$$I_{o(av)} = 10 \text{ A}, \quad \alpha = 30^\circ \text{ or } \frac{\pi}{6} \text{ radians}$$

i) RMS supply current

$$I_{s(rms)} = I_{o(av)} = 10 \text{ A} \qquad \text{By equation (2.3.17)}$$

ii) Fundamental component of input current

$$I_{s_1} = \frac{2\sqrt{2}\, I_{o(av)}}{\pi} \qquad \text{By equation (2.3.16)}$$

$$= \frac{2\sqrt{2}\times 10}{\pi} = 9 \text{ A}$$

iii) Displacement factor

$$DF = \cos\phi_1 = \cos\alpha = \cos\frac{\pi}{3} = 0.866$$

iv) Harmonic factor

$$HF = 0.4834 \text{ or } 48.34 \text{ \%}$$

By equation (2.3.21)

v) Power factor

$$PF = \frac{2\sqrt{2}}{\pi}\cos\alpha = \frac{2\sqrt{2}}{\pi}\cos\frac{\pi}{6} = 0.779$$

vi) Output voltage

$$V_{o(av)} = \frac{2V_m}{\pi}\cos\alpha = \frac{2\times 311.12}{\pi}\cos\frac{\pi}{6} = 171.53 \text{ V}$$

Example 2.3.11 *A single-phase fully controlled bridge converter supplies an inductive load. Assuming that the output current is virtually constant and is equal to I_d, determine the following performance measures, if the supply voltage is 230 V and if the firing angle is maintained at (π/6) radians.*

i) Average output voltage ii) Fundamental power factor or Displacement Factor (DF)

iii) Supply power factor (PF) iv) Supply Harmonic Factor (HF). **SPPU : May-07, Marks 8**

Solution : Given : $I_{o(av)} = I_d$

$$V_{s(rms)} = 230 \text{ V Hence } V_m = V_{s(rms)}\sqrt{2} = 230\sqrt{2}$$

$$\alpha = \frac{\pi}{6} \text{ radians}$$

i) Average output voltage

$$V_{o(av)} = \frac{2V_m}{\pi}\cos\alpha = \frac{2\times 230\sqrt{2}}{\pi}\cos\frac{\pi}{6} = 179.33$$

ii) Displacement factor (DF)

$$DF = \cos\alpha = \cos\frac{\pi}{6} = 0.866$$

iii) Supply power factor (PF)

$$PF = \frac{2\sqrt{2}}{\pi}\cos\alpha = \frac{2\sqrt{2}}{\pi}\cos\frac{\pi}{6} = 0.78$$

iv) Supply harmonic factor (HF)

$$HF = 0.4834 \text{ for fully controlled bridge.}$$

Example 2.3.12 *For a 1 ϕ fully controlled bridge having continuous and ripple free current obtain, i) Active power and ii) Reactive power.* **SPPU : Dec.-2000, Marks 6**

Solution : i) Active power

Active power is given as,

$$P_{active} = V_s I_{s1}\cos\phi_1$$

$$= V_s\cdot\frac{2\sqrt{2}\ I_{o(av)}}{\pi}\cos(-\alpha), \quad \text{since } \phi_1 = -\alpha$$

$$= 2\cdot\frac{\sqrt{2}V_s I_{o(av)}}{\pi}\cos(\alpha)$$

$$= \frac{2V_m I_{o(av)}}{\pi}\cos\alpha \qquad \ldots(2.3.23)$$

ii) Reactive power

Reactive power is given as,

$$P_{reactive} = V_s I_{s1}\sin\phi_1$$

$$= V_s\cdot\frac{2\sqrt{2}\ I_{o(av)}}{\pi}\sin(-\alpha)$$

$$= -2\cdot\frac{\sqrt{2}V_s I_{o(av)}}{\pi}\sin\alpha$$

$$= -\frac{2V_m I_{o(av)}}{\pi} \sin\alpha \qquad \ldots(2.3.24)$$

The negative sign indicates that the power is reactive.

Comment

Compare the reactive powers of full converter and half converter. They are as follows :

$$P_{reactive}(\text{HCB}) = -\frac{V_m I_{o(av)}}{\pi} \sin\alpha$$

$$P_{reactive}(\text{FCB}) = -\frac{2V_m I_{o(av)}}{\pi} \sin\alpha$$

From above two equations we have,

$$P_{reactive}(\text{FCB}) = 2 \times P_{reactive}\ (\text{HCB})$$

- Thus half controlled bridge draws 50 % reactive power compared to that of full controlled bridge.

Example 2.3.13 *A single phase fully controlled bridge operates with 230 V, 50 Hz ac input and supplies continuous ripple free output current of 5 A. If bridge is operated at a firing angle of 45°. Find, i) Average output voltage ii) RMS supply current iii) Harmonic factor iv) RMS value of 3^{rd} harmonic of input current.*

SPPU : May-01, 08, Marks 6

Solution : Given : 1ϕ FCB

V_s = 230 V, $V_m = 230\sqrt{2}$ = 325.27 V, $I_{o(av)}$ = 5 A,

α = 45° or $\frac{\pi}{4}$ radians

i) Average output voltage

$$V_{o(av)} = \frac{2V_m}{\pi} \cos\alpha$$

$$= \frac{2 \times 325.27}{\pi} \cos\frac{\pi}{4} = 146.42 \text{ V}$$

ii) RMS supply current

$$I_{s(rms)} = I_{o(av)} = 5 \text{ A}$$

iii) Harmonic factor

For 1 ϕ FCB with highly inductive load, HF is constant.

i.e., $\quad HF = 0.4834$ or 48.34 %

iv) RMS value of 3rd harmonic

$$I_{sn} = \frac{c_n}{\sqrt{2}} = \frac{4\,I_{o(av)}/n\pi}{\sqrt{2}} = \frac{2\sqrt{2}\,I_{o(av)}}{n\pi}$$

$$\therefore \qquad I_{s3} = \frac{2\sqrt{2}\,I_{o(av)}}{3\pi} = \frac{2\sqrt{2}\times 5}{3\pi} = 1.5 \text{ A}$$

2.3.3 Inversion in 1ϕ Full Converter

The waveforms of 1ϕ full converter for inductive load are given in Fig. 2.3.9. Observe that the output voltage v_o goes negative for some duration. These intervals are 0 to α, π to $\pi+\alpha$, ... and so on. The output current i_o remains positive always. Thus output instantaneous power becomes negative in such intervals. In other words, load power flows to source when v_o goes negative. The average output voltage is given by equation (2.3.5). i.e.,

$$V_{o(av)} = \frac{2V_m}{\pi}\cos\alpha$$

The variation of $V_{o(av)}$ with respect to α is shown in Fig. 2.3.15. In this figure observe that the $V_{o(av)}$ is positive from 0 to $\frac{\pi}{2}$. For $\alpha = 90°$ or $\frac{\pi}{2}$, the $V_{o(av)}$ is zero.

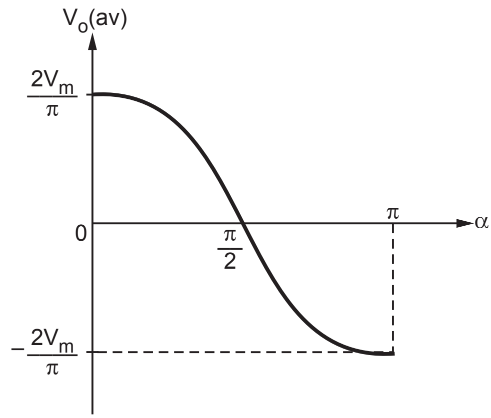


Fig. 2.3.15 Variation of output average voltage with respect to firing angle

Fig. 2.3.15 shows the waveform of v_o for $\alpha = 90°$ or $\frac{\pi}{2}$. The SCRs conduct, current flows in the load but $V_{o(av)} = 0$. This means power fluctuates between load and the source. No power is consumed by the load. The load inductance stores power from source when v_o is positive (i.e. rectification). And this stored power is fed back to the source when v_o is negative (i.e. inversion). When the firing angle is increased above 90°, the average output voltage becomes negative as shown in Fig. 2.3.15. Hence net power is fed from output (load) to the source. But where does this power comes from ? Because load inductance cannot supply more power than it stores. At $\alpha = 90°$, stored power and power supplied to the source are equal. For $\alpha > 90°$, the stored power is less and more power needs to be supplied to the source. Hence an external DC source is to be connected in the load as shown in Fig. 2.3.17. This DC source maintains the forward bias on the SCRs. Hence they keep on conducting even though $\alpha > 90°$. Such output voltage waveform is shown in Fig. 2.3.16. The average output voltage $V_{o(av)}$ is negative. Hence power flows from load side to the source. The DC supply provides this

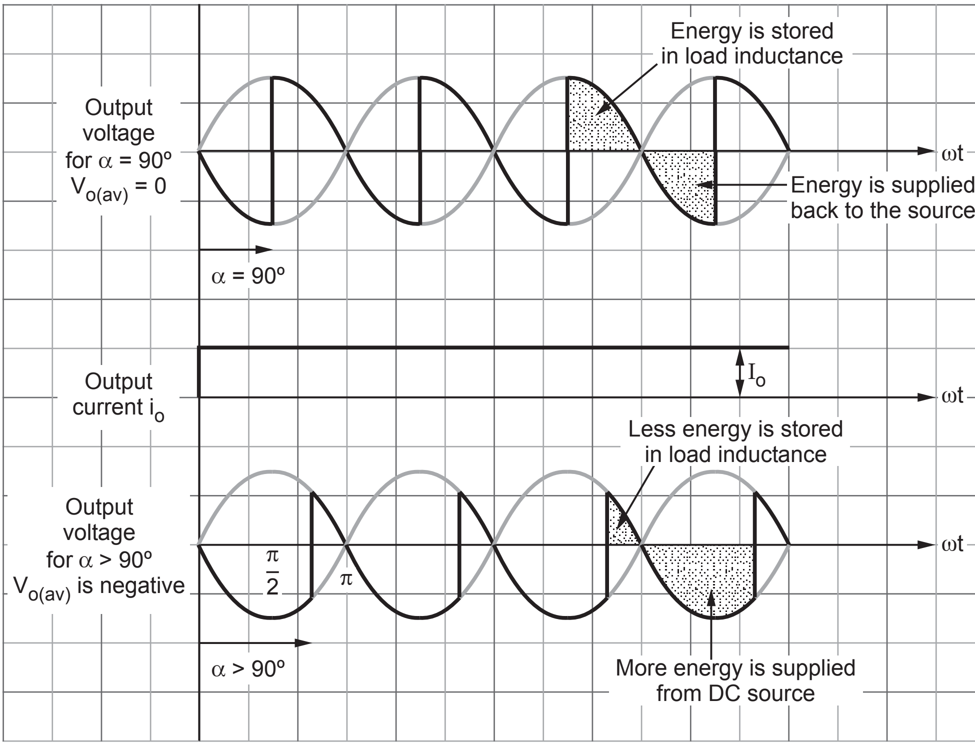


Fig. 2.3.16 Inversion in 1φ full converters

power. Thus DC power at the output is converted to AC power at the source or input. This is called as *inverting* operation of converter. It is also called as inversion. Note that for $\alpha < 90°$, converter operates in rectification mode. For $\alpha > 90°$, converter operates in inverting and at $\alpha = 90°$, output voltage is zero. Table 2.3.2 gives these details.

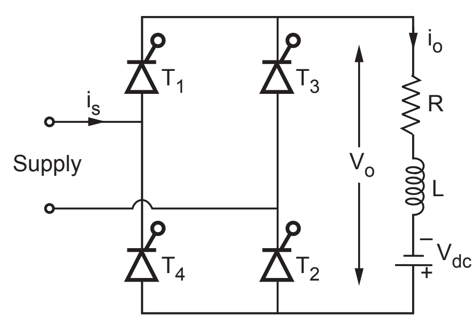


Fig. 2.3.17 Inverting operation in 1φ full converter

Triggering angle	Mode of operation	Power flow	Output voltage
$\alpha < 90°$	Rectification	Source to load	$V_{o(av)}$ positive
$\alpha = 90°$	None	None	$V_{o(av)} = 0$
$\alpha > 90°$	Inversion	Load to source	$V_{o(av)}$ negative

Table 2.3.2 Operating modes of 1φ full converter

Example 2.3.14 *A single phase fully controlled bridge rectifier has an AC voltage of 230 rms applied to it. If it is to act as an inverter with a DC source of 150 V, estimate the trigger angle delay.*

Solution : In Fig. 2.3.17 we have seen that the DC voltage source is connected at the output of converter. The converter then acts as an inverter. Since the conduction is continuous the output average voltage will be,

$$V_{o(av)} = \frac{2V_m}{\pi}\cos\alpha \qquad \text{... (2.3.25)}$$

Here the voltage drop across the load is not given. Hence we can assume zero voltage drop in the load. Hence the DC source voltage becomes as average output voltage. i.e.,

$$V_{o(av)} = -150 \text{ V}$$

Here 150 V is the DC source voltage and it is negative as shown in Fig. 2.3.16. Supply voltage is,

$$V_s = 230 \text{ V} \quad \text{Hence } V_m = \sqrt{2}\times 230 \text{ V}$$

Putting values in equation (2.3.21),

$$-150 = \frac{2\times\sqrt{2}\times 230}{\pi}\cos\alpha$$

$$\therefore \quad \cos\alpha = -0.724383$$

$$\therefore \quad \alpha = 136.41^\circ$$

Example 2.3.15 *A single phase fully controlled bridge operating from the 240 V, 50 Hz mains, is used to charge a 144 V DC battery bank through a smoothing reactor and current limiting resistor. The internal resistance of the battery bank is 0.25 Ω and winding resistance of the reactor is 0.25 Ω .*

i) Calculate the value of the current limiting resistor required for nominal charging current of 15 A if the firing angle is 30°.

ii) Calculate the maximum and minimum firing angles to maintain the current constant if the mains supply voltage varies by + 10 % to – 10 %.

iii) The above bridge is now operated in the inverting mode by reversing the battery polarity and adjusting the firing angle appropriately. Calculate the firing angle such that the battery discharge current is 10 A with nominal mains supply voltage. Also obtain the power supplied by the battery and power fedback to the mains. Neglect all device drops.

SPPU : May-06, Marks 16

Solution : Given : $V_s = 240$ V

Internal resistance $(R_{batt}) = 0.25 + 0.25 = 0.5\ \Omega$

$$V_{batt} = 144 \text{ V}$$

i) To obtain current limiting resistor

$$\text{Here } \alpha = 30°$$

and $$I_{o(av)} = I_{batt} = 15 \text{ A}$$

$$V_{o(av)} = \frac{2V_m}{\pi}\cos\alpha$$

$$= \frac{2\times 240\times\sqrt{2}}{\pi}\cos 30°$$

$$= 187.127 \text{ V}$$

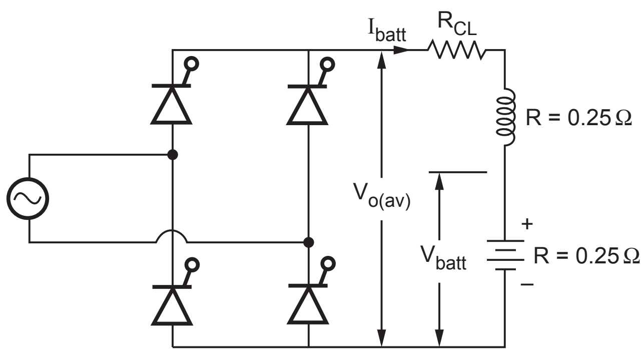


Fig. 2.3.18 Battery charging

The current limiting resistor is given from Fig. 2.3.18 as,

$$R_{CL} + 0.5\ \Omega = \frac{V_{o(av)} - V_{batt}}{I_{batt}} = \frac{187.127 - 144}{15}$$

$$\therefore \quad R_{CL} = 2.375\ \Omega$$

ii) Range of firing angles for $V_s \pm 10$ %

$$V_{s(max)} = 240 + 10 \text{ \% of } 240 = 240 + 24 = 264 \text{ V}$$

$$V_{s(min)} = 240 - 10 \text{ \% of } 240 = 240 - 24 = 216 \text{ V}$$

To maintain constant charging current $V_{o(av)}$ should remain constant. Hence range of firing angles can be calculated as follows :

$$V_{o(av)} = \frac{2V_{m(max)}}{\pi}\cos\alpha_{max}$$

$$187.127 = \frac{2 \times 264 \times \sqrt{2}}{\pi} \cos \alpha_{max}$$

$$\therefore \quad \alpha_{max} = 38°$$

And $$V_{o(av)} = \frac{2 V_{m(\min)}}{\alpha} \cos \alpha_{min}$$

$$187.127 = \frac{2 \times 216 \times \sqrt{2}}{\pi} \cos \alpha_{min}$$

$$\therefore \quad \alpha_{min} = 15.79°$$

Thus α can be varied from 15.79° to 38° to maintain constant charging current.

iii) To obtain firing angle and powers in inverting mode

From Fig. 2.3.19 we can obtain $V_{o(av)}$ as,

$$V_{o(av)} + 144 - I_{batt} R_{batt} = 0$$

$$\therefore \quad V_{o(av)} = -144 + 10 \times 0.5 = -139 \text{ V}$$

$$V_{o(av)} = \frac{2V_m}{\pi} \cos \alpha$$

$$-139 = \frac{2 \times 240 \times \sqrt{2}}{\pi} \cos \alpha$$

$$\therefore \quad \alpha = 130°$$

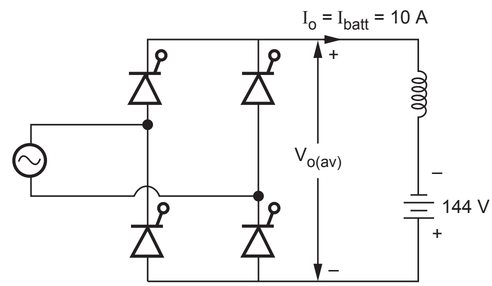


Fig. 2.3.19 Inverting mode

To obtain the power supplied by the battery

Battery current is 10 A and its voltage is 144 V. Hence power supplied by battery will be,

$$\text{Battery power} = 10 \times 144 = 1440 \text{ W.}$$

To obtain power fedback to mains

The combined resistance of the reactor and battery is $0.5\ \Omega$. Hence power loss due to this resistance will be $(10)^2 \times 0.5 = 50$ W. The remaining power is given back to mains. i.e.,

Power supplied to mains = 1440 – 50 = 1390 W

2.3.4 Comparison of Half Controlled and Full Controlled Rectifiers

Now let us compare the half controlled and fully controlled bridge rectifiers. Table 2.3.3 shows this comparison.

Sr. No.	Half controlled converter	Fully controlled converter
1.	This consists of half number of SCRs and half number of diodes.	This consists of all the SCRs as controlled devices.
2.	This operates in only one quadrant.	This can operate in two quadrants.
3.	Output voltage is always positive.	Output voltage can be negative in case of inductive loads.
4.	Inherent freewheeling action is present.	External freewheeling diode is to be connected for freewheeling.
5.	Power factor is better.	Power factor is poor than half converter.
6.	Inversion is not possible.	Inversion is possible.
7.	Used for battery chargers, lighting and heater control.	Used for DC motor drives.

Table 2.3.3 Comparison of half and fully controlled bridges

Example 2.3.16 *A single phase fully controlled bridge rectifier is given 230 V, 50 Hz supply. The firing angle is 45° and load is highly inductive.*

Determine : i) Average output voltage ii) O/P rms voltage iii) Power factor.

SPPU : Dec.-11, Marka 6

Solution : $V_s = 230\ V,\ \alpha = \frac{\pi}{4}$ *or 45°, Highly inductive load.*

i) Average output voltage

$$V_{o(av)} = \frac{2V_m}{\pi}\cos\alpha \qquad \text{for continuous load current}$$

$$= \frac{2\times 230\sqrt{2}}{\pi}\cos 45^\circ = 146.42\ \text{V}$$

ii) Output rms voltage

$$V_{o(rms)} = V_s = 230\ \text{V}$$

iii) Power factor

$$\text{PF} = \frac{2\sqrt{2}}{\pi}\cos\alpha = 0.9\cos 45^\circ = 0.637 \text{ lagging}$$

Examples for Practice

Example 2.3.17 : *A 1ϕ full converter is operated from 230 V/ 50 Hz mains and is delivering power to the resistance R_L = 10 Ω in series wtih a large smoothing inductor. Find out the follwing if α = 45°. i) $V_{o(av)}$ ii) $V_{o(rms)}$ iii) FF iv) RF.*

[Ans. : $V_{o(av)}$ = 146.75, $V_{o(rms)}$ = 230, FF = 1.57, RF = 1.21]

Example 2.3.18 : *With the help of neat circuit diagram and waveforms explain the operation of 1 ϕ full converter.*

Example 2.3.19 : *Derive an expression for average and rms output voltage for 1 ϕ full bridge converter.*

Example 2.3.20 : *A single phase full converter is operated from a 120 V, 60 Hz supply. The load current with an average valve of I_a is continuous, with negligible ripple current. If the turns ratio of the transformer is unity, if the delay angle is $\alpha = \frac{\pi}{3}$. Calculate the i) HF of input current ii) DF iii) PF.*

[Ans. : *HF* = 48.34 %, *DF* = 0.5, *PF* = 0.45]

Review Questions

1. *Explain the inversion in 1ϕ full converter. OR Explain 2nd quadrant operation of LCC.*

   SPPU : Dec.-01, 06, Marks 5; May-02, Marks 8; Nov.-07, Marks 6

2. *Draw the circuit diagram and relevant waveforms of output voltage, input current and fundamental component of input current for fully controlled bridge feeding a continuous ripplefree current. Derive an expression for nth harmonic current (rms) and power factor.*

   SPPU : Dec.-04, May-01, Marks 10, Dec.-07, Marks 8, May-2000, Marks 6

3. *Explain the rectifying and inverting modes of singles phase full converter with RL load.*

   SPPU : Dec.-09, May-12, Marks 8; Dec.-10, Marks 10

4. *Draw the circuit diagram for three phase fully controlled converter with R load. Draw load current and load voltage waveforms* **SPPU : Dec.-09, Marks 4**

5. *Describe the working of single-phase fully controlled bridge converter for R-L load for different modes with all waveforms. Also derive an expression for its rms output voltage.*

   SPPU : Dec.-13,15, April-15,16,17 In Sem, May-17 End Sem, Marks 8

6. *What are the effects of freewheeling diode in full converter for R-L load ?*

   SPPU : Dec.-13, April-16, Marks 4

7. *Describe the working of single phase fully controlled bridge converter for R-L load in the following modes : 1) Rectifying mode 2) Inversion mode. Also derive an expression for its average output voltage.* **SPPU : Dec.-11, Marks 8**
8. *Draw the circuit diagram of single phase full controller bridge rectifier with R-L load. Explain its operation. Draw the waveform of output voltage and current.* **SPPU : April-16, May-17, Marks 7**
9. *Draw and explain single phase full converter with highly inductive load with input and output waveforms at 60 °C and 120 °C.* **SPPU : May-18, End Sem, Marks 6**
10. *In a full AC to DC converter, explain the rectification mode and line commutated inverter mode of operation with relevant waveforms.* **SPPU : Dec.-18, End Sem, Marks 7**
11. *With the help of neat circuit diagram and waveforms, explain the operation of 1ϕ Full-converter for α = 30° and α = 60° with R load.* **SPPU : April-19, In Sem, Marks 5**
12. *Draw and explain working of single phase fully controlled rectifier for R load. Draw input output Voltage waveforms. State equation for average output voltage.* **SPPU : May-19, End Sem, Marks 7**

2.4 Effect of Source Inductance

SPPU : Dec.-18, April-19

2.4.1 Effect of Source Inductance on Semiconverter

The input AC power sources supplying power to AC to DC converter are assumed to be ideal with no source impedance. Although this assumption helps in to simplify the analysis of the converters, in most practical situations, they are not fully justified. Generally AC to DC converter is supplied from transformers. The series impedance of the transformer cannot always be neglected. Even though no transformer is used, the impedance of the feeder line comes in series with the source. In many cases this impedance is predominantly inductive with negligible resistive component. The presence of source inductance does have substantial effect on the performance of the converter. With source inductance present the output voltage of a converter does not remain constant for a given firing angle. Instead it decreases gradually with load current. The converter output voltage and input current waveforms also change significantly.

Single Phase Fully Controlled Converter with Source Inductance :

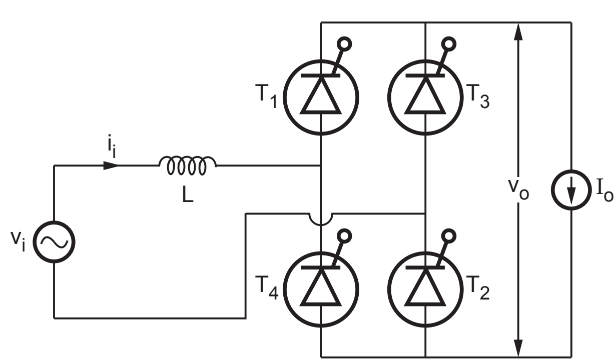
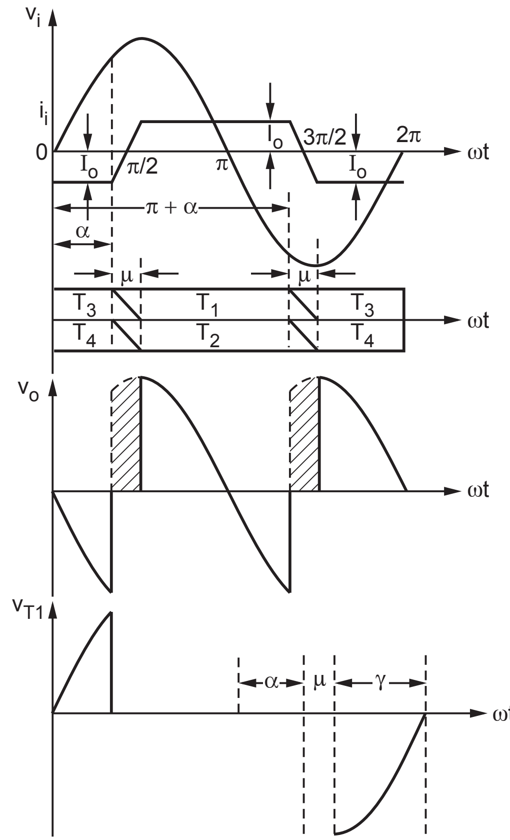


Fig. 2.4.1 (a) Circuit diagram

Fig. 2.4.1 (a) shows a single phase fully controlled converter with source inductance. For simplicity it has been assumed that the converter operates in the continuous conduction mode. Further, it has been assumed that the load current ripple is negligible and the load can be replaced by a dc current source the magnitude of which equals the average load current. Fig. 2.4.1 (b) shows the corresponding waveforms. It is assumed that the thyristors T3 and T4 were conducting at t = 0. T1 and T2 are fired at $\omega t = \alpha$. If there were no source inductance T3 and T4 would have commutated as soon as T1 and T2 are turned ON. The input current polarity would have changed instantaneously. However, if a source inductance is present the commutation and change of input current polarity cannot be instantaneous. Therefore, when T1 and T2 are turned ON T3 T4 does not commutate immediately. Instead, for some interval all four thyristors continue to conduct as shown in Fig. 2.4.1 (b). This interval is called "overlap" interval.



(b) Waveforms

Fig. 2.4.1 Operation of single phase fully controlled converter with source inductance

During this period the load current freewheels through the thyristors and the output voltage is clamped to zero. On the other hand, the input current starts changing polarity as the current through T1 and T2 increases and T3 T4 current decreases. At the end of the overlap interval the current through T3 and T4 becomes zero and they commutate, T1 and T2 starts conducting the full load current. The same process repeats during commutation from T1-T2 to T3-T4 at $\omega t = \pi + \alpha$.

From Fig. 2.4.1 (b) it is clear that, commutation overlap not only reduces average output dc voltage but also reduces the extinction angle γ which may cause commutation failure in the inverting mode of operation if α is very close to 180°.

2.4.2 Effect of Source Inductance on Full Converter

The presence of transfer leakage reactance doesn't allow the current to transfer from one SCR to other. Instanteneously but takes finite time to complete the commutation. During the commutation current in conducting SCR decreases gradually transfering the load to other SCR and both SCR conducts simultenously providing SCKT of the transformer secondary through leakage reactance.

$$E_x = 2fL_{c2}I_e$$

$$E_x = \frac{1}{2\pi}\alpha^2 \int_{\propto}^{\propto+\mu} V_m \sin wt\, dwt$$

$$= \frac{V_m}{\pi}\left[\propto - \cos(\propto + \mu)\right] \qquad \text{... (2.4.1)}$$

At no load, average output voltage (R-L load)

$$\boxed{E_o = \frac{2V_m}{\pi}\cos\alpha}$$

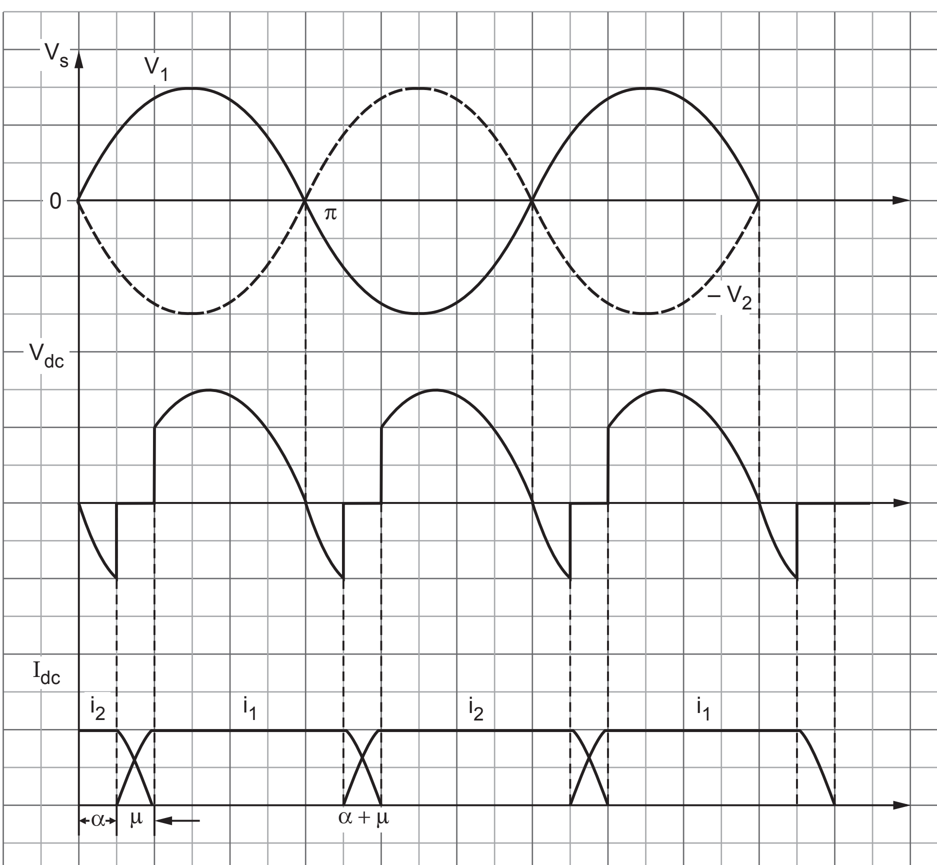


Fig. 2.4.2

$\therefore$ At any load output voltage

$$\boxed{V_{dc} = E_o - Ex}$$

$$V_{dc} = \frac{V_m}{\pi}[\cos\alpha + \cos(\alpha+\mu)]$$

But $$E_x = 2\,fl_{c_2}\,I_e$$

$$2\,fL_{c2}\,I_c = \frac{V_m}{\pi}[\cos\alpha - \cos(\alpha+\mu)]$$

$$\cos(\alpha+\mu) = \cos\alpha - \frac{wL_{c2}I_e}{V_m}$$

$$\therefore \quad V_{dc} = \frac{V_m}{\pi}\left[2\cos\alpha - \frac{\omega L_{c2}I_e}{V_m}\right]$$

$$\boxed{V_{dc} = \frac{2V_m\cos\alpha}{\pi} - \frac{wL_{c2}I_e}{\pi}}$$

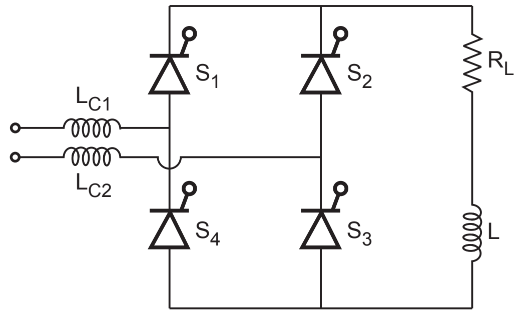


Fig. 2.4.3 Effort of transformer leakage reactance

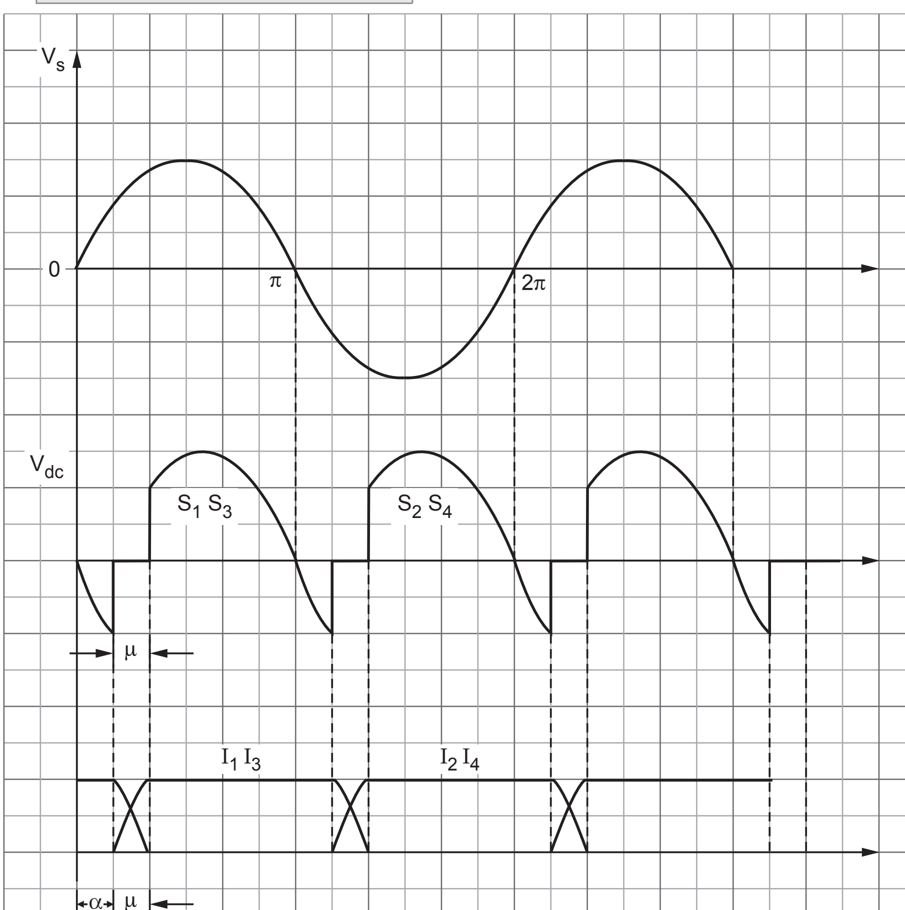


Fig. 2.4.4

Review Questions

1. *Explain effect of source impedance on the performance of 1Φ full converter. Derive the expression for average output voltage.* **SPPU : Dec.-18, End Sem, Marks 6**
2. *Explain effect of source Inductance on the performance of 1 Φ full converter. Derive the expression for average output voltage.* **SPPU : April-19, In Sem, Marks 4**

2.5 Significance of Power Factor and its Improvement using PWM based Techniques

The term power factor comes into picture in AC circuits only. Mathematically it is cosine of the phase difference between source voltage and current. It refers to the fraction of total power (apparent power) which is utilized to do the useful work called

$$\cos\phi = \frac{\text{Active power}}{\text{Apparent power}}$$

Need for Power Factor Improvement

- Real power is given by P = VI cos ϕ. To transfer a given amount of power at certain voltage, the electrical current is inversely proportional to cos ϕ. Hence higher the PF lower will be the current flowing. A small current flow requires less cross sectional area of conductor and thus it saves conductor and money.
- From above relation we saw having poor power factor increases the current flowing in conductor and thus copper loss increases. Further large voltage drop occurs in alternator, electrical transformer and transmission and distribution lines which gives very poor voltage regulation.
- Further the KVA rating of machines is also reduced by having higher power factor as,

$$\text{kVA} = \frac{KW}{\cos\phi}$$

- Hence, the size and cost of machine also reduced. So, electrical power factor should be maintained close to unity.

2.5.1 Methods of Power Factor Improvement

- For phase-controlled operation in both single phase full wave half and full controlled bridge converters as discussed in this module, the displacement factor (or power factor, which is lagging) decreases, as the average value of output voltage (V_{dc}) decreases, with the increase in firing angle delay, α. This is also applicable for both three phase half wave and full wave (bridge) converters. The three schemes used for power factor (PF) improvement are :

1. Extinction angle control
2. Symmetrical angle control
3. Pulse Width Modulation (PWM) control

2.5.2 Extinction Angle Control

Fig. 2.5.1 shows the circuit diagram of 1ϕ half controlled bridge. The SCRs T_1 and T_2 are shown by dotted blocks.

This means T_1 and T_2 include their commutation circuits. BJT, MOSFET or IGBTs can also be employed in place of T_1 and T_2. Here T_1 and T_2 are turned-on or turned-off at required instants.

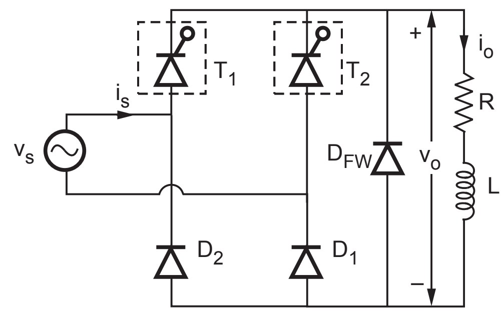


Fig. 2.5.1 Circuit diagram of full converter for PF improvement

Operation and Waveforms

Fig. 2.5.2 shows the waveforms of extinction angle control.

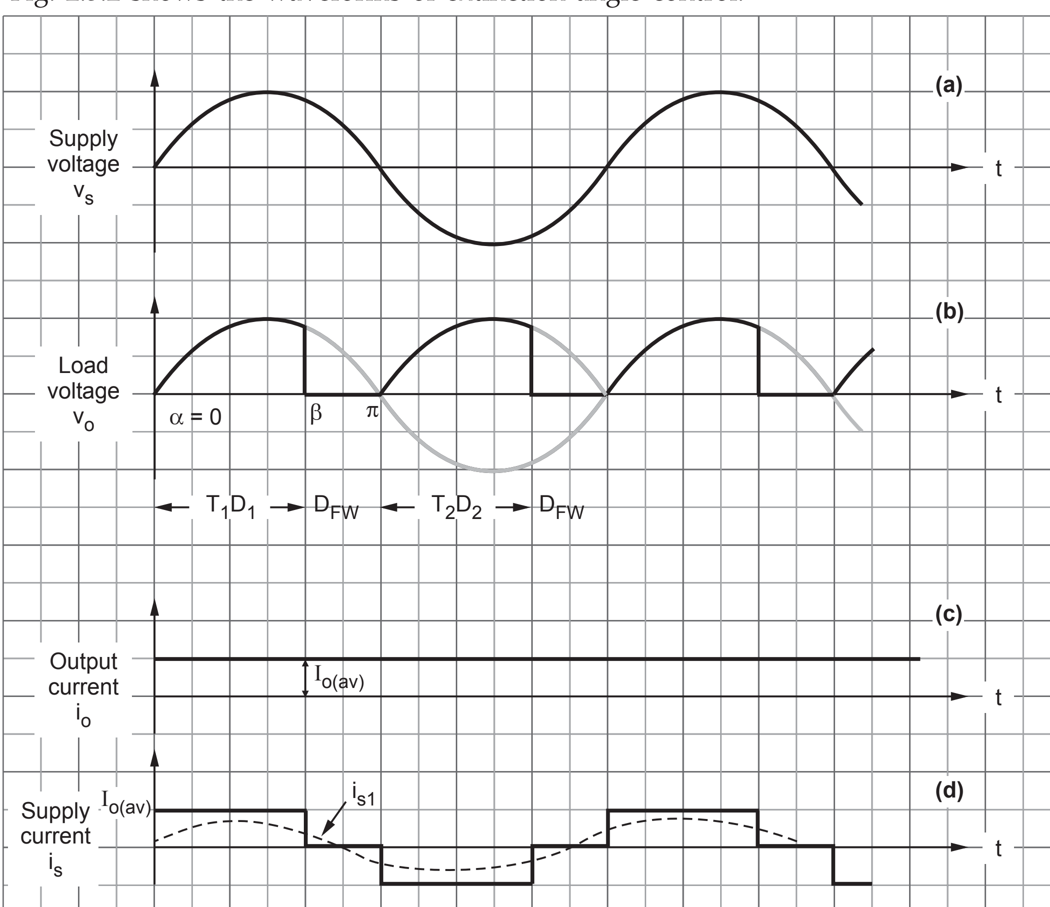


Fig. 2.5.2 Waveforms of EAC

- The SCRs T_1 and T_2 are always triggered at the beginning of cycle, i.e. $\alpha = 0$. And T_1 is turned off by forced commutation at β. The variation of β changes the average output voltage and other parameters of the circuit.
- Fig. 2.5.2 (d) shows the supply current for ripple free load current. The dotted line shows fundamental component (first harmonic i_{S1}) of supply current.
- Here note that the fundamental component of supply current (i_{S1}) leads supply voltage. Hence extinction angle control provides leading power factor.

Mathematical Analysis

Average output voltage obtained as,

$$V_{o(av)} = \frac{1}{T}\int_0^T v_s(\omega t)\, d\omega t = \frac{1}{\pi}\int_0^\beta V_m \sin \omega t\, d\omega t$$

$$= \frac{V_m}{\pi}(1-\cos\beta) \qquad \dots (2.5.1)$$

RMS value of supply current is obtained as,

$$I_{s(rms)} = \left[\frac{1}{T}\int_0^T i_s^2(\omega t)\, d\omega t\right]^{\frac{1}{2}} = \left[\frac{1}{\pi}\int_0^\beta I_{o(av)}^2\, d\omega t\right]^{\frac{1}{2}}$$

$$= I_{o(av)}\sqrt{\frac{\beta}{\pi}} \qquad \dots (2.5.2)$$

Similarly other parameters can be obtained using Fourier series. RMS value of n^{th} harmonic of supply current will be,

$$I_{sn} = \frac{2\sqrt{2}\, I_{o(av)}}{n\pi}\sin\frac{n\beta}{2} \quad \text{for} \quad \text{odd } n \qquad \dots (2.5.3)$$

Displacement angle of n^{th} harmonic of supply current will be,

$$\phi_n = n\left(\frac{\pi}{2}-\frac{\beta}{2}\right) \qquad \dots (2.5.4)$$

Supply power factor will be,

$$PF = \frac{\sqrt{2}(1-\cos\beta)}{\sqrt{\pi\beta}} \qquad \dots (2.5.5)$$

Displacement factor will be,

$$DF = \sin\frac{\beta}{2} \text{ (leading)} \qquad \dots (2.5.6)$$

Harmonic factor will be,

$$HF = \sqrt{\frac{\pi\beta}{4(1-\cos\beta)} - 1} \qquad \dots (2.5.7)$$

The performance of extinction angle control is similar to that of phase angle control discussed in the operation of 1ϕ semiconverter earlier. The only difference is that displacement factor is leading in extinction angle control, whereas it is lagging in phase angle control.

2.5.3 Symmetrical Angle Control (SAC)

Fig. 2.5.3 shows the waveforms of symmetrical angle control.

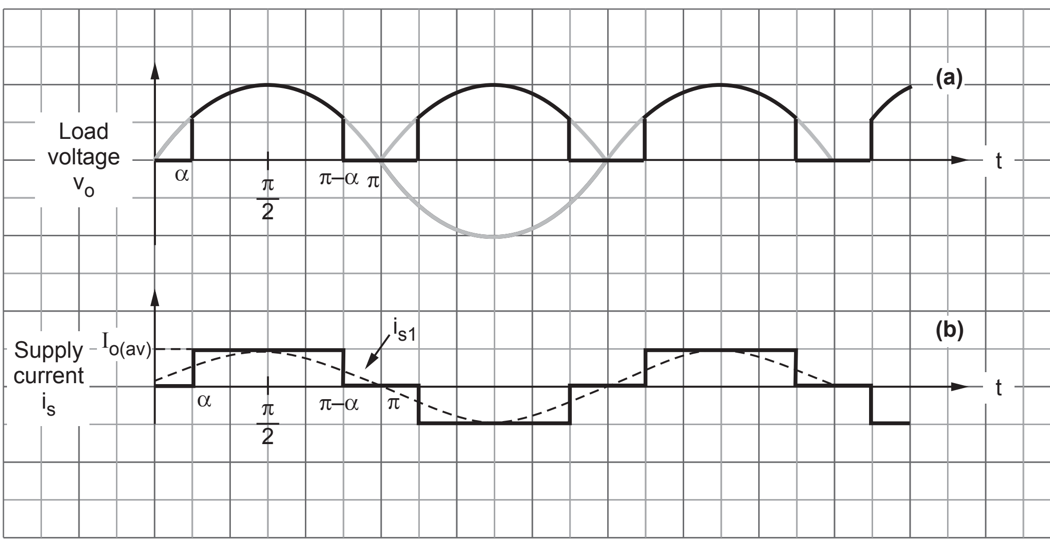


Fig. 2.5.3 Waveforms of symmetrical angle control

- The SCR T_1 is triggered at α and turned off at $\pi - \alpha$. Thus $\beta = \pi - \alpha$. Fig. 2.5.3 (b) shows the supply current waveform for ripple free load current. Observe that the supply current pulse is symmetric around $\frac{\pi}{2}$.
- The dotted line in Fig. 2.5.3 (b) shows fundamental component (i_{s1}) of supply current. Note that this fundamental component is in phase with respect to supply voltage. Therefore displacement factor is unity. This improves power factor.

Mathematical Analysis

Average output voltage,

$$V_{o(av)} = \frac{1}{T}\int_0^T v_o(\omega t)\, d\omega t$$

$$= \frac{1}{\pi}\int_{\alpha}^{\pi-\alpha} V_m \sin\omega t \, d\omega t \;=\; \frac{2V_m}{\pi}\cos\alpha \qquad \ldots (2.5.8)$$

RMS value of supply current is obtained as,

$$I_{s(rms)} = \left[\frac{1}{T}\int_0^T i_s^2(\omega t)\, d\omega t\right]^{\frac{1}{2}} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi-\alpha} I_{o(av)}^2 \, d\omega t\right]^{\frac{1}{2}}$$

$$= I_{o(av)}\sqrt{1-\frac{2\alpha}{\pi}} \qquad \ldots (2.5.9)$$

Similarly other values can be obtained using Fourier series. RMS value of n^{th} harmonic of supply current will be,

$$I_{sn} = \frac{2\sqrt{2}\, I_{o(av)}}{n\pi}\cos n\alpha \quad \text{for odd n} \qquad \ldots (2.5.10)$$

Displacement angle, $\phi_n = 0$ … (2.5.11)

Power factor, $PF = \dfrac{2\sqrt{2}\cos\alpha}{\pi\sqrt{1-\frac{2\alpha}{\pi}}}$

Displacement factor, $DF = 1$

Harmonic factor, $HF = \sqrt{\dfrac{\pi(\pi-2\alpha)}{8\cos^2\alpha}-1}$ … (2.5.12)

2.5.4 Pulse Width Modulation (PWM)

Fig. 2.5.4 shows the waveforms of PWM.

- The triangular wave and DC control voltage is compared in the control circuit. This comparison gives start and end of multiple pulses in each half cycle.
- The SCR T_1 is triggered at α_1 and commutated at β_1. This results first pulse of voltage across output as shown in Fig. 2.5.4 (b). Again T_1 is triggered at α_2 and commutated at β_2. This repeats till π.
- In one half cycle there are multiple pulses of output. The average value of output voltage can be varied by changing amplitude of DC control valtage in Fig. 2.5.4 (a).
- The lowest harmonic present is supply current depends upon number of pulses per half cycle.

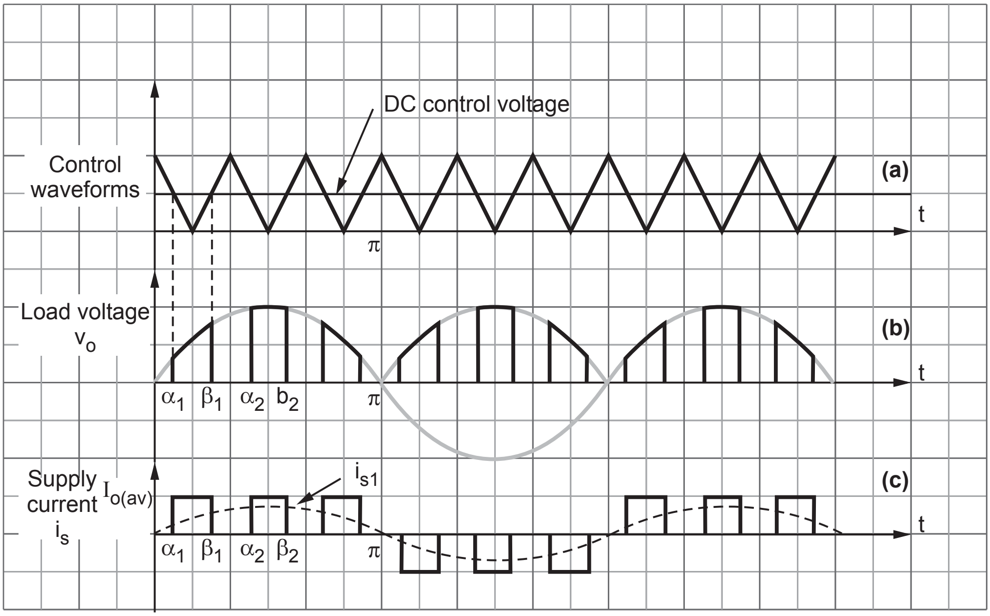


Fig. 2.5.4 Waveforms of PWM

Mathematical Analysis

Output average voltage,

$$V_{o(av)} = \frac{1}{T}\int_0^T v_s(\omega t)\, d\omega t$$

$$= \frac{1}{\pi}\sum_{k=1}^{p}\int_{\alpha_k}^{\beta_k} V_m \sin(\omega t)\, d\omega t, \text{ Here } p \text{ is number of pulses per half cycle.}$$

$$= \frac{V_m}{\pi}\sum_{k=1}^{p}(\cos\alpha_k - \cos\beta_k) \qquad \ldots (2.5.13)$$

RMS value of supply current,

$$I_{s(rms)} = \left[\frac{1}{T}\int_0^T i_s^2(\omega t)\, d\omega t\right]^{\frac{1}{2}}$$

$$= \left[\frac{1}{\pi}\sum_{k=1}^{p}\int_{\alpha_k}^{\beta_k} I_{o(av)}^2\, d\omega t\right]^{\frac{1}{2}}$$

$$= I_{o(av)}\sqrt{\frac{\sum_{k=1}^{p}(\beta_k - \alpha_k)}{\pi}} \qquad \ldots (2.5.14)$$

2.5.5 Sinusoidal Pulse Width Modulation

In the last section we studied square pulse width modulation. Now let us consider sinusoidal pulse width modulation. Its waveforms are shown in Fig. 2.5.5.

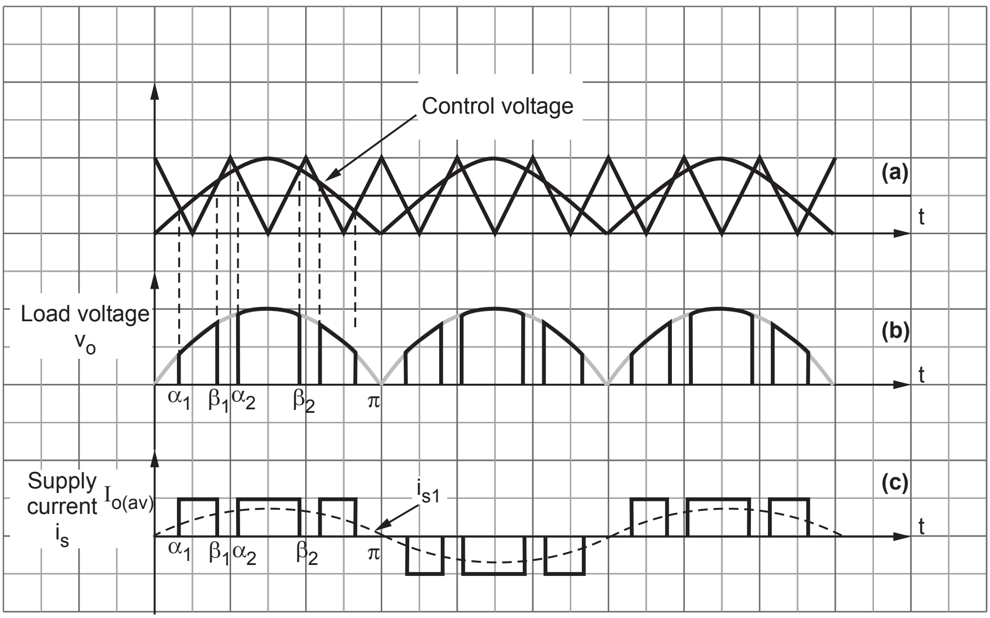


Fig. 2.5.5 Waveforms of sinusoidal PWM

- The widths of the pulses are not same, rather they are sinusoidally weighted. The triangular wave and rectified sine wave are compared in the control circuit. This comparison gives starting and ending point of each pulse.
- The width of the pulses can be varied by changing the amplitude of rectified sine wave in control circuit. The modulation index is given by

$$m = \frac{\text{Amplitude of sine wave}}{\text{Amplitude of triangular wave}} \quad \text{... (2.5.15)}$$

Mathematical Analysis

Output average voltage, $$V_{o(av)} = \frac{V_m}{\pi} \sum_{k=1}^{p} (\cos\alpha_k - \cos\beta_k) \quad \text{... (2.5.16)}$$

RMS value of supply current, $$I_{s(rms)} = I_{o(av)} \sqrt{\frac{\sum_{k=1}^{p} (\beta_k - \alpha_k)}{\pi}} \quad \text{... (2.5.17)}$$

Displacement angle, $$\phi_n = 0$$

RMS value of n^{th} harmonic, $$I_{sn} = \frac{\sqrt{2}\, I_{o(av)}}{n\pi} \sum_{k=1}^{p} (\cos n\alpha_k - \cos n\beta_k) \quad \dots (2.5.18)$$

Power factor, $$PF = \frac{I_{s1}}{I_{s(rms)}}$$

Displacement factor, $$DF = \cos\phi_1 = \cos 0 = 1 \quad \dots (2.5.19)$$

Harmonic factor, $$HF = \sqrt{\frac{I_{s(rms)}^2 - I_{s1}^2}{I_{s1}^2}} \quad \dots (2.5.20)$$

Advantages of sinusoidal pulse width modulation

1. In EAC and SAC, there is only one pulse per half cycle. Hence lowest harmonic present in supply current is third. But in PWM, multiple pulses per half cycle are used hence lowest harmonic present in supply current is of higher order. For example, if there are four pules per half cycle, then lowest harmonic is fifth.
2. Power factor of PWM is better than EAC and SAC.

Disadvantages

1. Because of multiple switchings per half cycle, losses are increased in the devices.
2. The control circuit becomes complex.

2.6 Single Phase Dual Converters

SPPU : April-19

Dual converter, the name itself says two converters. It is really an electronic converter or circuit which comprises of two converters. One will perform as rectifier and the other will perform as inverter. Therefore, we can say that double processes will occur at a moment. Here, two full converters are arranged in anti-parallel pattern and linked to the same dc load. These converters can provide four quadrant operations. The basic block diagram is shown below.

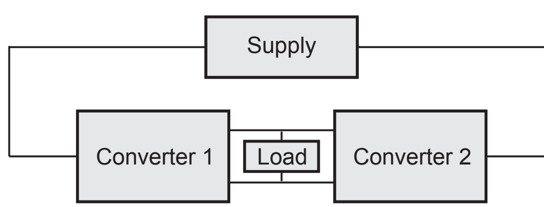


Fig. 2.6.1

Modes of Operation of Dual Converter

There are two functional modes: Non-circulating current mode and circulating mode.

Non Circulating Current Mode

- One converter will perform at a time. So there is no circulating current between the converters.

- During the converter 1 operation, firing angle (α_1) will be $0 < \alpha_1 < 90°$; V_{dc} and I_{dc} are positive.
- During the converter 2 operation, firing angle (α_2) will be $0 < \alpha_2 < 90°$; V_{dc} and I_{dc} are negative.

Circulating Current Mode

- Two converters will be in the ON condition at the same time. So circulating current is present.
- The firing angles are adjusted such that firing angle of converter 1 (α_1) + firing angle of converter 2 (α_2) = 180°.
- Converter 1 performs as a controlled rectifier when firing angle be $90° < \alpha_1 < 180°$ and Converter 2 performs as an inverter when the firing angle be $90° < \alpha_1 < 180°$. In this condition, V_{dc} and I_{dc} are positive.
- Converter 1 performs as an inverter when firing angle be $90° < \alpha_1 < 180°$ and Converter 2 performs as a controlled rectifier when the firing angle be $90° < \alpha_2 < 180°$ In this condition, V_{dc} and I_{dc} are negative.
- The four quadrant operation is shown below.

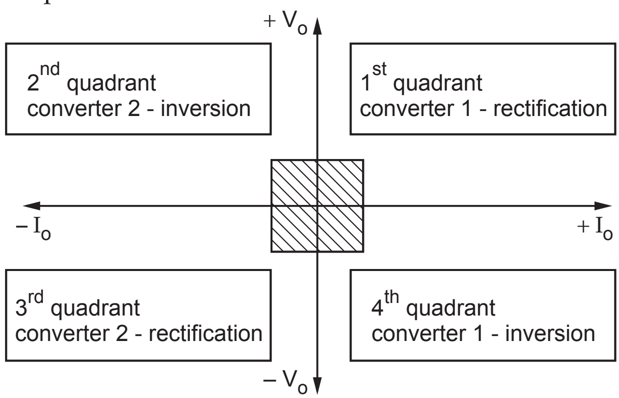


Fig. 2.6.2

Ideal Dual Converter

The term 'ideal' refers to the ripple free output voltage. For the purpose of unidirectional flow of DC current, two diodes (D_1 and D_2) are incorporated between the converters. However, the direction of current can be in any way. The average output voltage of the converter 1 is V_{01} and converter 2 is V_{02}. To make the output voltage of the two converters in same polarity and magnitude, the firing angles of the thyristors have to be controlled.

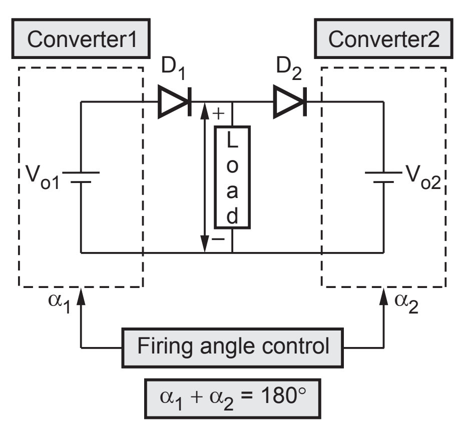


Fig. 2.6.3

2.6.1 Types of Dual Converters

They are of two types : Single-phase dual converter and three-phase dual converter.

Single Phase Dual Converter

The source of this type of converter will be single-phase supply. Consider, the converter is in non-circulating mode of operation. The input is given to the converter 1 which converts the AC to DC by the method of rectification. It is then given to the load after filtering. Then, this DC is provided to the converter 2 as input. This converter performs as inverter and converts this DC to AC. Thus, we get AC as output. The circuit diagram is shown in Fig. 2.6.4.

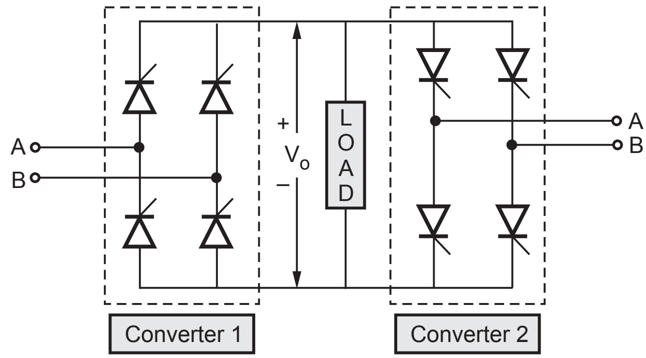


Fig. 2.6.4

Operation :

A.C input given to converter 1 for rectification in this process positive cycle of input is given to first set of forward biased thyristors which gives a rectified D.C. on positive cycle, as well negative cycle is given to set of reverse biased thyristors which gives a D.C. on negative cycle completing full wave rectified output can be given to load. During this process converter 2 is blocked using an inductor. As thyristor only start conducting when current pulse is given to gate and continuous conducting until supply of current is stopped. Output of thyristor bridge can be as follows when it is given to different loads.

Single Phase Dual Converter with Inductive Load :

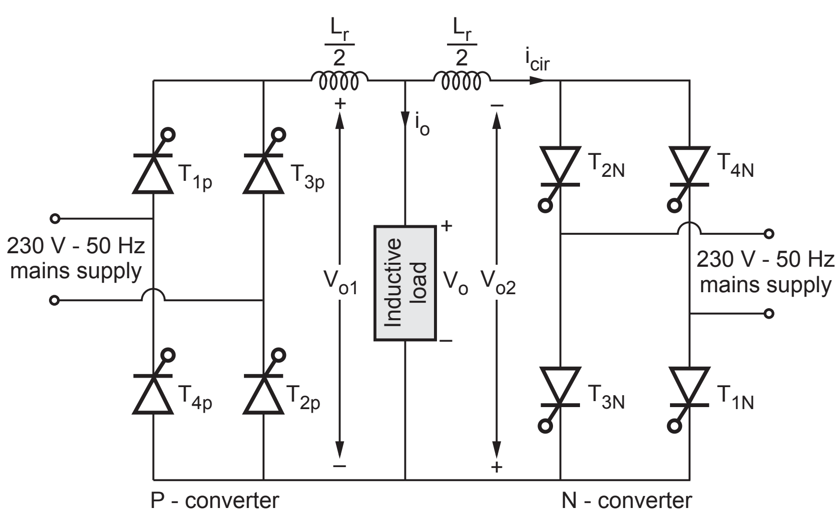
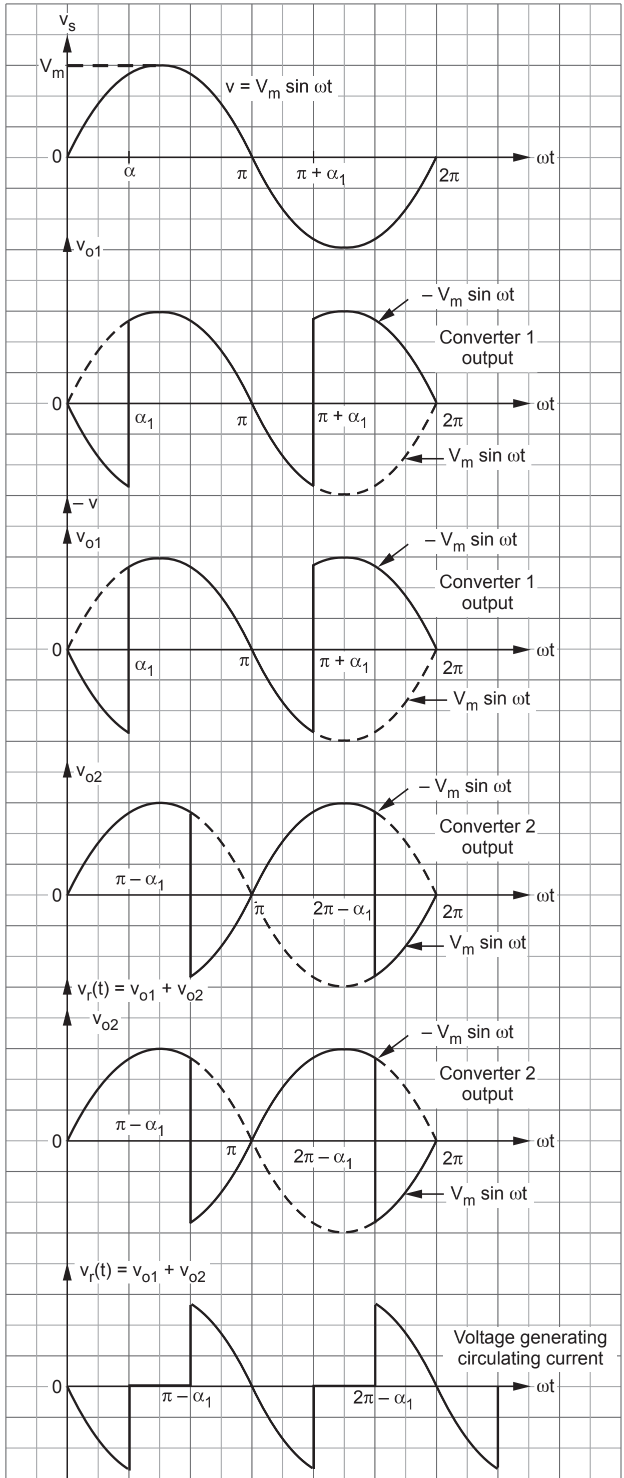


Fig. 2.6.5



v_s
V_m
$v = V_m \sin \omega t$
0
α
π
$\pi + \alpha_1$
2π
ωt
v_{o1}
$- V_m \sin \omega t$
Converter 1
output
0
α_1
π
$\pi + \alpha_1$
2π
ωt
$V_m \sin \omega t$
$- v$
v_{o1}
$- V_m \sin \omega t$
Converter 1
output
0
α_1
π
$\pi + \alpha_1$
2π
ωt
$V_m \sin \omega t$
v_{o2}
$- V_m \sin \omega t$
Converter 2
output
$\pi - \alpha_1$
0
π
$2\pi - \alpha_1$
2π
ωt
$V_m \sin \omega t$
$v_r(t) = v_{o1} + v_{o2}$
v_{o2}
$- V_m \sin \omega t$
Converter 2
output
$\pi - \alpha_1$
0
π
$2\pi - \alpha_1$
2π
ωt
$V_m \sin \omega t$
$v_r(t) = v_{o1} + v_{o2}$
Voltage generating
circulating current
0
$\pi - \alpha_1$
$2\pi - \alpha_1$
ωt

Fig. 2.6.6

Application of dual converter

- Direction and speed control of DC motors.
- Applicable wherever the reversible DC is required.
- Industrial variable speed DC drives.

Review Question

1. *Draw and explain the single phase dual converter. Explain the 4 quadrant operation of dual converter.* **SPPU : April-19, In Sem, Marks 5**

2.7 Three Phase Semiconverters **SPPU : Dec.-06,08,16,19 May-15,19, April-16**

We have discussed 1ϕ semiconverter earlier. The 3ϕ semiconverter delivers more power. It uses three SCRs T_1, T_3 and T_5 and three diodes D_4, D_6 and D_2. Fig. 2.7.1 shows the circuit diagram of 3ϕ semiconverter. Fig. 2.7.1 (a) shows the waveforms of supply phase voltages R, Y and B. Note that these are phase voltages. These are the voltages with respect to neutral N. In Fig. 2.7.1 (3ϕ semiconverter), when any SCR and diode conducts, line voltage is applied to the load. Hence it is necessary to draw the line voltage waveforms.

Fig. 2.7.2 shows the phasor diagram of supply phase and line voltages. In this diagram observe that line voltage RB lags phase R by 30°. This is clear from waveforms of Fig. 2.7.3 (b) also. The phase shift between two line voltages is 60°.

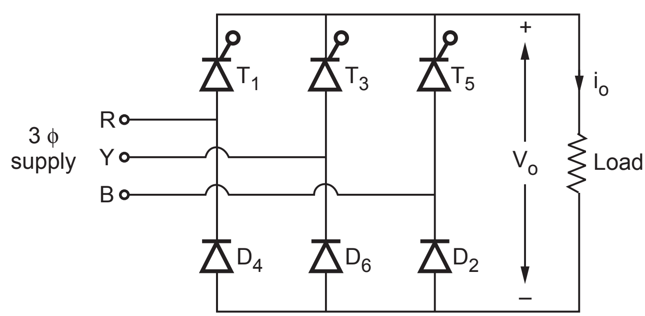


Fig. 2.7.1 3 ϕ semiconverter or half bridge converter

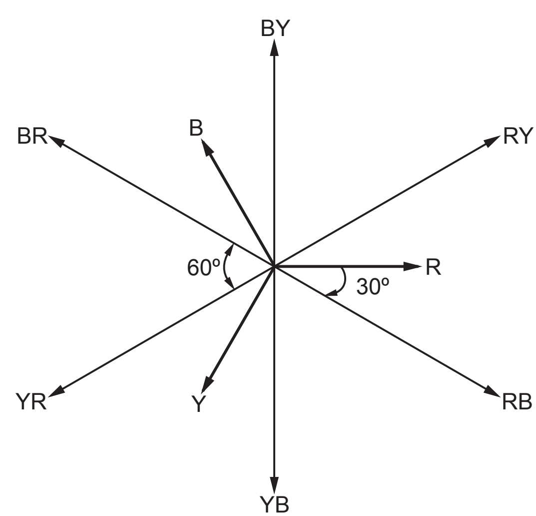


Fig. 2.7.2 Phasor diagram showing the relationship between phase and line voltages of 3ϕ supply

When $\alpha < 60°$

T_1 is triggered at $\alpha = 30°$ (see Fig. 2.7.3 (c)). SCR T_1 and diode D_6 conducts. Hence line voltage RY is applied to the load from $\left(\frac{\pi}{6}+\alpha\right)$ to $\frac{\pi}{2}$. At $\frac{\pi}{2}$, diode D_2 is more forward biased and hence it starts conducting.

Hence line voltage RB is applied to the load. T_1 D_2 keeps on conducting till next SCR T_3 is triggered at $\left(\frac{5\pi}{6}+\alpha\right)$. The load voltage waveform for $\alpha = 30°$ is shown in Fig. 2.7.3 (c). The devices conducting are also shown in respective intervals.

Observe that one period of the ripple in output voltage waveform is,

$$T = \left(\frac{5\pi}{6}+\alpha\right) - \left(\frac{\pi}{6}+\alpha\right) = \frac{2\pi}{3} \qquad \text{... (2.7.1)}$$

Thus there are three cycles of output ripple in one cycle of the supply. Hence ripple frequency is three times of the supply frequency. i.e.,

$$f_{ripple} = 3 \times 50 = 150 \text{ Hz}$$

In the Fig. 2.7.3 (c), observe that each SCR conducts for the maximum duration of $120° \left(\text{i.e. } \frac{2\pi}{3}\right)$.

The current waveform for resistive load will be similar to voltage waveform since,

$$i_o = \frac{V_o}{R}$$

Example 2.7.1 *Derive an expression for the average output voltage of 3ϕ semiconverter having resistive load for $\alpha \le 60°$.*

Solution : We know that the average output voltage is given as,

$$V_{o(av)} = \frac{1}{T}\int_0^T v_o(\omega t)\, d\omega t$$

Observe the waveform of V_o given in Fig. 2.7.3 (c). The period T can be considered from $\left(\frac{\pi}{6}+\alpha\right)$ to $\left(\frac{5\pi}{6}+\alpha\right)$ which is $\frac{2\pi}{3}$. Hence above equation becomes,

$$V_{o(av)} = \frac{1}{\left(\frac{2\pi}{3}\right)} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} v_o(\omega t)\, d\omega t$$

$$= \frac{3}{2\pi}\left\{\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}} V_{RY}(\omega t)\, d\omega t + \int_{\frac{\pi}{2}}^{\frac{5\pi}{6}+\alpha} V_{RB}(\omega t)\, d\omega t\right\} \qquad \text{... (2.7.2)}$$

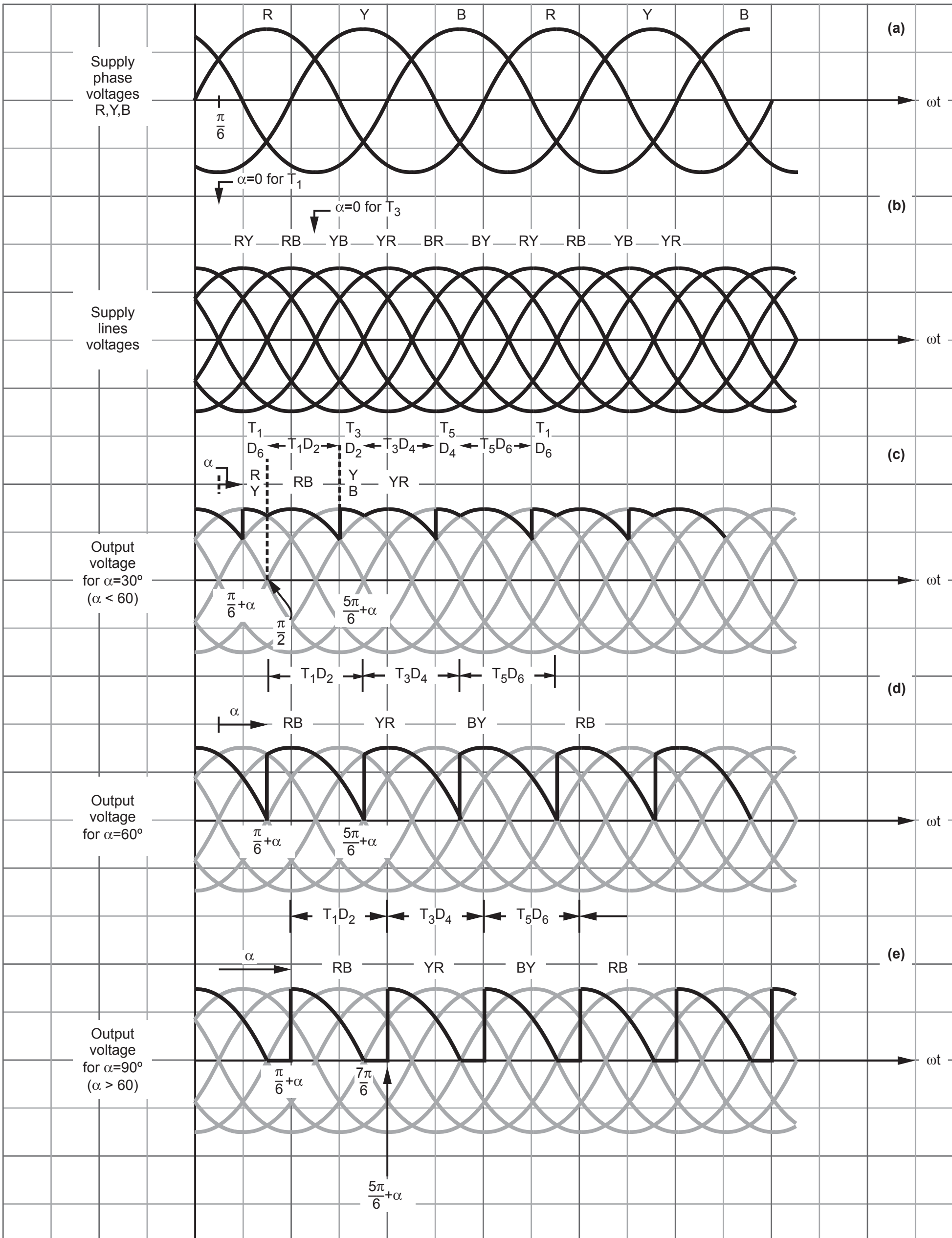


Fig. 2.7.3 Waveforms of 3ϕ semiconverter for resistive load

The equations for V_{RY} and V_{RB} can be written from Fig. 2.7.3 (b) as follows,

$$\left.\begin{aligned} V_{RY}(\omega t) &= \sqrt{3}\, V_m \sin\left(\omega t + \frac{\pi}{6}\right) \\ V_{RB}(\omega t) &= \sqrt{3}\, V_m \sin\left(\omega t - \frac{\pi}{6}\right) \end{aligned}\right\} \quad \text{... (2.7.3)}$$

Here V_m is the peak value of the phase voltage. Putting above expressions in equation 2.7.2,

$$V_{o(av)} = \frac{3}{2\pi}\left\{\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}} \sqrt{3}\, V_m \sin\left(\omega t+\frac{\pi}{6}\right) d\omega t + \int_{\frac{\pi}{2}}^{\frac{5\pi}{6}+\alpha} \sqrt{3}\, V_m \sin\left(\omega t-\frac{\pi}{6}\right) d\omega t\right\}$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left\{\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}} \sin\left(\omega t+\frac{\pi}{6}\right) d\omega t + \int_{\frac{\pi}{2}}^{\frac{5\pi}{6}+\alpha} \sin\left(\omega t-\frac{\pi}{6}\right) d\omega t\right\}$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left\{\left[-\cos\left(\omega t+\frac{\pi}{6}\right)\right]_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}} + \left[-\cos\left(\omega t-\frac{\pi}{6}\right)\right]_{\frac{\pi}{2}}^{\frac{5\pi}{6}+\alpha}\right\}$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left\{-\cos\left(\frac{\pi}{2}+\frac{\pi}{6}\right)+\cos\left(\frac{\pi}{6}+\alpha+\frac{\pi}{6}\right)-\cos\left(\frac{5\pi}{6}+\alpha-\frac{\pi}{6}\right)+\cos\left(\frac{\pi}{2}-\frac{\pi}{6}\right)\right\}$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}(1+\cos\alpha) \qquad \text{... (2.7.4)}$$

This is the expression for average output voltage for $\alpha \leq 60$.

When $\alpha = 60$

Fig. 2.7.3 (d) shows the output voltage waveform for $\alpha = 60°$. Observe that the voltage waveform is just continuous. When T_1 is triggered at $\alpha = 60°$, the line voltage RB is applied across the load. T_1 and D_2 conducts from $\left(\frac{\pi}{6}+\alpha\right)$ to $\left(\frac{5\pi}{6}+\alpha\right)$. Similarly next SCR T_3 is triggered at $\left(\frac{5\pi}{6}+\alpha\right)$ and T_3 D_4 conduct. The current waveform will be similar to voltage waveform for resistive load. The average output voltage is given by equation (2.7.4), since voltage waveform is continuous.

When $\alpha > 60$

Fig. 2.7.3 (e) shows the output voltage waveform for $\alpha = 90°$. SCR T_1 is triggered at $\left(\frac{\pi}{6}+\alpha\right)$. T_1 and D_2 conducts and line voltage RB is applied across the load. In the waveform observe that, output voltage becomes zero at $\frac{7\pi}{6}$. In Fig. 2.7.3 (b) observe that line voltage RB becomes zero at $\frac{7\pi}{6}$. Hence SCR T_1 is turned off. Since T_3 is not triggered, the output voltage becomes zero. At $\left(\frac{5\pi}{6}+\alpha\right)$ T_3 is triggered and T_3 D_4 conducts.

Line voltage YR is applied across the load. Thus for $\alpha > 60$, the output voltage is discontinuous. Since the load is resistive, the current is also discontinuous. The current waveform will be similar to voltage waveform.

Example 2.7.2 *Derive an expression for average output voltage of 3ϕ semiconverter having resistive load for $\alpha > 60°$.*

Solution : Fig. 2.7.3 (e) shows the waveform of output voltage for $\alpha = 90°$ (i.e. $\alpha > 60°$). Observe that the period of ripple cycle is

$$T = \left(\frac{5\pi}{6}+\alpha\right)-\left(\frac{\pi}{6}+\alpha\right) = \frac{2\pi}{3}$$

When $T_1 - D_2$ conducts voltage V_{RB} is applied across the load from $\left(\frac{\pi}{6}+\alpha\right)$ to $\frac{7\pi}{6}$.

Hence

$$v_o = V_{RB} \text{ from } \frac{\pi}{6}+\alpha \text{ to } \frac{7\pi}{6}$$

From Fig. 2.7.3, we can write an equation for V_{RB} as,

$$V_{RB} = \sqrt{3}\, V_m \sin\left(\omega t - \frac{\pi}{6}\right)$$

Output average voltage is given as,

$$V_{o(av)} = \frac{1}{T}\int_0^T v_o(\omega t)\, d\omega t$$

We know that $v_0(\omega t) = V_{RB}$, hence above equation can be written as,

$$V_{o(av)} = \frac{1}{2\pi/3}\int_{\frac{\pi}{6}+\alpha}^{\frac{7\pi}{6}} \sqrt{3}\, V_m \sin\left(\omega t - \frac{\pi}{6}\right) d\omega t$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left[-\cos\left(\omega t - \frac{\pi}{6}\right)\right]_{\frac{\pi}{6}+\alpha}^{7\pi/6}$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left[-\cos\left(\frac{7\pi}{6}-\frac{\pi}{6}\right)+\cos\left(\frac{\pi}{6}+\alpha-\frac{\pi}{6}\right)\right]$$

$$\therefore \quad \boxed{V_{o(av)} = \frac{3\sqrt{3}\, V_m}{2\pi}(1+\cos\alpha)} \quad \text{... (2.7.5)}$$

Observe that the above equation is same as equation (2.7.4) for $\alpha \leq 60$. Thus above equation can be used for continuous as well as discontinuous mode of operation of 3ϕ semiconverter.

Example 2.7.3 *With the circuit diagram and waveforms explain operation of a 3ϕ half controlled full wave bridge rectifier. The SCRs are triggered at a delay angle of 40°. The input voltage is 440 V, 3ϕ, 50 Hz. Find average DC voltage available at the bridge terminals. Derive any formula used.*

Solution : This is 3ϕ semiconverter. Since the load is not mentioned, we will assume resistive load. The operation of this converter is explained with waveforms in section 2.7.1. The given data is,

$$\alpha = 40^\circ$$

$$V_{s(line)} = 440 \text{ V}$$

$$\therefore \quad V_{s(ph)} = \frac{440}{\sqrt{3}}$$

$$\therefore \quad V_m = \sqrt{2}\, V_{s(ph)} = \sqrt{2} \cdot \frac{440}{\sqrt{3}} = \sqrt{\frac{2}{3}}\ 440 \text{ V}$$

We have derived an expression for average value of output voltage earlier. For $\alpha \le 60$, $V_{o(av)}$ is given by equation (2.7.5) as,

$$V_{o(av)} = \frac{3\sqrt{3}\ V_m}{2\pi}(1+\cos\alpha)$$

Here V_m is peak value of phase voltage. Putting values in above equation,

$$V_{o(av)} = \frac{3\sqrt{3} \cdot \sqrt{\frac{2}{3}} \cdot 440}{2\pi}(1+\cos 40^\circ) = 524.7 \text{ volts}$$

Example for Practice

Example 2.7.4 : *Derive an expression for average value of output voltage for 3ϕ semiconverter.*

Review Questions

1. *With the help of circuit diagram and waveforms, explain the operation of three phase semiconverter for 'R' load for* $\alpha = 0^\circ, 30^\circ, 60^\circ$ *and* 90°. **SPPU : Dec.-06, 08, Marks 10**
2. *Draw and explain three phase semiconverter for R load with input and output voltage waveforms.* **SPPU : April-16, May-19, Dec.-16, End Sem, Marks 7**
3. *Draw and explain three phase half controlled bridge converter for R load with output voltage waveforms.* **SPPU : May-15, Marks 7**
4. *With the help of neat circuit diagram and waveforms explain the operation of 3-ϕ semi converter for R-load with* $\alpha = 60^\circ$. **SPPU : Dec.-19 (End Sem), Marks 7**

2.8 Three Phase Full Converters SPPU : May-07, 08, April-15,17, Dec.-07,19

Three phase half converters operate only in first quadrant of $v_o - i_o$. The output voltage v_o is always positive for resistive as well as inductive loads. The output current i_o is also always positive. Hence 3ϕ semiconverter operates in first quadrant only. Three phase full converters can operate in two quadrants. The output voltage of 3ϕ full converter can be positive as well as negative. It uses six SCRs as shown in Fig. 2.8.1.

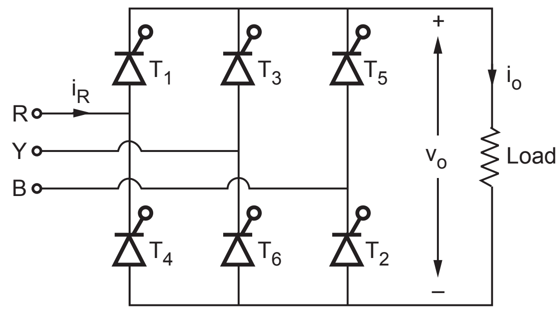


Fig. 2.8.1 3 ϕ full converter

Let us consider the operation of 3ϕ full converter having resistive load. Fig. 2.8.2 shows the waveforms of 3ϕ full converter having resistive load. Fig. 2.8.2 (a) shows the supply phase voltages R, Y and B. Fig. 2.8.2 (b) shows the supply line voltages. These supply voltage waveforms are drawn according to the phasor diagram shown in Fig. 2.8.2. Fig. 2.8.2 (c) shows the gate drives for $\alpha = 30°$. For six SCRs, there are six gate drives. See Fig. 2.8.2 on next page.

In Fig. 2.8.2, observe that in interval-I, gate drives are given to SCRs T_6 and T_1. Hence line voltage V_{RY} is applied across the load. The equivalent circuit for this interval is shown in Fig. 2.8.3.

In the above figure observe that SCRs T_6 and T_1 (normally written as 6-1) conduct. Hence,

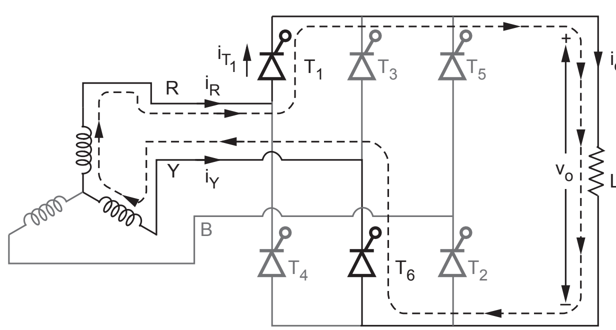


Fig. 2.8.3 Operation of 3 ϕ full converter in interval-I $(T_6 - T_1)$

$$v_o = v_{RY}$$

Observe that output current i_o and R-phase current i_R flows in the same direction. Hence,

$$i_R = i_o$$

Similarly observe that Y-phase current i_y and output current i_o are in opposite directions. Hence,

$$i_Y = -i_o$$

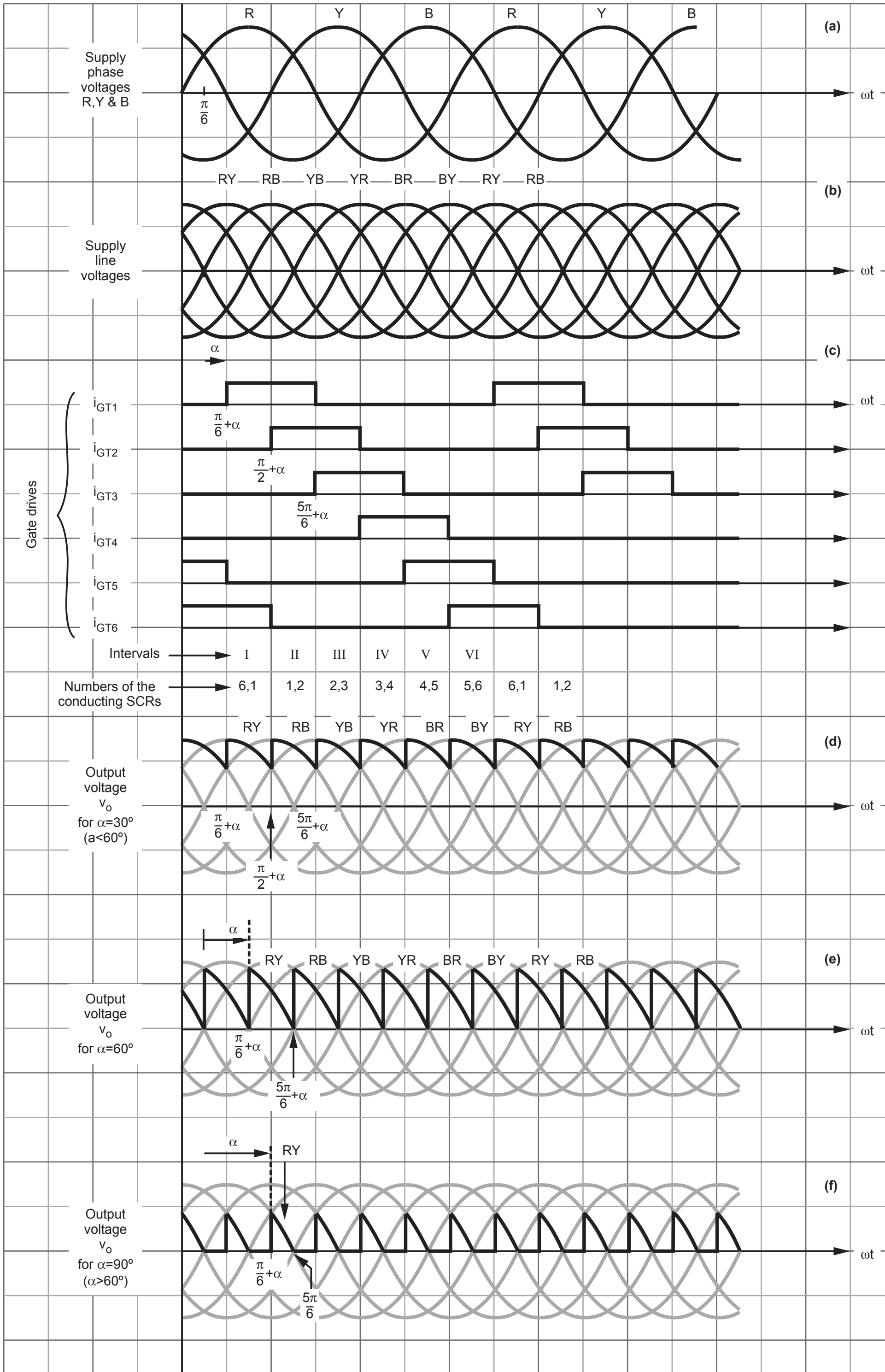


Fig. 2.8.2 Waveforms of 3ϕ full converter having resistive load

The SCR pair T_6 - T_1 conduct from $\left(\frac{\pi}{6}+\alpha\right)$ to $\left(\frac{\pi}{2}+\alpha\right)$. Line voltage V_{RY} is applied during this period. At $\left(\frac{\pi}{2}+\alpha\right)$ SCR T_2 is triggered (Fig. 2.8.2 (c)). Here note that T_6 turns-off, since T_2 is triggered. Hence T_1 - T_2 starts conducting and it is marked as interval-II. In this interval supply line voltage V_{RB} is applied across the load. At $\left(\frac{5\pi}{6}+\alpha\right)$, T_3 is triggered. Hence T_1 turns-off and T_2 - T_3 starts conducting. Therefore line voltage V_{YB} is applied across the load. It is marked as interval-III.

Load and supply currents

Fig. 2.8.4 shows the waveforms of output current and supply current of R-phase.

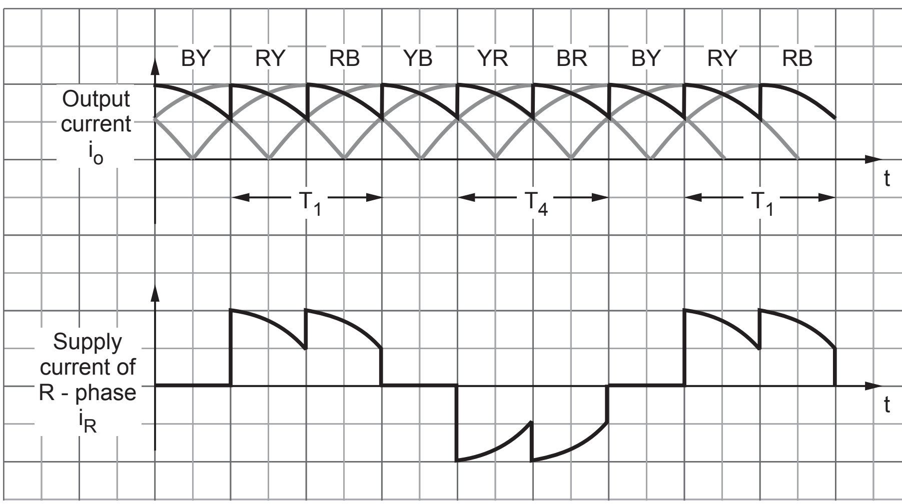


Fig. 2.8.4 Output current and supply current waveforms for α = 30°

- Since the load is resistive, the shape of output current waveform will be similar to that of output voltage. Its amplitude will be $i_o = \frac{v_o}{R}$.
- Whenever T_1 conducts, R-phase current will be positive and whenever T_4 conducts, R-phase current will be negative.

The following points are important about 3ϕ full converter operation.

i) Only two SCRs conduct in any interval.

ii) Each SCR conduct for 120°.

iii) Each SCR pair conduct for one interval of 60°.

iv) SCRs are triggered in following sequence :

........T_1 - T_2 - T_3 - T_4 - T_5 - T_6 - T_1 - T_2 ....

The triggering delay between indvidual SCRs is 60°.

v) The output voltage waveforms is continuous upto $\alpha = 60°$ and it is discontinuous for $\alpha > 60°$. Since the load is resistive, output current waveform is simiilar to output voltage waveform.

Example 2.8.1 *For the 3ϕ full converter having resistive load find the following :*

i) Ripple frequency f_{ripple} ii) Output average voltage $V_{o(av)}$

Solution : i) To determine ripple frequency :

In the load voltage waveforms of Fig. 2.8.2 observe that line voltage V_{RY} is applied across the load from $\left(\frac{\pi}{6}+\alpha\right)$ to $\left(\frac{\pi}{2}+\alpha\right)$, i.e. $\frac{\pi}{3}$. Similarly other line voltages are also applied across the load for the period of $\frac{\pi}{3}$. The load voltage has the ripple period of $\frac{\pi}{3}$. In one cycle of supply, six such ripple cycles are present in output waveform. Hence ripple frequency must be six times of the supply frequency. i.e.,

$$f_{ripple} = 6 \times 50 = 300 \text{ Hz}$$

Thus ripple frequency of 3ϕ full converter is higher than 3ϕ semiconverter. This is true for all the firing angles.

ii) To determine output average voltage

We know that average value is given as,

$$V_{o(av)} = \frac{1}{T}\int_0^T v_o(\omega t)\, d\omega t \qquad \text{... (2.8.1)}$$

Case - I : $\alpha \le 60°$

Consider the case when $\alpha \le 60°$ i.e. for continuous output voltage waveform. Fig. 2.8.2 (d) shows the output voltage waveform for $\alpha = 30°$. Consider the period $\left(\frac{\pi}{6}+\alpha\right)$ to $\left(\frac{\pi}{2}+\alpha\right)$ when voltage V_{RY} is applied across the load. This period is,

$$T = \left(\frac{\pi}{2}+\alpha\right)-\left(\frac{\pi}{6}+\alpha\right) = \frac{\pi}{3}$$

From Fig. 2.8.2 (b) we can write an equation for line voltage V_{RY} as,

$$V_{RY} = \sqrt{3}\, V_m \sin\left(\omega t + \frac{\pi}{6}\right)$$

V_m is peak value of the phase voltage.

Putting the above values in equation (2.8.1),

$$V_{o(av)} = \frac{1}{\pi/3} \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3}\, V_m \sin\left(\omega t + \frac{\pi}{6}\right) d\,(\omega t)$$

$$= \frac{3\sqrt{3}\, V_m}{\pi} \left[-\cos\left(\omega t + \frac{\pi}{6}\right) \right]_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha}$$

$$\therefore \quad \boxed{V_{o(av)} = \frac{3\sqrt{3}\, V_m}{\pi} \cos\alpha} \qquad \text{... (2.8.2)}$$

Case II : $\alpha > 60°$

Now consider the case when $\alpha > 60°$. For this firing angle, the output voltage waveform is discontinuous. Fig. 2.8.2 (f) shows the output voltage waveform for $\alpha = 90°$. Putting the integration limits and V_{RY} in equation (2.8.1) for this case.

$$V_{o(av)} = \frac{1}{\pi/3} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}} \sqrt{3}\, V_m \sin\left(\omega t + \frac{\pi}{6}\right) d\,\omega t$$

$$= \frac{3\sqrt{3}\, V_m}{\pi} \left[-\cos\left(\omega t + \frac{\pi}{6}\right) \right]_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}}$$

$$\therefore \quad \boxed{V_{o(av)} = \frac{3\sqrt{3}\, V_m}{\pi} \left[1 + cos\left(\frac{\pi}{3} + \alpha\right) \right]} \qquad \text{... (2.8.3)}$$

This is the equation for average output voltage for $\alpha > 60°$.

Example 2.8.2 *For a 3 ϕ fully controlled SCR bridge converter operating from 400 V, 3 phase AC supply, calculate the average DC output voltage for a firing angle of 45°.*

Solution : The given data is,

$$V_{line} = 400 \text{ V (rms)}$$
$$\alpha = 45°$$

Hence rms value of phase voltage is,

$$V_{ph} = \frac{400}{\sqrt{3}}$$

Hence peak value of phase voltage is,

$$V_m = \sqrt{2}\, V_{ph} = \sqrt{2} \cdot \frac{400}{\sqrt{3}} \text{ V}$$

Here firing angle is 45°. Hence the conduction will be continuous for resistive as well as inductive load. Therefore the average DC output is given by equation (2.8.2) i.e.,

$$V_{o(av)} = \frac{3\sqrt{3}\,V_m}{\pi}\cos\alpha$$

Putting values in above equation,

$$V_{o(av)} = \frac{3\sqrt{3}\times\sqrt{2}\cdot\dfrac{400}{\sqrt{3}}}{\pi}\cos 45° = 382 \text{ volts}$$

Example 2.8.3 *A 3 ϕ full converter operated from 3 ϕ – Y connected 208 V, 60 Hz, supply with R_L = 10 Ω. It is required to obtain 50 % of the maximum possible output voltage. Calculate - i) Delay angle α ii) rms and average currents iii) rms and average thyristor ratings iv) η of rectification v) PF*

Solution : Given data

$$V_{line} = 208 \text{ V}$$

Hence $V_{ph} = \frac{V_{line}}{\sqrt{3}} = \frac{208}{\sqrt{3}} = 120 \text{ V}$

$\therefore$ $V_m = \sqrt{2}\,V_{ph} = \sqrt{2}\times 120 = 169.7 \text{ V}$

Load resistance, R = 10 Ω

Output voltage $V_{o(av)}$ = 50 % of $V_{o(av)max}$

i) To obtain delay angle α

Average output voltage of 3 ϕ full converter is given by equation (2.8.2) as,

$$V_{o(av)} = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha$$

Maximum value of output voltage will be obtained when α = 0. i.e.,

$$V_{o(av)max} = \frac{3\sqrt{3}V_m}{\pi} = \frac{3\sqrt{3}\times 169.7}{\pi} = 280.68 \text{ V}$$

Since output voltage is 50 % of its maximum value,

$$V_{o(av)} = 0.5\ V_{o(av)max}$$

$$= 0.5 \times 280.68 = 140.34 \text{ V}$$

Consider the formula for output voltage,

$$V_{o(av)} = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha$$

Putting values in this equation,

$$140.34 = \frac{3\sqrt{3}\times 169.7}{\pi}\cos\alpha$$

$$\therefore \qquad \alpha = 60°$$

ii) Average and rms output currents

Average output current is given as,

$$I_{o(av)} = \frac{V_{o(av)}}{R} = \frac{140.34}{10} = 14.034 \text{ A}$$

To obtain rms current, we have to obtain rms output voltage, for $\alpha \le 60$, the output voltage waveform is continuous as shown in Fig. 2.8.2 (d). Consider the period from $\left(\frac{\pi}{6}+\alpha\right)$ to $\left(\frac{\pi}{2}+\alpha\right)$ when voltage V_{RY} is applied arrows the load. This period is,

$$T = \left(\frac{\pi}{2}+\alpha\right)-\left(\frac{\pi}{6}+\alpha\right) = \frac{\pi}{3}$$

From Fig. 2.8.2 (b) we can write an equation for line voltage V_{RY} as,

$$V_{RY} = \sqrt{3}V_m \sin\left(\omega t+\frac{\pi}{6}\right)$$

Here V_m is the peak valve of phase voltage. RMS value is given as,

$$V_{o(rms)} = \left[\frac{1}{T}\int_0^T V_0^2(\omega t)\, d\omega t\right]^{\frac{1}{2}}$$

$$= \left[\frac{1}{\pi/3}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha}\left[\sqrt{3}V_m \sin\left(\omega t+\frac{\pi}{6}\right)\right]^2 d\omega t\right]^{\frac{1}{2}}$$

$$= \left[\frac{3}{\pi}\cdot 3V_m^2\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha}\sin^2\left(\omega t+\frac{\pi}{6}\right) d\omega t\right]^{\frac{1}{2}}$$

$$= \left[\frac{9V_m^2}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha}\frac{1-\cos 2\left(\omega t+\frac{\pi}{6}\right)}{2} d\omega t\right]^{\frac{1}{2}}$$

$$\therefore \quad \boxed{V_{o(rms)} = 3V_m \sqrt{\frac{\frac{\pi}{3} + \frac{\sqrt{3}}{2}\cos 2\alpha}{2\pi}}} \quad \text{... (2.8.4)}$$

Putting values in above equation,

$$V_{o(rms)} = 3 \times 169.7 \sqrt{\frac{\frac{\pi}{3} + \frac{\sqrt{3}}{2}\cos(2 \times 60°)}{2\pi}}$$

$$= 159.17 \text{ V}$$

Therefore rms output current will be,

$$I_{o(rms)} = \frac{V_{o(rms)}}{R} = \frac{159.17}{10} = 15.917 \text{ A}$$

iii) rms and average thyristor ratings

In the waveforms of Fig. 2.8.2, observe that two thyristors conduct at a time. The load current is carried equally by three thyristors in one cycle. These three thyristors are T_1, T_3, T_5 and T_4, T_6, T_2. Hence the average output current is shared by these three thyristors. Hence average current of single thyristor becomes,

$$I_{T(av)} = \frac{I_{o(av)}}{3} \quad \text{... (2.8.5)}$$

$$= \frac{14.034}{3} = 4.678 \text{ A}$$

This is the average current carried by each thyristor.

The rms current is also shared by three thyristors. Hence we can write,

$$I^2_{o(rms)} = I^2_{T(rms)} + I^2_{T(rms)} + I^2_{T(rms)}$$

Above equation shows the relationship between output rms current and rms current of three thyristors. RMS current of each thyristor is same. Hence,

$$I^2_{o(rms)} = 3I^2_{T(rms)}$$

$$\therefore \quad I_{T(rms)} = \frac{I_{o(rms)}}{\sqrt{3}} \quad \text{... (2.8.6)}$$

$$= \frac{15.917}{\sqrt{3}} = 9.189 \text{ A}$$

iv) Rectification efficiency (η)

Rectification efficiency is given as,

$$\eta = \frac{\text{Average or dc load power}}{\text{rms load power}} = \frac{V_{o(av)}\, I_{o(av)}}{V_{o(rms)}\, I_{o(rms)}}$$

$$= \frac{140.34 \times 14.034}{159.17 \times 15.917} = 0.777 \text{ or } 77.7 \text{ \%}$$

v) To obtain power factor

The active load power is the power consumed in the load. It can be calculated as,

$$\text{Active load power} = I_{o(rms)}^2 \times R = (15.917)^2 \times 10$$

$$= 2533.5 \text{ W}$$

At any time instant two thyristors conduct. Hence the supply current can be given in terms of thyristor currents as,

$$I_{s(rms)}^2 = 2I_{T(rms)}^2 = 2 \cdot \frac{I_{o(rms)}^2}{3}$$

$$\therefore \quad I_{s(rms)} = I_{o(rms)} \sqrt{\frac{2}{3}} \qquad \text{... (2.8.7)}$$

$$= 15.917 \sqrt{\frac{2}{3}} = 13 \text{ A}$$

For 3 ϕ supply, the total supply volt-ampere will be,

$$\text{Supply VA} = 3\, V_s\, I_s$$

$$= 3 \times 120 \times 13 = 4680 \text{ VA}$$

The power factor is given as,

$$\text{PF} = \frac{\textit{Active load power}}{\textit{Total supply power}\,(\text{VA})}$$

$$= \frac{2533.5}{4680} = 0.5413 \text{ (lagging)}$$

2.8.1 Comparison between 3ϕ and 1ϕ Converters

Sr. No.	Parameter	1ϕ converter	3ϕ converters
1.	Ripple content in output	More	Less
2.	Output power	Less upto 5 kW	More than 5 kW
3.	Supply current waveform	Square wave for 1ϕ full converter	Quasi square wave for 3ϕ full converter

4.	Ripple frequency	100 Hz	150 Hz and 300 Hz
5.	Control and complexity	Less complex and easy control	Complex control and implementation
6.	Maximum supply power factor	0.9	0.955
7.	Supply and load derating	Higher	Less

Table 2.8.1 Comparison of 3ϕ and 1ϕ converters

It shows that it is preferable to use 3ϕ converters for better power efficiency. Hence for higher load power requirement 3ϕ converters are always preferred. But for simple and low power applications 1ϕ converters are used because of their simplicity of implementation.

Review Questions

1. *Draw the circuit diagram, voltage and current waveform for* $\alpha = 30°$, *resistive load of three phase full bridge converter.* **SPPU : May-07, Dec.-07, Marks 8, May-08, April-17, Marks 10**
2. *Draw and explain three phase fully controlled bridge converter for R load with o/p voltage waveforms.* **SPPU : April-15 (In Sem), Marks 7**
3. *Explain the operation of symmetric 1ϕ semi converter with continuous load current. Draw the waveforms and state the equation for average output* **SPPU : Dec.-19 (End Sem), Marks 7**

2.9 1ϕ and 3ϕ Controlled Rectifiers using IGBT

- Earlier we discussed different methods to improve power factor of the converter. Extinction angle control, symmetric angle control and pulse width modulation control do not use natural commutation. These methods use forced commutation of the SCRs.
- Rather than using SCRs for extinction angle control, symmetric angle control and pulse width modulation, IGBT based controlled rectifiers can be used.
- The on/off times of IGBTs can be fully controlled and hence it is possible to achieve power factor close to unity in IGBT based rectifiers.

2.9.1 1ϕ IGBT based Rectifier

Circuit diagram : Fig. 2.9.1 shows the circuit diagram of 1ϕ controlled rectifier using IGBT. There are four IGBTs and one freewheeling diode.

- The load is inductive, may be motor or similar load.
- IGBTs, $T_1 - T_2$ conduct in positive half cycle of the supply and $T_3 - T_4$ conduct in negative half cycle of the supply.

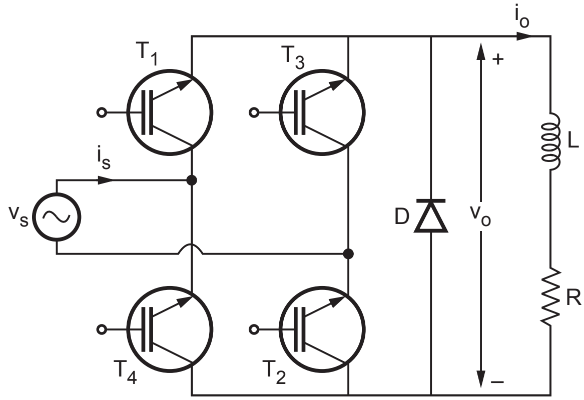


Fig. 2.9.1 1φ IGBT based controlled rectifier

Operation and waveforms for PWM output :

- Let us discuss the operation of rectifier of Fig. 2.9.1 for sinusoidal pulse width modulated output. Fig. 2.9.2 shows the waveforms.

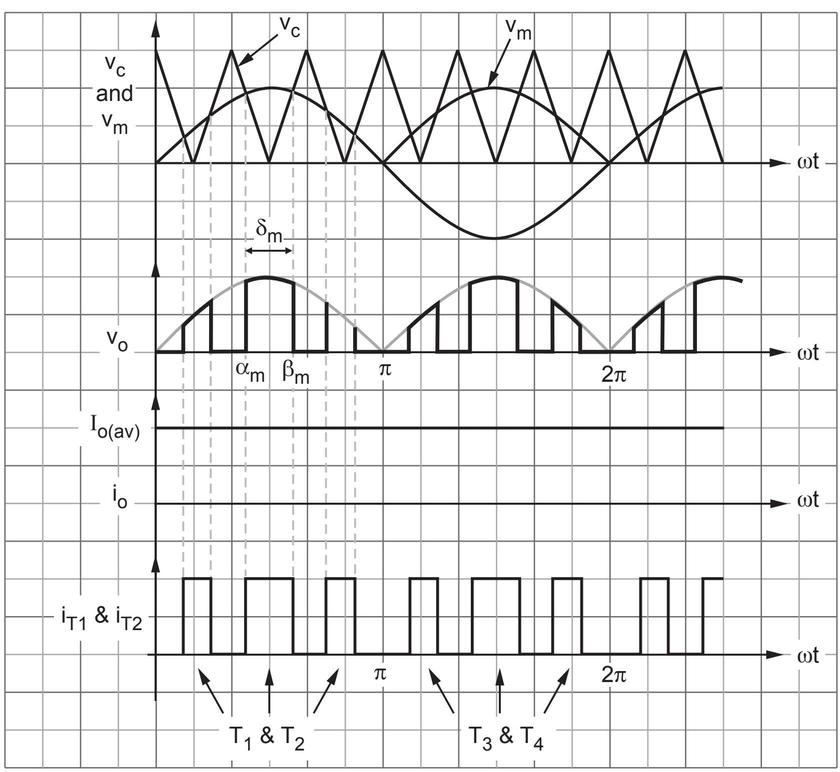


Fig. 2.9.2 Waveforms of IGBT based rectifier

- When the supply voltage v_m (which is also modulating signal) is positive, IGBTs T_1 and T_2 conduct. And when supply voltage is negative, IGBTs, T_3 and T_4 conduct.

- Observe that the output voltage waveform is sinusoidally weighted pulse width modulation. The fundamental component of supply current will have a power factor of unity.
- The m^{th} pulse have firing angle of α_m and IGBTs turn off at angle β_m. The conduction period of IGBTs for m^{th} pulse is δ_m.
- The load is assumed to be highly inductive, hence output current is continuous and ripple free.
- The load current is carried by the freewheeling diode D, when all IGBTs are off.
- The sinusoidal PWM is generated by comparison of triangular carrier wave and modulating sinusoidal wave. The comparator output pulses give the on and off time of IGBTs.

2.9.2 3ϕ IGBT based Rectifier

Circuit diagram : Fig. 2.9.3 shows the circuit diagram of a 3ϕ IGBT based rectifier. Here observe that there are six IGBTs T_1 to T_6. The load is inductive and diode D is free-wheeling diode.

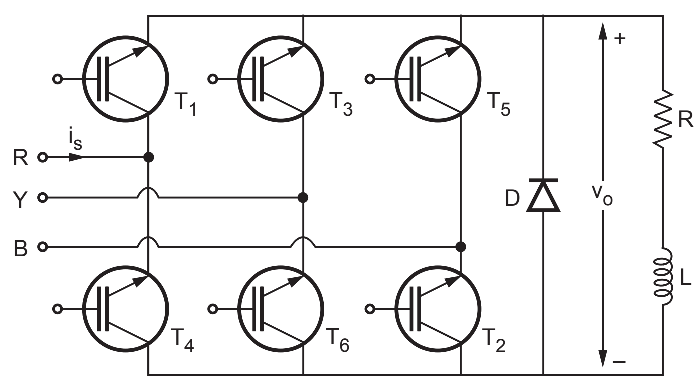


Fig. 2.9.3 3ϕ IGBT based rectifier

- The operation is just like 3ϕ SCR converter discussed before. At a time two IGBTs conduct.
- A PWM control can be introduced in 3ϕ IGBT based rectifier by modulating three phases seprately.

2.9.3 Difference between SCR based Conventional Rectifiers and IGBT based Rectifiers

Following is the comparison between SCR based converters and IGBT based converters.

Sr. No.	SCR based converters	IGBT based converters
1.	Uses natural commutation.	Uses forced on/off.
2.	Power factor cannot be controlled.	Power factor can be controlled.

3.	Harmonic content is high in supply current.	Harmonic content is reduced in supply current.
4.	Used for high voltage and high power applications.	Used for low voltage and low power applications.
5.	Mainly used for rectification.	Used for rectification as well as inversion.
6.	PF can be controlled from ac source in limited way by firing angle.	PF can be controlled from ac source to dc load and vice versa.

2.10 Multiple Choice Questions

Q.1 A fully controlled converter uses ________ .

a diodes only
b thyristors only
c both diodes and thyristors
d none of the mentioned

Q.2 A single phase full-converter using R load is a _________ quadrant converter and that using an RL load without FD is a __________ quadrant converter.

a one, one
b two, one
c one, two
d two, two

Q.3 A single phase full controlled bridge converter (B-2) uses ________ .

a 4 SCRs and 2 diodes
b 4 SCRs
c 6 SCRs
d 4 SCRs and 2 diodes

Q.4 In a B-2 type full controlled bridge converter ________ .

a one SCR conducts at a time
b two SCRs conduct at a time
c three SCRs conduct at a time
d four SCRs conduct at a time

Q.5 In a controlled rectifier a freewheeling diode is necessary if the load is ________ .

a inductive
b resistive
c capacitive
d any of the above

Q.6 The expression for the average value of the output voltage can be given by ______.

a $2\,V_m/\pi$
b V_m/π
c $V_m/\sqrt{2}$
d $2\,V_m/\sqrt{2}$

Q.7 The average output voltage is maximum when SCR is triggered at ωt =

a π

b 0

c $\pi/2$

d $\pi/4$

Q.8 In a single phase half-wave thyristor circuit with R load & $V_s = V_m \sin \omega t$, the maximum value of the load current can be given by ________ .

a $2 V_m/R$

b V_s/R

c V_m/R

d $V_s/2$

Q.9 A fully controlled converter uses ________ .

a diodes only

b thyristors only

c both diodes and thyristors

d none of the mentioned

Q.10 A single phase full-converter using R load is a _________ quadrant converter.

a one

b two

c three

d four

Q.11 In a single-phase half-wave circuit with RL load and a freewheeling diode, the load voltage during the freewheeling period will be ________ .

a zero

b positive

c negative

d positive than negative

Q.12 A single-phase symmetrical semi-converter employs ________ .

a one SCR and one diode in each leg

b two SCRs and two diodes in each leg

c two SCRs in each leg

d two diodes in each leg

Q.13 A single full converter alone can given a ________ .

a four quadrant operation

b three quadrant operation

c two quadrant operation

d none of the mentioned

Q.14 AC voltage controllers convert ________ .

a fixed ac to fixed dc

b variable ac to variable dc

c fixed ac to variable ac

d variable ac to fixed ac

Q.15 The AC voltage controllers are used in __________ applications.

a power generation

b electric heating

c conveyor belt motion

d power transmission

Q.16 In the principle of phase control ________ .

a the load is on for some cycles and off for some cycles

b control is achieved by adjusting the firing angle of the devices

c control is achieved by adjusting the number of on off cycles

d control cannot be achieved

Q.17 A single-phase half wave voltage controller consists of ________ .

a one SCR is parallel with one diode

b one SCR is anti parallel with one diode

c two SCRs in parallel

d two SCRs in anti parallel

Q.18 Single phase half wave AC voltage controller has Vs = 230 V and R = 20 Ω. Find the value of the average output voltage at the R load for a firing angle of 45°.

a 224 V

b – 15.17 V

c 15.17 V

d – 224 V

Q.19 A single phase voltage controller has input of 230 V and a load of 15 Ω resistive. For 6 cycles on and 4 cycles off, determine the rms output voltage.

a 189 V

b 260 V

c 156 V

d 178 V

Q.20 A three-phase full converter supplied from a 230 V source is working as a line commutated inverter. The load consists of RLE type with R = 5 Ω, E = 200 V and L = 1 mH. A continuous current of 10 A is flowing through the load, find the value of the firing angle delay.

a 119°

b 127°

c 156°

d 143°

Q.21 A three-phase three pulse type controlled converter is constructed using 3 SCR devices. The circuit is supplying an R load with α < 30°. As such, each SCR device would conduct for ________ .

a 60°each cycle

b 120°each cycle

c 180°each cycle

d 360° each cycle

Explanations :

Q.1 Explanation : Fully controlled implies that all the elements are "fully controlled" hence, it uses SCRs only except the FD.

Q.2 Explanation : In R load both V and I are positive, in RL load the voltage can be negative but current is always positive.

Q.3 Explanation : 4 SCR's are connected in a bridge fashion.

Q.4 Explanation : B-2 is the bridge type controller, in which 2 devices conduct at a time. One acting as the current supplying path and other acts as a return path.

Q.6 Explanation : The voltage waveform is a pulsating voltage with peak value V_m and symmetrical about π.

$V_o = (1/\pi) \int \pi \; V_m \; \sin \omega t \; d(\omega t)$

Q.7 Explanation : The sooner the conduction starts the higher the average power. Though practically a device cannot be triggered at exactly zero degrees.

Q.8 Explanation : Vm is the peak value of the load as well as supply voltage.

$I = V_m/R$.

Q.9 Explanation : Fully controlled implies that all the elements are "fully controlled" hence, it uses SCRs only except the FD.

Q.10 Explanation : In R load both V and I are positive.

Q.11 Explanation : The FD short circuits the load and voltage across a short circuit would be = 0.

Q.12 Explanation : Asymmetrical semi-converter will have one SCR and one diode in each leg. Twolegs connected in parallel with each other having a symmetrical configuration.

Q.13 Explanation : A single full converter alone gives two quadrant operation, hence for all four quadrant operation two full converter circuits are connected in antiparallel.

Q.14 Explanation : Voltage controllers convert the fixed ac voltage to variable ac by changing the values of the firing angle.

Q.20 Explanation : $V_o = 200 - 10 \times 5 = 150$ V as the circuit is operating as an inverter $V_o = -150$ V Now, $V_o = (3\ V_{ml} l/\pi) \cos \alpha$

$\alpha = \cos^{-1}(-150\,\pi / 3\sqrt{2} \times 230) = 118.88°$.

Q.21 Explanation : Each conduct for 120° per cycle is the firing angle is less than 30°. $120 \times 3 = 360°$.

Answer Keys for Multiple Choice Questions :

Q.1	b	**Q.2**	c	**Q.3**	b	**Q.4**	b	**Q.5**	a
Q.6	a	**Q.7**	b	**Q.8**	c	**Q.9**	b	**Q.10**	a
Q.11	a	**Q.12**	a	**Q.13**	c	**Q.14**	c	**Q.15**	b
Q.16	b	**Q.17**	b	**Q.18**	b	**Q.19**	d	**Q.20**	a
Q.21	b								

❑❑❑

UNIT III

3 DC to AC Converters

Syllabus

Single phase half and full bridge square wave inverter for R and R-L load using MOSFET / IGBT and its performance analysis and numerical, Cross conduction in inverter, need of voltage control and strategies in inverters, classifications of voltage control techniques, control of voltage using various PWM techniques and their advantages, concept and need of harmonic elimination / reduction in inverters, Three Phase voltage source inverter for balanced star R load with 120 and 180 degree mode of operation, device utilization factor, Advanced Converters like matrix inverter, multi-level inverters and their topologies and its driver circuits (no derivation and numerical).

Contents

3.1 Single Phase Half Bridge Inverter

SPPU : Dec.-2000,03

3.1.1 Operation with Resistive Load

Fig. 3.1.1 shows the circuit diagram of single phase half bridge inverter. The two MOSFETs T_1 and T_2 are used as switching devices. They can be MOSFET, GTO, SCR, IGBT etc. Fig. 3.1.2 shows the waveforms of the half bridge inverter having resistive load.

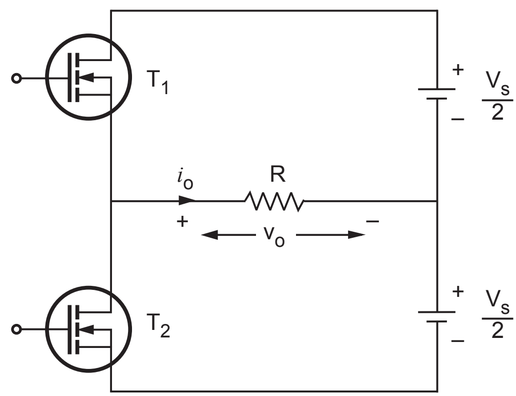


Fig. 3.1.1 Single phase half bridge inverter

MOSFET T_1 conducts from 0 to $\frac{T}{2}$. Hence the output voltage is positive and it is $\frac{V_s}{2}$. In equivalent circuit - I in Fig. 3.1.2, observe that current flows from point A to B in the load. MOSFET T_2 conducts from $\frac{\text{T}}{2}$ to T and T_1 is off. Equivalent circuit - II in Fig. 3.1.2 shows the situation when T_2 conducts. Current flows from point B to A in the load. The output voltage is $-\frac{V_s}{2}$. This is the negative half cycle of output. Since the load is resistive, output current waveform is same as voltage waveform. Fig. 3.1.2 also shows the currents through the MOSFET. The output of this inverter is a square wave. Since there are two MOSFET in the bridge, it is called half bridge inverter. (Refer Fig. 3.1.2 on next page)

3.1.2 Half Bridge Inverter with Inductive Load

Just now we discussed the operation of half bridge inverter having resistive load. Now let us see what happens with inductive load. Fig. 3.1.3 shows the circuit diagram of half bridge inverter for inductive load. Diodes D_1 and D_2 are connected across MOSFETs. These diodes conduct for inductive load.

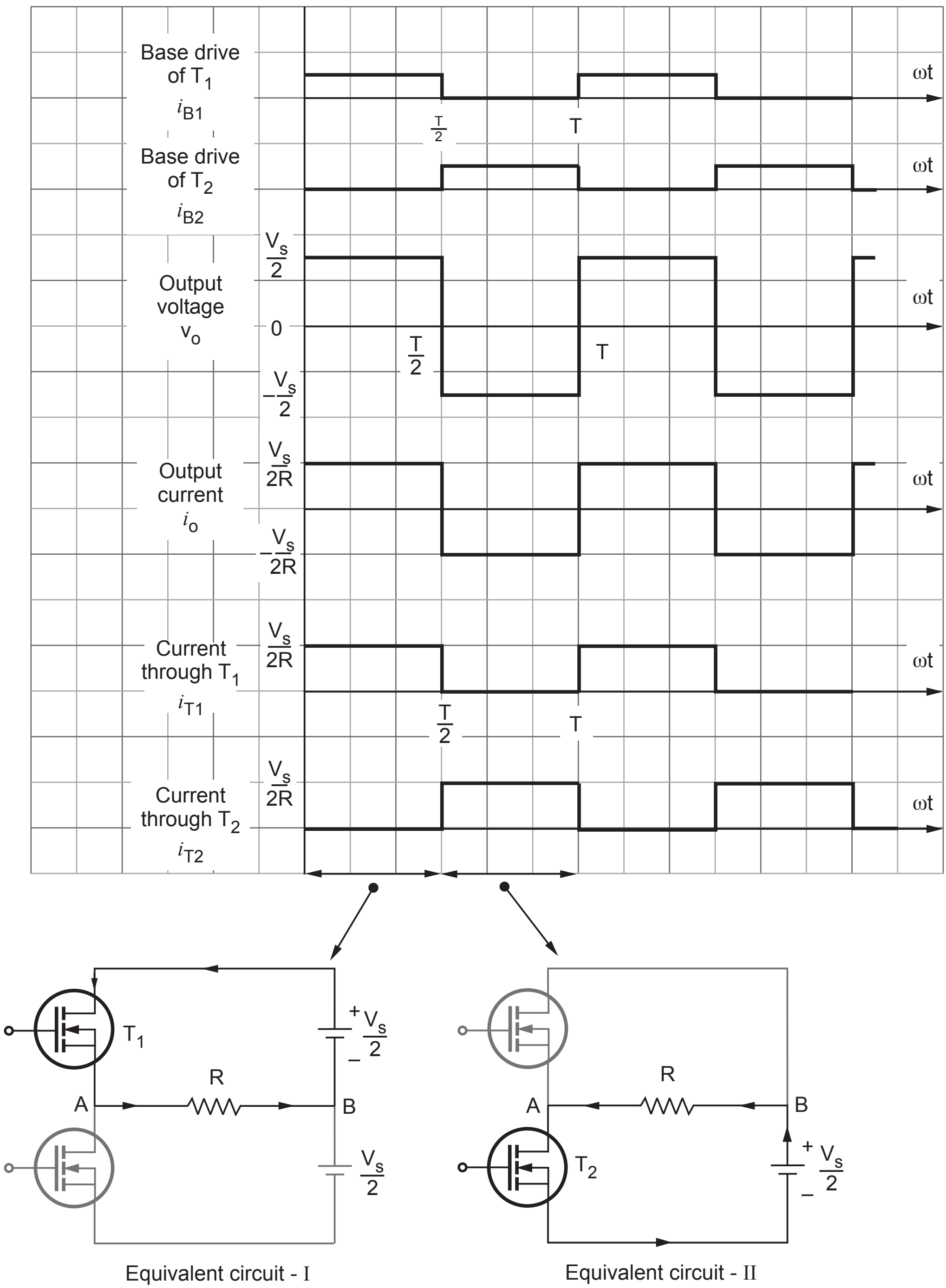


Fig. 3.1.2 Operation and waveforms of half bridge inverter

The waveforms of this circuit are shown in Fig. 3.1.4. T_1 is applied the drive from 0 to $\frac{T}{2}$. But diode D_1 is conducting from 0 to t_1. The output current i_0 decreases from negative maximum towards zero. Hence T_1 is reverse biased and it doesnot conduct till D_1 stops conducting at t_1.

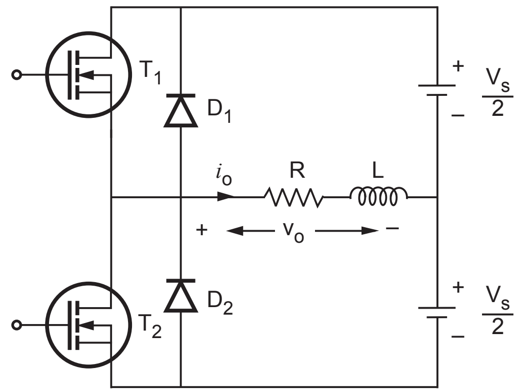


Fig. 3.1.3 Half bridge inverter having inductive load

Then MOSFET T_1 conducts from t_1 to $\frac{T}{2}$. The output current increases from zero to I_{max}. Equivalent circuit-II in Fig. 3.1.4 shows this situation. The current is supplied by dc supply.

At $\frac{T}{2}$, T_1 is turned off and base drive to T_2 is applied. But T_2 doesnot conduct. The load current is tried to maintained in the same direction by the load inductance. Hence it generates a large voltage $L\,\frac{di_o}{dt}$. This voltage polarity forward biases diode D_2 as shown by equivalent circuit-III in Fig. 3.1.4. Here $L\frac{di_o}{dt} > \frac{V_s}{2}$, hence output current flows against the supply. It flows through D_2. This current goes on decreasing and becomes zero at t_2. During this period $\left(\frac{T}{2} \text{ to } t_2\right)$ energy is supplied by the load inductance to the DC supply. Hence it is also called feedback operation.

At t_2 diode current becomes zero and T_2 starts conducting. T_2 conducts from t_2 to T. Equivalent circuit-IV in Fig. 3.1.4 shows this situation. The output current is negative and it increases from zero to $-I_{max}$. The output voltage is also negative.

At T, MOSFET T_2 is turned off and T_1 is applied the base drive. The load inductance generates large voltage $L\,\frac{di_o}{dt}$ with the polarity as shown in equivalent circuit-I of Fig. 3.1.4. Hence diode D_1 conducts. The load current is negative and decreases towards zero. Thus the cycle repeats.

When T_1 and T_2 conduct, the energy is supplied by the dc supplies. When diodes D_1 and D_2 conduct, the energy is supplied by load inductance to the DC supplies. Hence diodes are also called feedback diodes. The input current is the combined current due to both the DC supplies. (See Fig. 3.1.4 on next page)

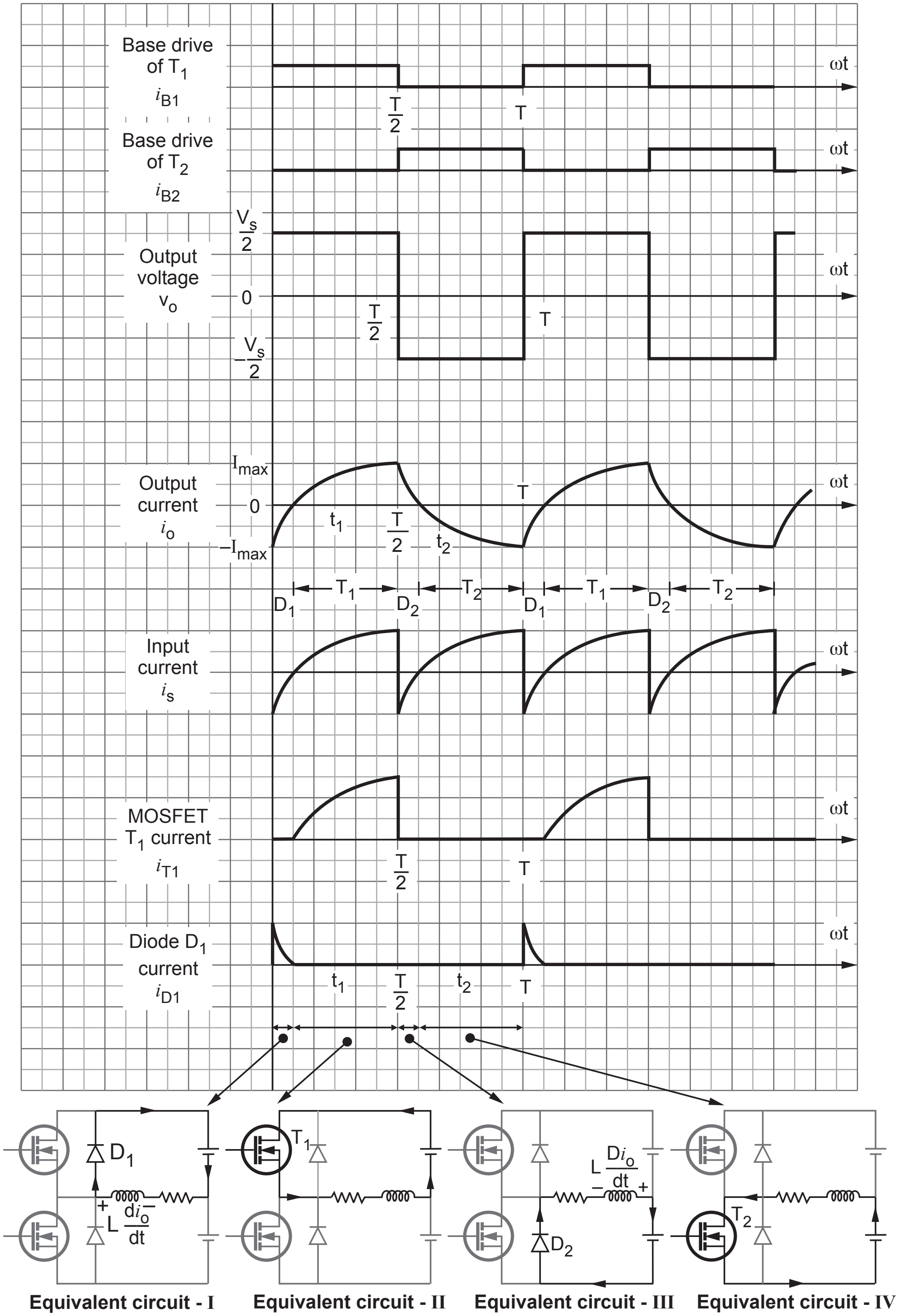


Fig. 3.1.4 Operation and waveforms of half bridge inverter for inductive load

Example 3.1.1 *Derive an expression for rms value of output voltage for half bridge inverter having square wave output. The peak value of output is $\frac{V_s}{2}$.*

Solution : Observe the waveforms of Fig. 3.1.2 (resistive load) and Fig. 3.1.4 (inductive load). The output voltage waveform is same in both the cases. Hence rms value of output voltage remains same for resistive as well as inductive loads. The rms value is given as,

$$V_{o(rms)} = \left[\frac{1}{T}\int_0^T v_0^2(\omega t)\, d\omega t\right]^{\frac{1}{2}}$$

Putting the value of $v_o(\omega t)$ from Fig. 3.1.4,

$$V_{o(rms)} = \left\{\frac{1}{T}\left[\int_0^{\frac{T}{2}} \left(\frac{V_s}{2}\right)^2 dt + \int_{\frac{T}{2}}^{T} \left(-\frac{V_s}{2}\right)^2 dt\right]\right\}^{\frac{1}{2}}$$

$$= \left\{\frac{1}{T}\left(\frac{V_s}{2}\right)^2\left[\int_0^{\frac{T}{2}} dt + \int_{\frac{T}{2}}^{T} dt\right]\right\}^{\frac{1}{2}}$$

$$V_{o(rms)} = \frac{V_s}{2} \qquad \text{... (3.1.1)}$$

Thus the rms value is same as peak value of waveform. This is true for square wave.

Example 3.1.2 *Obtain Fourier series for the output voltage waveform of half bridge inverter. Determine the rms value of the fundamental component of output voltage.*

Solution : i) To obtain Fourier series

Fig. 3.1.5 shows the waveform of output voltage observe that it is square wave of amplitude $\pm\frac{V_s}{2}$. The period of this square wave is T.

The general expression for Fourier series is given as,

$$v_o(\omega t) = V_{o(av)} + \sum_{i=1}^{\infty} c_n \sin(n\omega t + \phi_n) \qquad \text{... (3.1.2)}$$

where

$$c_n = \sqrt{a_n^2 + b_n^2}$$

$$\phi_n = \tan^{-1}\left(\frac{a_n}{b_n}\right)$$

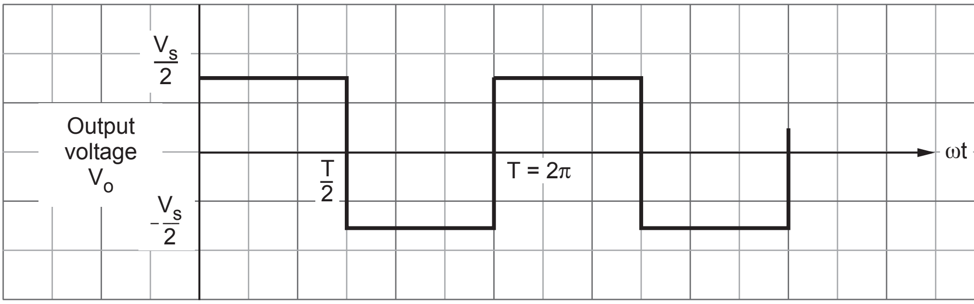


Fig. 3.1.5 Output voltage waveform of half bridge inverter

Here $$a_n = \frac{2}{T}\int_0^T v_o(\omega t)\cos n\omega t\ d\omega t$$

From the waveform of Fig. 3.1.5 we can write,

$$a_n = \frac{2}{2\pi}\left[\int_0^{\pi} \frac{V_s}{2}\cos n\omega t\ d\omega t + \int_{\pi}^{2\pi}\left(-\frac{V_s}{2}\right)\cos\ n\omega t\ d\omega t\right]$$

$$= \frac{V_s}{2\pi}\left\{\int_0^{\pi}\cos n\omega t\ d\omega t - \int_{\pi}^{2\pi}\cos\ n\omega t\ d\omega t\right\}$$

$$= \frac{V_s}{2n\pi}\left\{[\sin\ n\omega t]_0^{\pi} - [\sin\ n\omega t]_{\pi}^{2\pi}\right\}$$

$$= 0 \qquad \text{for all values of n.} \qquad \text{... (3.1.3)}$$

Now the value of b_n can be calculated as,

$$b_n = \frac{2}{T}\int_0^T v_o(\omega t)\ \sin\ n\omega t\ d\omega t$$

From the waveform of Fig. 3.1.5, we can write,

$$= \frac{2}{2\pi}\left[\int_0^{\pi}\frac{V_s}{2}\sin n\omega t\ d\omega t + \int_{\pi}^{2\pi}\left(-\frac{V_s}{2}\right)\sin\ n\omega t\ d\omega t\right]$$

$$= \frac{V_s}{2\pi}\left\{\int_0^{\pi}\sin n\omega t\ d\omega t - \int_{\pi}^{2\pi}\sin n\omega t\ d\omega t\right\}$$

$$= \frac{V_s}{2n\pi}\left\{[-\cos\ \omega t]_0^{\pi} - [-\cos\ \omega t]_{\pi}^{2\pi}\right\}$$

$$= \frac{V_s}{2n\pi}\left\{2(1-\cos\ n\pi)\right\}$$

$$= \frac{V_s}{n\pi}(1-\cos n\pi)$$

Here

$$\cos n\pi = \begin{cases} 1 & \text{for } n = 2, 4, 6, \ldots \text{i.e. even values} \\ -1 & \text{for } n = 1, 3, 5, \ldots \text{i.e. odd values} \end{cases}$$

Hence b_n becomes,

$$b_n = \begin{cases} \frac{2V_s}{n\pi} & \text{for odd values of n} \\ 0 & \text{for even values of n} \end{cases} \qquad \ldots (3.1.4)$$

$$c_n = \sqrt{a_n^2 + b_n^2} = \sqrt{0 + b_n^2} = b_n$$

$$\therefore \quad c_n = \frac{2V_s}{n\pi} \quad \text{for odd n} \qquad \ldots (3.1.5)$$

And $\quad \phi_n = \tan^{-1}\frac{a_n}{b_n} = \tan^{-1} 0 = 0$

The waveform of Fig. 3.1.5 has symmetric positive and negative half cycles. Hence average value of such waveform is zero i.e.,

$$V_{o(av)} = 0$$

Therefore fourier series of equation (3.1.2) can be written as,

$$v_o(\omega t) = \sum_{n=1,3,5,\ldots}^{\infty} \frac{2V_s}{n\pi} \sin n\omega t \qquad \ldots (3.1.6)$$

Thus output voltage contains only odd harmonics.

ii) To obtain rms value of the fundamental

From equation (3.1.6), we can write an equation for the fundamental component of output voltage by taking
n = 1 i.e.,

$$v_1(\omega t) = \frac{2V_s}{\pi}\sin \omega t \qquad \ldots (3.1.7)$$

This has same frequency (ωt) as that of square wave. The peak value of fundamental is,

$$c_1 = \frac{2V_s}{\pi}$$

rms value of the fundamental is,

$$V_{1(rms)} = \frac{c_1}{\sqrt{2}} = \frac{2V_s}{\sqrt{2}\,\pi} = 0.45\ V_s \qquad \text{... (3.1.8)}$$

Similarly rms values of other harmonics can be calculated as,

$$V_{n(rms)} = \frac{2V_s}{\sqrt{2}\,n\pi} = \frac{\sqrt{2}\ V_s}{n\pi} = \frac{0.45\ V_s}{n} \qquad \text{... (3.1.9)}$$

Example 3.1.3 *For a half bridge inverter feeding RL load, derive an expression for output current. Determine maximum and minimum values of load current.*

Solution : Fig. 3.1.6 shows the output current waveform for half bridge inverter. Let the current in positive half cycle be $i_1(t)$. During this period $\left(0 \text{ to} \frac{T}{2}\right)$ the load voltage is $\frac{V_s}{2}$. Fig. 3.1.7 shows an equivalent circuit. Writing KVL to this loop we get,

$$L\frac{di_1(t)}{dt} + Ri_1(t) = \frac{V_s}{2}$$

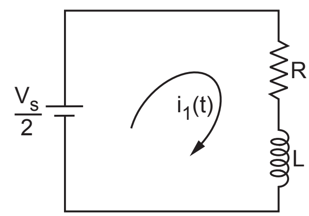


Fig. 3.1.7

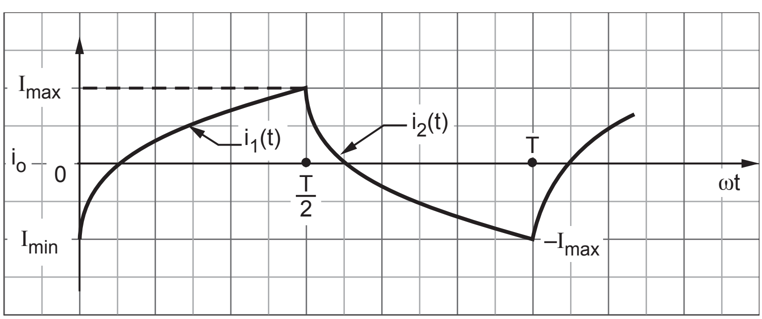


Fig. 3.1.6 Output current waveform

Taking Laplace transform of above equation,

$$L[sI_1(s) - I_1(0)] + RI_1(s) = \frac{V_s}{2s}$$

$$\therefore \qquad I_1(s)[R + sL] = \frac{V_s}{2s} + LI_1(0)$$

$$\therefore \qquad I_1(s) = \frac{V_s}{2s(R+sL)} + \frac{L\,I_1(0)}{(R+sL)}$$

$$= \frac{V_s}{2L} \cdot \frac{1}{s\left(s+\frac{R}{L}\right)} + \frac{I_1(0)}{s+\frac{R}{L}}$$

$$= \frac{V_s}{2R}\left(\frac{1}{s} - \frac{1}{s+\frac{R}{L}}\right) + I_1(0) \cdot \frac{1}{s+\frac{R}{L}}$$

Taking inverse Laplace transform of above equation,

$$i_i(t) = \frac{V_s}{2R}(1 - e^{-t \cdot R/L}) + i_1(0) e^{-t \cdot R/L}$$

Let $\tau = \frac{L}{R}$ be the load time constant. Then above equation will be,

$$i_i(t) = \frac{V_s}{2R}(1 - e^{-t/\tau}) + i_1(0) e^{-t/\tau} \quad \text{...(3.1.10)}$$

In the positive half cycle the load voltage is $+\frac{V_s}{2}$ and in the negative half cycle the load voltage is $-\frac{V_s}{2}$. Hence positive and negative peak amplitudes will be same. Therefore,

$$I_{\min} = -I_{\max} \quad \text{...(3.1.11)}$$

In Fig. 3.1.6 observe that $i_1(0) = I_{\min} = -I_{\max}$.

Putting this value in equation (3.1.10) becomes,

$$i_1(t) = \frac{V_s}{2R}(1 - e^{-t/\tau}) - I_{\max} e^{-t/\tau} \quad \text{...(3.1.12)}$$

At t = $\frac{T}{2}$, $i_1(t)$ = $I_{\max}$. Therefore above equation will be,

$$I_{\max} = \frac{V_s}{2R}(1 - e^{-T/2\tau}) - I_{\max} e^{-T/2\tau}$$

$$I_{\max}(1 + e^{-T/2\tau}) = \frac{V_s}{2R}(1 - e^{-T/2\tau})$$

$$\therefore \quad I_{\max} = \frac{V_s}{2R} \frac{1 - e^{-T/2\tau}}{1 + e^{-T/2\tau}} \quad \text{...(3.1.13)}$$

and hence, $$I_{\min} = -\frac{V_s}{2R} \frac{1 - e^{-T/2\tau}}{1 + e^{-T/2\tau}} \quad \text{...(3.1.14)}$$

From equation (3.1.12) we can write the equation for $i_2(t)$ keeping in mind that (i) $i_2(t)$ is delayed by $\frac{T}{2}$ and (ii) Polarities are reversed. i.e.,

$$i_2(t) = -\frac{V_s}{2R}(1 - e^{-\left(t - \frac{T}{2}\right)/\tau}) + I_{\max} e^{-\left(t - \frac{T}{2}\right)/\tau} \quad \text{...(3.1.15)}$$

Example 3.1.4 *A single phase half bridge inverter operates from 200 V split DC supply (100 V and –100 V) and supplies a purely inductive load of 5 mH at a switching frequency of 1 kHz. Calculate -*

i) Peak load current assuming the load current to have no DC component.

ii) Duration for which the load supplies power to the DC supply in each half-cycle.

iii) Average value of the switch current.

iv) rms value of the switch current. **SPPU : Dec.-03, Marks 10**

Solution : Given : V_s = 200 V, L = 5 mH, f = 1 kHz

$$\therefore \qquad T = \frac{1}{f} = \frac{1}{1\,k\,Hz} = 1\times 10^{-3}$$

i) To obtain peak value of load current

When there is no resistance, the complete voltage will appear across the inductance. Then the equivalent circuit will be as shown in Fig. 3.1.8.

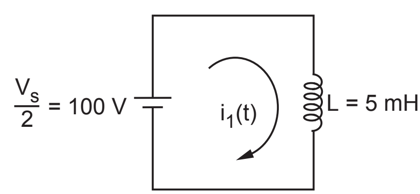


Fig. 3.1.8 Equivalent circuit in positive half cycle

Applying KVL to the circuit

$$L\frac{d\,i_1(t)}{dt} = \frac{V_s}{2}$$

Taking Laplace transform of above equation,

$$L[sI_1(s) - I_1(0)] = \frac{V_s/2}{s}$$

$$\therefore \qquad I_1(s) = \frac{V_s/2}{s^2 L} + \frac{I_1(0)}{s}$$

Taking inverse Laplace transform,

$$i_1(t) = \frac{V_s}{2L}\cdot t + i_1(0)$$

We have shown in example 3.1.3 that $i_1(0) = I_{min} = -I_{max}$. Hence above equation becomes,

$$i_1(t) = \frac{V_s}{2L}\cdot t - I_{max} \qquad \ldots(3.1.16)$$

Again at $t = \frac{T}{2}$, $i_1(t) = I_{max}$ as deduced in example 3.1.3.

Therefore above equation becomes,

$$I_{max} = \frac{V_s}{2L}\cdot\frac{T}{2} - I_{max}$$

$$\therefore \qquad I_{max} = \frac{V_s T}{8L}$$

Putting values in above equation,

$$I_{max} = \frac{200 \times 1 \times 10^{-3}}{8 \times 5 \times 10^{-3}} = 5 \text{ A}$$

ii) Duration of energy feedback

Putting value of $I_{max} = 5\,\text{A}$ and other values in equation (3.1.16) we get,

$$i_1(t) = \frac{200}{2 \times 5 \times 10^{-3}} t - 5$$

$$\therefore \qquad i_1(t) = 20{,}000t - 5$$

Note that this is the equation of straight line. We know that value of $i_1(t) = 5$ A at $t = \frac{T}{2} = 0.5 \times 10^{-3}$. Similarly $I_{min} = -5$ at t = 0. Fig. 3.1.9 shows the current waveform based on these conclusions. Note that $i_2(t)$ is obtained simply by changing the direction of $i_1(t)$. It is triangular waveform due to purely inductive load.

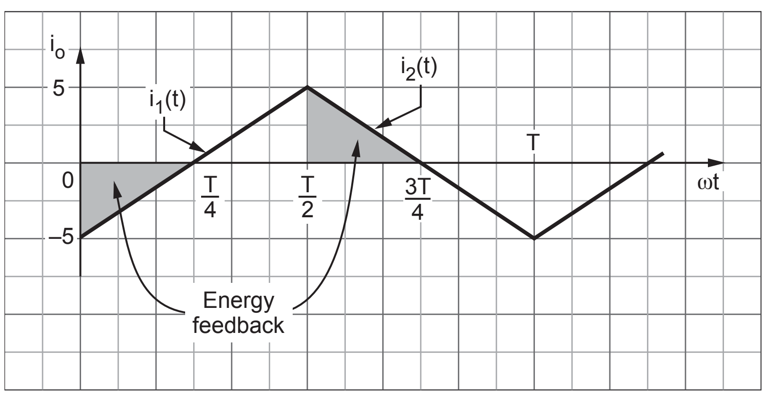


Fig. 3.1.9 Current waveform for purely inductive load

Note that energy is transferred from load to source when load voltage and current polarities are opposite.

From the waveform of Fig. 3.1.9 it is clear that the energy will be transferred from 0 to $\frac{T}{4}$ in positive half cycle and $\frac{T}{2}$ to $\frac{3T}{4}$ during negative half cycle.

$$\therefore \qquad \text{Duration of energy feedback} = \left(\frac{T}{4} - 0\right) + \left(\frac{3T}{4} - \frac{T}{2}\right)$$

$$= \frac{T}{2} = \frac{1 \times 10^{-3}}{2}$$

$$= 0.5 \text{ msec.}$$

iii) Average value of switch current

From Fig. 3.1.10, the average switch current can be expressed as follows

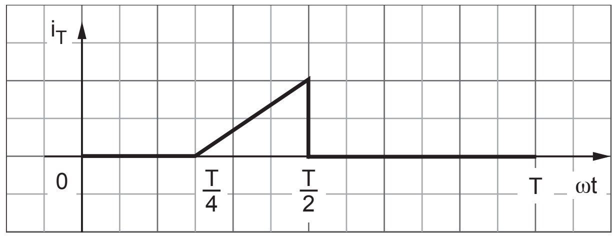


Fig. 3.1.10 Switch current waveform

$$I_{T(av)} = \frac{1}{T}\int_0^T i_T(\omega t)\, d\omega t = \frac{1}{T}\int_{T/4}^{T/2} (20{,}000t - 5)\, dt$$

$$= \frac{1}{T}\left\{20{,}000\left[\frac{t^2}{2}\right]_{\frac{T}{4}}^{\frac{T}{2}} - 5[t]_{\frac{T}{4}}^{\frac{T}{2}}\right\} = \frac{1}{T}\left\{10{,}000\left[\frac{T^2}{4} - \frac{T^2}{16}\right] - 5\left[\frac{T}{2} - \frac{T}{4}\right]\right\}$$

$$= 10{,}000 \cdot \frac{3T}{16} - \frac{5}{4} \qquad \text{since } \mathrm{T} = 1\times 10^{-3}$$

$$= 0.625 \text{ A.}$$

iv) RMS switch current

$$I_{T(rms)} = \left[\frac{1}{T}\int_0^T i_T^2(\omega t)\, d\omega t\right]^{\frac{1}{2}} = \left[\frac{1}{T}\int_{\frac{T}{4}}^{\frac{T}{2}} (20{,}000t - 5)^2\, d\omega t\right]^{\frac{1}{2}}$$

$$= \left\{\frac{1}{T}\int_{\frac{T}{4}}^{\frac{T}{2}} [(20{,}000t)^2 - (2\times 5\times 20{,}000\, t) + 25]\, d\omega t\right\}^{\frac{1}{2}}$$

$$= \left\{\left[\left[(20{,}000)^2 \cdot \frac{t^3}{3}\right]_{\frac{T}{4}}^{\frac{T}{2}} - 2\times 10^5 \cdot \left[\frac{t^2}{2}\right]_{\frac{T}{4}}^{\frac{T}{2}} + 25[t]_{\frac{T}{4}}^{\frac{T}{2}}\right]\right\}^{\frac{1}{2}}$$

$$= \left\{\frac{1}{T}\left[\frac{(20{,}000)^2}{3}\left(\frac{T^3}{8} - \frac{T^3}{64}\right) - 1\times 10^5\left(\frac{T^2}{4} - \frac{T^2}{16}\right) + 25\left(\frac{T}{2} - \frac{T}{4}\right)\right]\right\}^{\frac{1}{2}}$$

$$= \left\{ \frac{(20{,}000)^2}{3} \left(\frac{T^2}{8} - \frac{T^2}{64} \right) - 1 \times 10^5 \left(\frac{T}{4} - \frac{T}{16} \right) + 25 \left(\frac{1}{2} - \frac{1}{4} \right) \right\}^{\frac{1}{2}}$$

$$= \left\{ \frac{(20{,}000)^2}{3} \cdot \frac{7T^2}{64} - 1 \times 10^5 \cdot \frac{3T}{16} + 25 \times \frac{1}{4} \right\}^{\frac{1}{2}}$$

$$= \left\{ \frac{(20{,}000)^2}{3} \cdot \frac{7}{64} \times (1 \times 10^{-3})^2 - 1 \times 10^5 \times \frac{3}{16} \times 1 \times 10^{-3} + \frac{25}{4} \right\}^{\frac{1}{2}}$$

$$= 1.443 \text{ A}$$

Review Questions

1. *Explain the working of half bridge inverter with the help of waveforms.*
SPPU : Dec.-03, Marks 6

2. *With the help of circuit diagram and relevant waveforms, explain operation of half bridge inverter for inductive load.* **SPPU : Dec.-2000, Marks 6**

3.2 Performance Parameters

SPPU : Dec.-02

The inverters generate the AC output. But the output voltage waveform can be square wave, quasi-square wave or low distorted sine wave. These waveforms contain harmonics (i.e. distortion). The performance parameters represent the amount of distortion in inverter output.

1. Harmonic factor of n^{th} harmonic (HF_n)

The harmonic factor of the n^{th} harmonic is defined as the ratio of rms value of n^{th} harmonic to rms value of the fundamental. i.e.,

$$HF_n = \frac{V_n}{V_1} \qquad \text{... (3.2.1)}$$

Here V_n is rms value of n^{th} harmonic

V_1 is rms value of fundamental

The harmonic factor (HF_n) indicates contribution of each harmonic to the harmonic distortion. This factor is evaluated to check the dominant harmonics in the output.

2. Total harmonic distortion (THD)

The total harmonic distortion is the ratio of rms values of all the harmonics to rms value of the fundamental component. i.e.,

$$\text{THD} = \frac{\left(\sum_{n=2,3,\ldots}^{\infty} V_n^2\right)^{\frac{1}{2}}}{V_1} \qquad \ldots (3.2.2)$$

The total harmonic distortion indicates the distortion in the waveform. It is the measure of closeness of the waveform to sine wave.

3. Distortion factor (DF)

The distortion factor is defined as,

$$\text{DF} = \frac{1}{V_1}\left[\sum_{n=2,3,\ldots\ldots}^{\infty} \left(\frac{V_n}{n^2}\right)^2\right]^{\frac{1}{2}} \qquad \ldots (3.2.3)$$

The distortion factor is the measure of harmonic distortion that remains in the particular waveform after filtering. Due to filtering higher order harmonics are eliminated. The distortion factor of n^{th} harmonic component is given as,

$$DF_n = \frac{V_n}{V_1 n^2} \qquad \ldots (3.2.4)$$

4. Lowest order harmonic (LOH)

The lowest order harmonic is the harmonic component which has nearest frequency to the fundamental and its amplitude is within 3 % of the fundamental component. The lowest order harmonic should have maximum possible frequency, so that the harmonic distortion is less.

Example 3.2.1 *The single phase half bridge inverter has the DC input of 48 V. The load resistance is 4.8 Ω. Determine*

i) RMS value of output voltage ii) RMS value of fundamental component iii) Total harmonic distortion.

Solution : Given $V_s = 48$ V and $R = 4.8$ Ω

i) The rms value of output voltage is $\frac{V_s}{2}$. i.e.,

$$V_{o(rms)} = \frac{V_s}{2} \qquad \ldots (3.2.5)$$

$$= \frac{48}{2} = 24\ V$$

ii) The output waveform of half bridge inverter is square wave of amplitude $\frac{V_s}{2}$. The fundamental component is given for such square wave is given by equation (3.1.8) as,

$$V_{1(rms)} = \frac{2\ V_s}{\sqrt{2}\ \pi} = 0.45\ V_s \quad \text{... (3.2.6)}$$

$$= 0.45 \times 48 = 21.6\ V$$

iii) The rms voltage due to all the harmonics can be obtained as,

$$V_{(harmonics)} = \left(\sum_{n=3,5,7}^{\infty} V_n^2 \right)^{\frac{1}{2}} \quad \text{... (3.2.7)}$$

The square wave contains only odd harmonics. This value can be obtained as,

$$V_{(harmonics)} = \left(V_{o(rms)}^2 - V_1^2 \right)^{\frac{1}{2}} \quad \text{... (3.2.8)}$$

$$= \left[(24)^2 - (21.6)^2 \right]^{\frac{1}{2}} = 10.46$$

The THD is obtained as the ratio of rms value due to harmonics to rms value of fundamental i.e.,

$$\text{THD} = \frac{10.46}{21.6} = 0.484 \quad \text{or} \quad 48.4\ \%$$

From equation (3.2.2), equation (3.2.7) and equation (3.2.8) we can obtain an expression for THD as,

$$\text{THD} = \frac{\sqrt{V_{o(rms)}^2 - V_1^2}}{V_1} = \sqrt{\left(\frac{V_{o(rms)}}{V_1} \right)^2 - 1} \quad \text{... (3.2.9)}$$

The square wave contains 48.4 % of harmonic distortion.

Example 3.2.2 *Calculate the following for a single phase transistorized half bridge inverter.*

i) RMS output voltage at fundamental frequency ii) Output power

Assume DC supply of 24 V and load resistance of 2 ohm. **SPPU : Dec.-02, Marks 4**

Solution : i) RMS output voltage at fundamental frequency

$$V_{1(rms)} = 0.45\ V_s = 0.45 \times 24 \quad \text{since } V_s = 24 \text{ V} = 10.8 \text{ V}$$

ii) Output power

RMS value of output voltage is,

$$V_{o(rms)} = \frac{V_s}{2} = \frac{24}{2} = 12 \text{ V}$$

$$\therefore \qquad P_{o(rms)} = \frac{V_{o(rms)}^2}{R} = \frac{12^2}{2} = 72 \text{ V}$$

Review Question

1. *State the various performance parameters used for inverters.*

3.3 Single Phase Full Phase Bridge Inverter

SPPU : Dec.-01,04,06,08,09,10,11,15,16,19, May-2000,04,05,06,07,08,10,11,12,15, April-15,16,17,19,

We studied half bridge inverter earlier. Fig. 3.3.1 shows the circuit diagram of full bridge inverter. Observe that there are four IGBTs and four diodes. The diodes are required for feedback when the load is inductive.

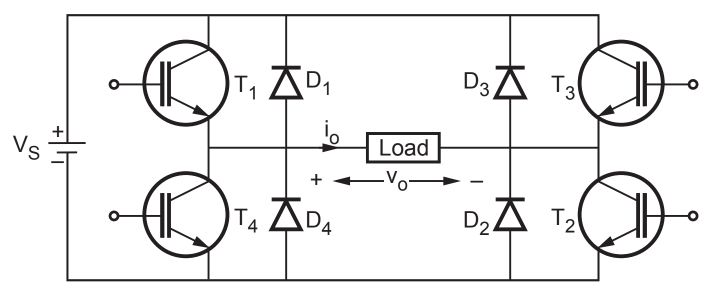


Fig. 3.3.1 Single phase bridge inverter

3.3.1 Operation with Resistive Load

When the load is resistive, the diodes doesnot carry any current. Fig. 3.3.2 shows the waveforms. The IGBTs T_1 and T_2 conduct from 0 to $\frac{T}{2}$. Equivalent circuit-I in Fig. 3.3.2 shows the current path when T_1 and T_2 conduct. The output voltage and current are positive. Note that the amplitude of load voltage is V_s.

(Refer Fig. 3.3.2 on next page)

At $\frac{T}{2}$, IGBTs T_1 and T_2 are turned off. IGBTs T_3 and T_4 conduct from $\frac{T}{2}$ to T. Equivalent circuit-II shows the current path. Note that the output current is negative. The voltage is also negative. Thus in positive half cycle, T_1 and T_2 conduct. And in negative half cycle, T_3 and T_4 conduct. The amplitude of the output voltage is $\pm V_s$. The output is the square wave. The currents through IGBTS are also shown in the Fig. 3.3.2.

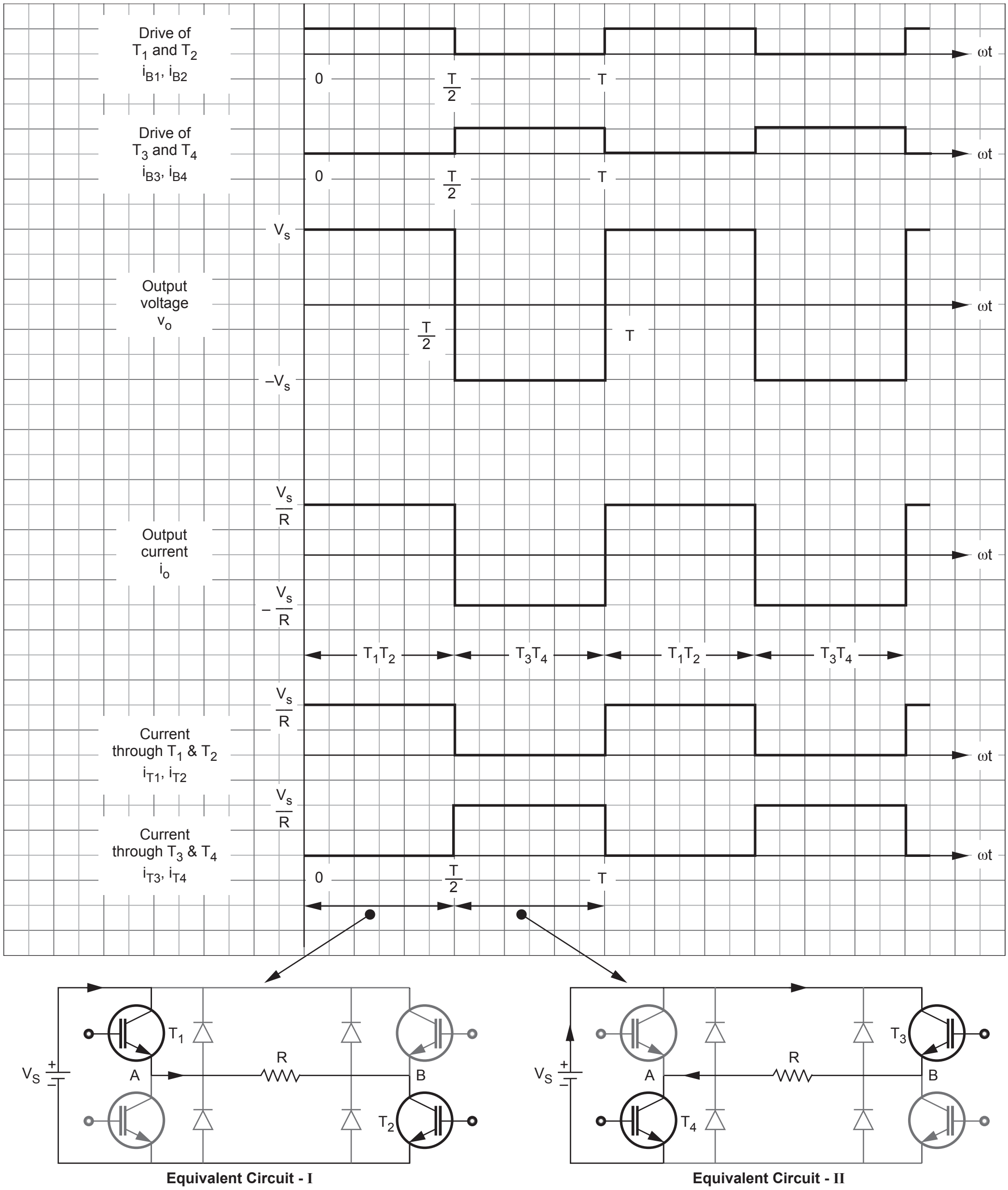


Fig. 3.3.2 Operation and waveforms of 1ϕ bridge inverter for resistive load

3.3.2 Operation with Inductive Load

Now let us consider the operation of 1ϕ bridge inverter with inductive (R - L) load. Fig. 3.3.3 shows the circuit diagram of bridge inverter having RL load. The waveforms of this circuit are shown in Fig. 3.3.4.

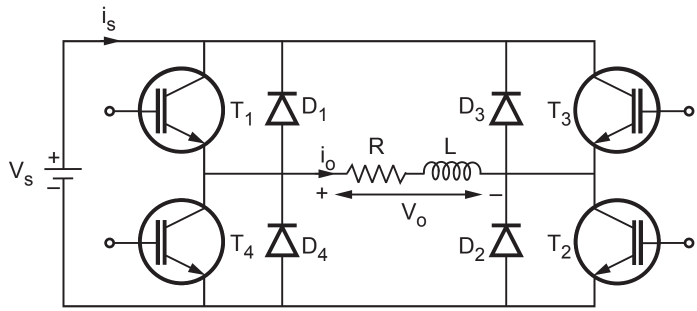


Fig. 3.3.3 1ϕ bridge inverter having inductive load

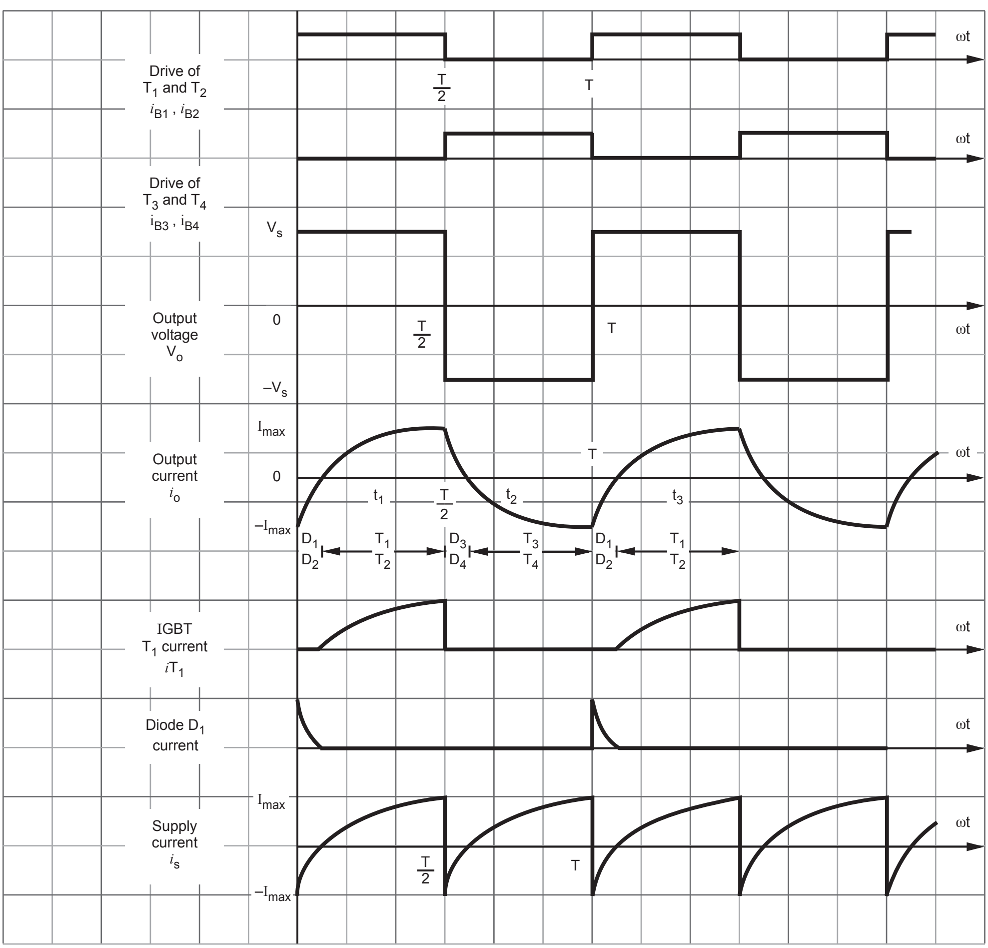


Fig. 3.3.4 Waveforms of bridge inverter for inductive load

The operation of this circuit can be explained in four modes as follows :

Mode - I (T_1, T_2 conducts)

T_1 and T_2 are applied the drive at $t = 0$. But they does not conduct till t_1. Diodes D_1 and D_2 conduct from 0 to t_1.

Hence T_1 and T_2 are reverse biased and they do not conduct. From t_1 to $\frac{T}{2}$, T_1 and T_2 conduct. The equivalent circuit is shown in Fig. 3.3.5. The load current is positive and it increases from zero to + $I_{\max}$. The output voltage is also positive.

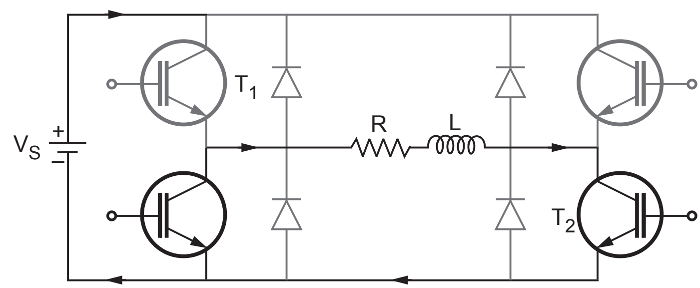


Fig. 3.3.5 T_1 and T_2 conduct from t_1 to $\frac{T}{2}$

Mode - II (D_3 and D_4 conducts)

At $\frac{T}{2}$, IGBTs T_1 and T_2 are turned off and T_3, T_4 are applied drives. The load inductance generates the large voltage $L\,\frac{d\,i_o}{dt}$ with polarities shown in Fig. 3.3.6. The diodes D_3 and D_4 are forward biased due to inductance voltage. These diodes conduct and output current flows through DC supply. The energy stored in the load inductance is supplied to the DC supply. This operation is called *feedback operation.* Note that the supply current i_s is negative when diodes D_3, D_4 are conducting. Due to conduction of D_3 and D_4, IGBTs T_3 and T_4 are reverse biased. Hence they do not conduct, even though base drives are applied. At t_2, the load current becomes zero. Hence IGBTs T_3 and T_4 start conducting.

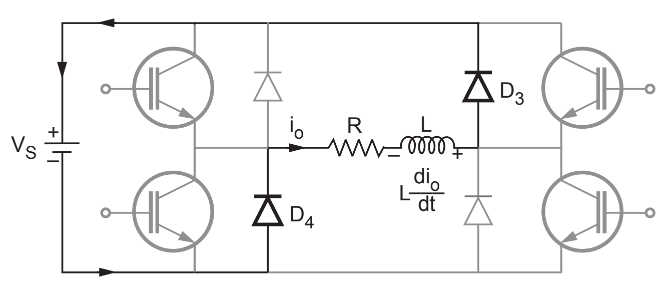


Fig. 3.3.6 D_3 and D_4 conduct from $\frac{T}{2}$ to t_2

Mode - III (T_3 and T_4 conduct)

At t_2 the IGBTs T_3 and T_4 start conducting. Fig. 3.3.7 shows the equivalent circuit for this operation. The output current is negative and increases towards $-I_{max}$. The supply current i_s is positive. The output voltage is negative during this period.

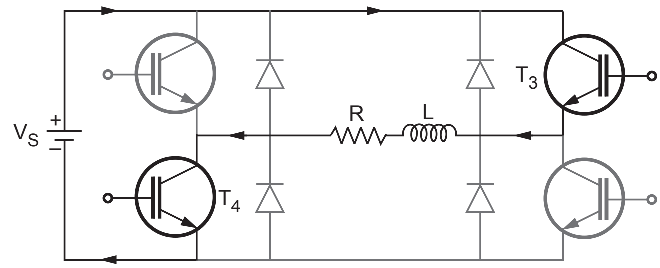


Fig. 3.3.7 T_3 and T_4 conduct from t_2 to T

Mode - IV (D_1 and D_2 conduct from T to t_3 i.e. from 0 to t_1)

At T, IGBTs T_3 and T_4 are turned off and T_1, T_2 are applied the drive. The output current is at $-I_{max}$. Hence load inductance generates the large voltage $L\,\frac{di_o}{dt}$ with polarities as shown in Fig. 3.3.8. Due to this voltage the diodes D_1 and D_2 are forward biased. Hence they start conducting.

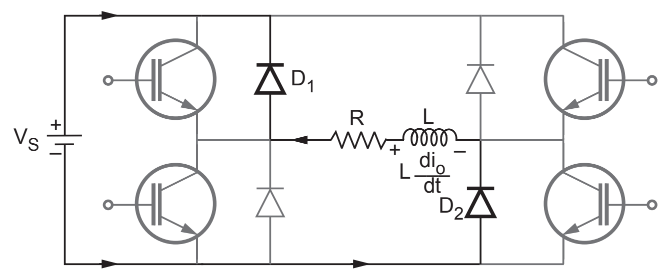


Fig. 3.3.8 D_1 and D_2 conduct from 0 to t_1 i.e. from T to t_3

The output current flows through the DC supply and it goes on decreasing. The energy stored in the load inductance is supplied to the DC supply during this period. This is called feedback operation. IGBTs T_1 and T_2 are reverse biased due to conduction of D_1 and D_2. Hence T_1 and T_2 do not conduct even if their base drive is applied. At t_3 (i.e. at t_1), the output current becomes zero. Hence T_1 and T_2 start conducting. The output current becomes positive. This is beginning of mode - I discussed earlier. Then the cycle repeats.

The load energy is feedback to DC supply whenever diodes conduct. The supply current is negative. And energy flows from supply to the load whenever IGBTS conduct. The supply current is positive when IGBTs conduct. The output voltage waveform is square wave having amplitudes of $\pm V_s$.

Example 3.3.1 *Derive the following for the single phase bridge inverter having square wave output :*

i) RMS value of output *ii) Fourier series for output voltage*

iii) RMS value of fundamental component of voltage.

SPPU : Dec.-04,08, April-19, Marks 6

Solution : i) RMS value of output

The RMS value of output voltage is given as,

$$V_{o\,(rms)} = \left[\frac{1}{T}\int_0^T v_0^2\,(\omega\,t)\,d\,\omega\,t\right]^{\frac{1}{2}}$$

For the bridge inverter, $v_o\,(\omega\,t)$ is the square wave having amplitudes of $+V_s$ and $-V_s$. Hence above equation can be written as,

$$V_{o\,(rms)} = \left\{\frac{1}{T}\left[\int_0^{\frac{T}{2}} V_s^2\,dt + \int_{\frac{T}{2}}^{T} (-V_s)^2\,dt\right]\right\}^{\frac{1}{2}}$$

$$= \left\{\frac{V_s^2}{T}\left[\int_0^{\frac{T}{2}} dt + \int_{\frac{T}{2}}^{T} dt\right]\right\}^{\frac{1}{2}} = V_s \qquad \text{... (3.3.1)}$$

Thus the rms value of the output voltage is same as the DC supply.

ii) Fourier series for output voltage

We have derived an expression for fourier series of output voltage for half bridge inverter. The output waveforms of half bridge inverter and full bridge inverter are same, i.e. square wave. There is only difference of amplitudes. The amplitude is $\pm\,V_s$ in full bridge inverter. Where as, it is $\pm\,\frac{V_s}{2}$ in half bridge inverter. Let us rearrange equation (3.1.6) as,

$$v_o(\omega t) = \sum_{n=1,3,5,\ldots\ldots}^{\infty} \frac{4\left(\frac{V_s}{2}\right)}{n\pi}\sin n\omega t$$

This is Fourier series for half bridge inverter. For full bridge inverter we have to replace $\frac{V_s}{2}$ by V_s i.e.

$$v_o(\omega t) = \sum_{n=1,3,5,\ldots\ldots}^{\infty} \frac{4V_s}{n\pi}\sin n\omega t \qquad \text{... (3.3.2)}$$

This is Fourier series for full bridge inverter. The output voltage waveform remain same for resistive and inductive loads. Hence above expression is applicable resistive as well as inductive loads. The above equation shows that output voltage contains only odd harmonics.

iii) rms value of fundamental components

With n = 1 in equation (3.3.2) we get equation of fundamental component of output voltage i.e.,

$$v_1(\omega t) = \frac{4V_s}{\pi}\sin\omega t$$

This has the same frequency (ωt) as that of square wave. The peak value of the fundamental is,

$$c_1 = \frac{4V_s}{\pi}$$

rms value of the fundamental is,

$$V_{1(rms)} = \frac{c_1}{\sqrt{2}} = \frac{4V_s}{\sqrt{2}\,\pi} = \frac{2\sqrt{2}\,V_s}{\pi} = 0.9\ V_s \qquad \text{... (3.3.3)}$$

This is the rms value of fundamental. Similarly rms value of n^{th} harmonic can be obtained as,

$$V_{n(rms)} = \frac{4V_s}{\sqrt{2}\ n\pi} = \frac{0.9\ V_s}{n} \qquad \text{... (3.3.4)}$$

Example 3.3.2 *For a full bridge inverter feeding RL load, derive an expression for output current. Determine maximum and minimum values of load current.*

SPPU : May-06, Marks 6

Solution : Fig. 3.3.9 shows the output current waveform for full bridge inverter.

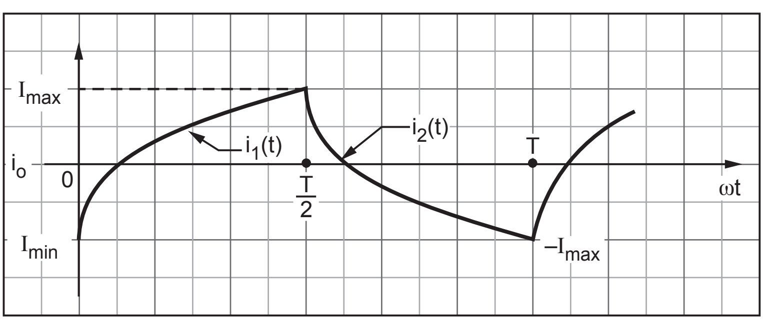


Fig. 3.3.9 Output current waveform

Note that this waveform is exactly same as that of 1φ half-bridge inverter shown in Fig. 3.1.6 earlier. But for full bridge inverter, the load voltage is V_s. In example 3.1.3 we have derived various expressions for currents. If $\frac{V_s}{2}$ is replaced by V_s, we get those expressions for full bridge inverter. i.e. from example 3.1.3 we have following results for 1 φ full bridge inverter.

$$i_1(t) = \frac{V_s}{R}(1-e^{-t/\tau}) - I_{max}e^{-t/\tau} \qquad \text{from equation (3.1.12)} \quad \ldots(3.3.5)$$

$$i_2(t) = -\frac{V_s}{R}\left(1-e^{-\left(t-\frac{T}{2}\right)/\tau}\right) + I_{max}e^{-\left(t-\frac{T}{2}\right)/\tau} \qquad \text{from equation (3.1.15)} \quad \ldots(3.3.6)$$

$$I_{max} = \frac{V_s}{R}\,\frac{1-e^{-T/2\tau}}{1+e^{-T/2\tau}} \qquad \text{from equation (3.1.13)} \quad \ldots(3.3.7)$$

$$I_{min} = -\frac{V_s}{R}\,\frac{1-e^{-T/2\tau}}{1+e^{-T/2\tau}} \qquad \text{from equation (3.1.14)} \quad \ldots(3.3.8)$$

In all the above equations $\frac{V_s}{2}$ is replaced by V_s.

Example 3.3.3 *Single phase full bridge inverter has a resistive load of R = 3 Ω, dc input voltage is 50 V.*

Calculate :

i) rms O/P voltage at the fundamental frequency f_1

ii) Output power P_o

iii) Average and peak currents of each thyristor.

SPPU : Dec.-11, Marks 8, Similar April-17, Marks 2

Solution : $R = 3\ \Omega$, $V_s = 50\ \text{V}$.

i) rms output voltage at f_1

$$V_{1(rms)} = 0.9\ V_s = 0.9 \times 50 = 45\ \text{V}$$

ii) Output power

$$P_o = \frac{V_{o(rms)}^2}{R} = \frac{V_s^2}{R}, \text{ since } V_{o(rms)} = V_s$$

$$= \frac{50^2}{3} = \mathbf{833.33\ VA}$$

iii) Average and peak thyristor current

$$i_{T(peak)} = \frac{V_s}{R} = \frac{50}{3}\ A \qquad \text{(from example 3.3.5)}$$

$$i_{T(av)} = i_{T(peak)} \times \text{Duty cycle}$$

$$= \frac{50}{3} \times 0.5 = \frac{25}{3} \qquad \text{(from example 3.3.5)}$$

Example 3.3.4 *A single phase MOSFET full bridge inverter operates from a 100 V DC supply and feeds a heating (resistive) load. If the rms current rating of the MOSFET is 10 A, calculate the maximum available heater power output.* **SPPU : Dec.-04, Marks 6**

Solution : Given : $V_s = 100 \text{ V}$

$$I_{T(rms)} = 10 \text{ A}$$

RMS current of MOSFET

$$I_{T(rms)} = \left[\frac{1}{T}\int_0^T i_T^2(\omega t)\,d\omega t\right]^{\frac{1}{2}} = \left[\frac{1}{T}\int_0^{T/2}\left(\frac{V_s}{R}\right)^2 d\omega t\right]^{\frac{1}{2}}$$

$$= \left[\frac{1}{T}\left(\frac{V_s}{R}\right)^2 \int_0^{T/2} d\omega t\right]^{\frac{1}{2}} = \frac{V_s}{\sqrt{2}\,R}$$

Since $I_{T(rms)} = 10 \text{ A}$,

$$10 = \frac{V_s}{\sqrt{2}\,R} \quad \text{or} \quad \frac{V_s}{R} = 10\sqrt{2}$$

RMS output current ($I_{o(rms)}$)

Since output current is square wave of amplitude $\pm\frac{V_s}{R}$, the rms value of output current is,

$$I_{o(rms)} = \frac{V_s}{R}$$

We know that $\frac{V_s}{R} = 10\sqrt{2}$, therefore above equation becomes,

$$I_{o(rms)} = 10\sqrt{2}$$

Output rms voltage

$$V_{o(rms)} = V_s = \mathbf{100 \text{ V}}$$

Output power

$$P_{o(rms)} = V_{o(rms)}\, I_{o(rms)} = 100 \times 10\sqrt{2} = \mathbf{1414.2 \text{ Watts.}}$$

Example 3.3.5 *The single phase full bridge inverter has a resistive load of R = 2.4 Ω, and the DC input voltage of V_s = 48 volts. Determine,*

i) r.m.s. output voltage at the fundamental frequency.

ii) The output power

iii) The peak and average currents of each transistor.

iv) Peak reverse blocking voltage (V_{BR})

v) THD **SPPU : May-07,15, April-16, Marks 10; Dec.-10, Marks 8, April-15, Marks 2**

Solution : Given $V_s = 48\ V,\quad R = 2.4\ \Omega$

i) To determine r.m.s. value of the fundamental

From equation 3.3.3, r.m.s. value of the fundamental component of output is given as,

$$V_1 = 0.9\ V_s = 0.9 \times 48 = 43.2 \text{ volts}$$

ii) To determine output power

From equation 3.3.1, the r.m.s. output voltage is,

$$V_{o(rms)} = V_s = 48 \text{ volts}$$

The output power can be calculated as,

$$P_o = \frac{V_{o(rms)}^2}{R} = \frac{(48)^2}{2.4} = 960 \text{ W.}$$

iii) To determine transistor currents

Fig. 3.3.2 shows the transistor current waveforms for resistive load. These waveforms are reproduced below for convenience.

In the below figure, observe that the transistor current is a square wave of amplitude $\frac{V_s}{R}$. Hence peak transistor current is,

$$i_{T(peak)} = \frac{V_s}{R} = \frac{48}{2.4} = 20 \text{ A}$$

Each transistor current is a square wave of duty cycle 0.5. Hence average transistor current will be equal to average value of square wave. i.e.

$$i_{T\ (av)} = i_{T(peak)} \times \text{duty cycle} = 20 \times 0.5 = 10 \text{ A}$$

iv) To obtain peak reverse blocking voltage (V_{BR})

The peak reverse blocking voltage should be greater than supply voltage i.e.,

$$V_{BR} \geq V_S \quad \text{i.e.} \quad V_{BR} \geq 48 \text{ V}$$

v) THD

Since the output waveform is square wave,

$$\text{THD} = 48.4\ \%\ \text{(fixed)}$$

3.3.3 Shoot through or Cross Conduction in Inverters

Definition of Cross Conduction

When the d.c. supply in inverters gets shorted through power devices of the same link, it is called cross conduction or shoot through.

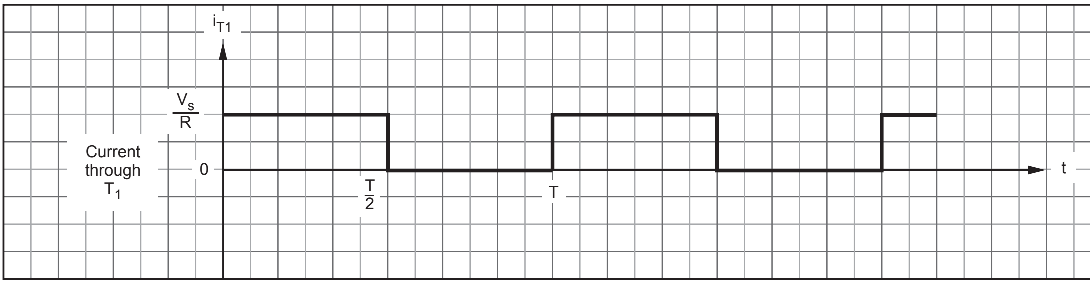


Fig. 3.3.10 Transistor current for 1ϕ bridge inverter

Effect : Due to cross conduction power devices are damaged.

Explanation

Fig. 3.3.3 shows the circuit diagram and Fig. 3.3.4 shows the waveforms of 1ϕ bridge inverter. Observe that at $\frac{T}{2}$, transistor T_1 is turned off and transistor T_4 is turned on. But due to switching delays, transistor T_1 may turn-off little after $\frac{T}{2}$. But by this time T_4 is turned on. Fig. 3.3.11 shows this situation.

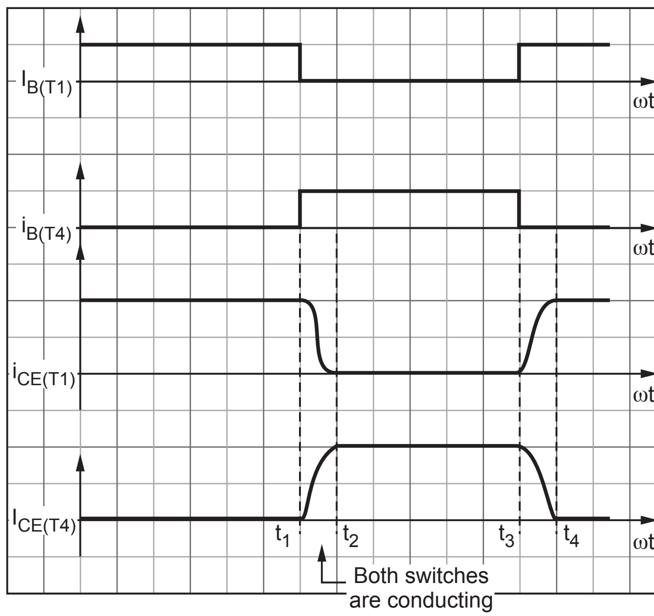


Fig. 3.3.11 Cross conduction in inverters

In this figure observe that in the time interval $t_1 - t_2$, $i_{CE(T_1)}$ is reducing and $i_{CE(T_4)}$ is increasing. Thus both T_1 and T_4 are in conduction state. This will short the DC supply through T_1-T_4.

How cross conduction is avoided ?

Cross conduction can be avoided by keeping the delay between the drives of switches in same link. For example, for single phase bridge inverter drives of T_1 and T_4 are delayed. Similarly drives of T_2 and T_3 are delayed.

Example 3.3.6 *For a single phase half bridge inverter DC input voltage is 200 V and feeds resistive load of 5 Ω. Determine,*

i) RMS output voltage *ii) The average current of each power MOSFET*

iii) The output power P_o *iv) 3^{rd} and 5^{th} harmonic rms content at output.*

SPPU : Dec.-2000; May-08, Marks 8

Solution : Given : Half bridge inverter

$$V_s = 200 \text{ V}, \quad R = 5\ \Omega$$

i) RMS output voltage

$$V_{o(rms)} = \frac{V_s}{2} = \frac{200}{2} = \mathbf{100\ V}.$$

ii) Average current of power MOSFET

Average current is given as,

$$I_{T(av)} = \frac{1}{T}\int_0^T i_T(\omega t)\, d\omega t = \frac{1}{T}\int_0^{T/2} \frac{V_s}{2R}\, d\omega t$$

$$= \frac{1}{T}\frac{V_s}{2R}\int_0^{T/2} d\omega t = \frac{1}{T}\cdot\frac{V_s}{2R}\cdot\frac{T}{2} = \frac{V_s}{4R}$$

Putting the values,

$$I_{T(av)} = \frac{V_s}{4R} = \frac{200}{4\times 5} = \mathbf{10\ A}$$

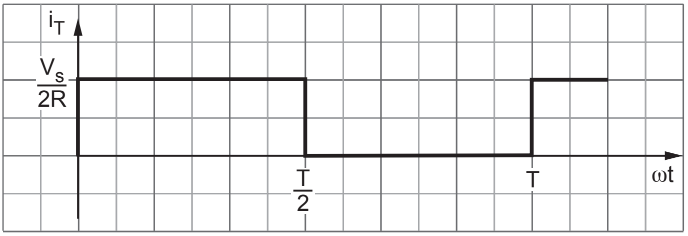


Fig. 3.3.12 Current waveform of power MOSFETs

iii) Output power P_o

$$P_o = \frac{V_{o(rms)}^2}{R} = \frac{100^2}{5} = \mathbf{2000\ Watt}$$

iv) RMS values of 3rd and 5th harmonics

RMS value of nth harmonic is given as,

$$V_{n(rms)} = \frac{0.45 V_s}{n}$$

$$\therefore \quad V_{3(rms)} = \frac{0.45\times 200}{3} = 30 \text{ V}$$

and $$V_{5(rms)} = \frac{0.45\times 200}{5} = \mathbf{18\ V}$$

Examples for Practice

Example 3.3.7 : *A single phase bridge inverter is operating from 230 V, 50 Hz ac supply rectified with LC filter. Find out rms output voltage, fundamental rms output voltage and fifth harmonic rms content in the output.*

SPPU : Dec.-01, Marks 5

[Hints and Ans. : $V_{o(rms)}$ = 325.27 V, $V_{o1(rms)}$ = 292.74 V, $V_{o5(rms)}$ = 58.57 V]

Example 3.3.8 : *A single phase bridge inverter having square wave output has the DC supply of 48 V and output resistance of 4.8 Ω.*
Determine i) r.m.s. value of output and ii) r.m.s. value of fundamental.

[Hints and Ans. : $V_{o(rms)}$ = 48 V and V_1 = 43.2 V]

Review Questions

1. *With the help of circuit diagram and waveforms, explain the working of 1ϕ bridge inverter.*
SPPU : Dec.01, Marks 10; Dec.-04, Marks 5, Dec.-08, Marks 4, Dec.-09, Marks 8; Dec.-10,15, May-07,10,11, Marks 6, May-12, Marks 9
2. *Write a short note on need for feedback diodes in inverters.*
SPPU : May-04,05, Marks 6; Dec.-10, Marks 3
3. *With the help of circuit diagram and waveforms explain the operation of full bridge inverter for an inductive load.* **SPPU : May-2000,10, Dec.-06, Marks 6**
4. *With the help of neat circuit diagram, mode equivalent circuits and waveforms of output voltage, output current, supply current and MOSFET current, explain the operation of a single phase square wave full bridge MOSFET inverter feeding RL load.*
SPPU : May-06, Marks 10; May-09, Marks 8
5. *What is shoot through fault ?* **SPPU : Dec.-06, Marks 2, Dec.-07, May-10,11, Marks 4**
6. *With the help of neat circuit diagram and waveforms, explain the working of single phase bridge inverter for R load. Derive the expression for RMS output voltage.*
SPPU : April-19 (In Sem). Marks 6
7. *Draw and explain single phase full bridge inverter for R-L load with o/p voltage and current waveforms.* **SPPU : April-15, Marks 5**
8. *Draw and explain single phase full bridge inverter for R-L load with o/p voltage and current waveforms.* **SPPU : April-16, Marks 6**
9. *Draw neat circuit diagram and explain single phase full bridge inverter with R-L load. Explain the effect of FWD on the operation of it.* **SPPU : Dec.-16, Marks 7**
10. *Draw and explain single phase full bridge inverter for R-L load with o/p voltage and current waveforms.* **SPPU : April-17, Marks 5**
11. *Explain 1-ϕ full bridge inverter for RL load using MOSFET draw necessary circuit diagram and waveforms.* **SPPU : Dec.-19, Marks 7**

3.4 Three Phase Voltage Source Inverters

SPPU : Dec.-06,07,08,09,11,13,15,16, April-15,16,17,19, May-07,08,11,12,13,15,17

Single phase inverters are used for low power applications. For higher powers and 3ϕ induction motor drives, 3ϕ inverters are used. An inverter generates 3ϕ output R,Y and B. The load can be connected to the inverter in star or delta mode. Fig. 3.4.1 shows the circuit diagram of a 3ϕ inverter which uses BJTs.

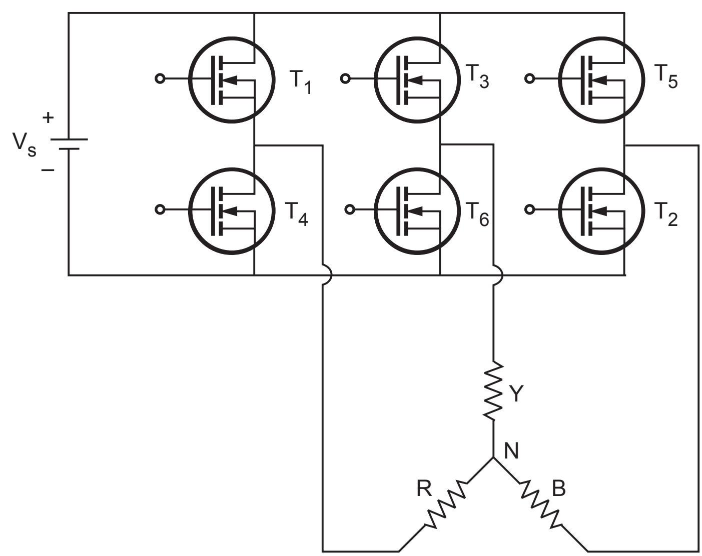


Fig. 3.4.1 Circuit diagram of 3ϕ bridge inverter with star load

As shown in above circuit, there are six MOSFETs, T_1, T_2, T_3, T_4, T_5 and T_6. Observe that the upper three MOSFETs are numbered as, T_1, T_3 and T_5. Similarly lower three MOSFETs are numbered as T_4, T_6 and T_2. Here T_1 and T_4 are connected to phase R. When T_1 conducts, R is connected to + V_s. When T_4 conducts, R is connected to $-V_s$. Similarly T_3 and T_6 are connected to y. And T_5 and T_2 are connected to B.

Depending upon the drives applied to MOSFETs, there are two types of 3ϕ inverters :

i) 180° conduction and ii) 120° conduction

In 180°, each MOSFET conducts for 180°, and in 120°, each MOSFET conducts for 120°.

3.4.1 180° Conduction Type 3 ϕ Inverter

The circuit diagram of Fig. 3.4.1 remains the same. The base drives of all the six MOSFETs are shown in Fig. 3.4.3. The base drive of T_1 is applied for 180° and it is off for remaining 180°. Base drive of T_2 is applied with 60° delay with respect to T_1.

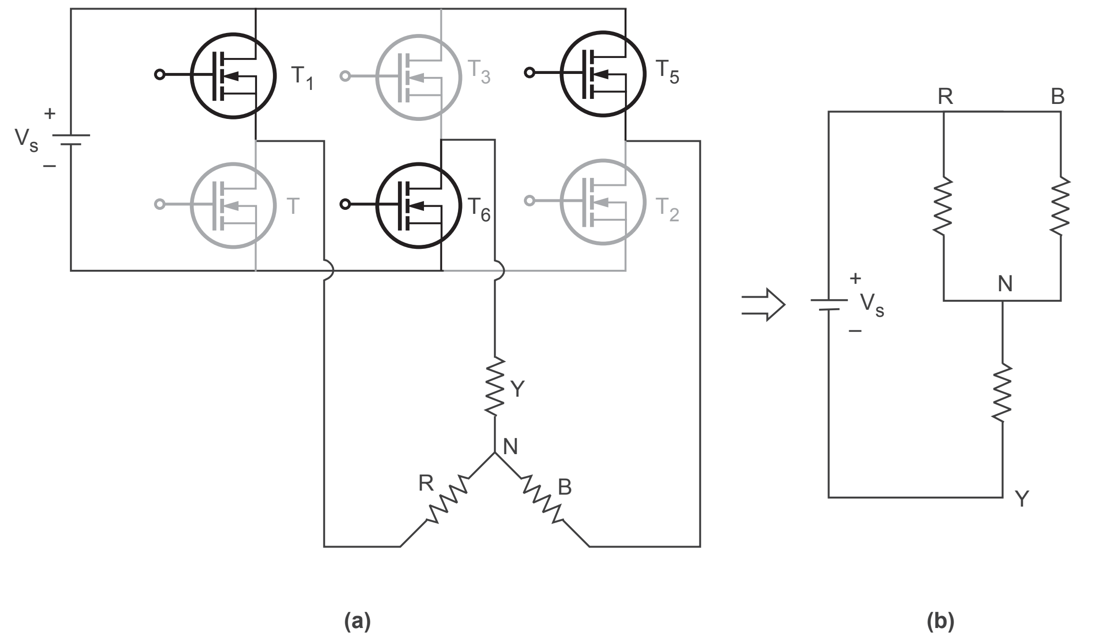


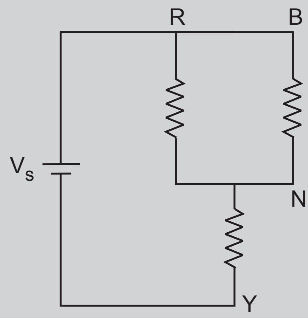
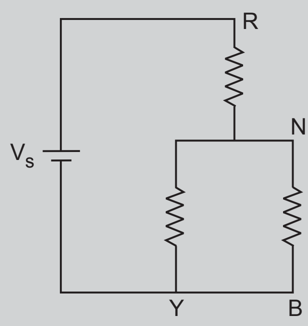
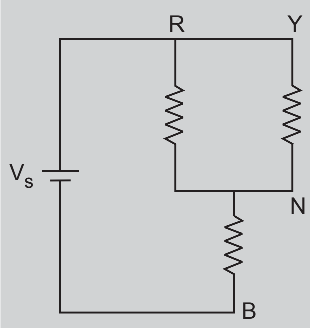
Fig. 3.4.2 Equivalent circuit for T_1, T_6, T_5 conduction

Similarly base drives of other MOSEFTs are also delayed by 60° with respect to previous one. One cycle of 360° is divided into six intervals of 60° each. These intervals are named as I, II III, IV, V and VI. In each interval three MOSFETs conduct. For example in interval I, T_1, T_5 and T_6 are applied the base drive. Thus in interval I, T_1, T_5 and T_6 are conducting. Fig. 3.4.2 shows an equivalent circuit for this interval. Normally the drop in MOSFETs can be neglected.

The simplified equivalent circuit is shown in Fig. 3.4.2 (b). Observe that 'R' is connected to $+V_s$ through T_1 and 'B' is connected to $+V_s$ through T_5. Similarly 'Y' is connected to $-V_s$ through T_6. Now the phase and line voltages can be easily evaluated i.e.,

$$V_{RY} = V_s, \quad V_{RN} = V_{BN} = \frac{V_s}{3}, \quad V_{YN} = -\frac{2V_s}{3}$$

Here it is assumed that all the phases of load have same resistance. This procedure is repeated for all the 6 intervals and shown in Table 3.4.1.

Interval	Conductintransistors	Equivalent circuit	Line voltage V_{RY}	Phase voltage, V_{RN}
I	5 6 1		V_s	$\frac{V_s}{3}$
II	6 1 2		V_s	$\frac{2V_s}{3}$
III	1 2 3		0	$\frac{V_s}{3}$

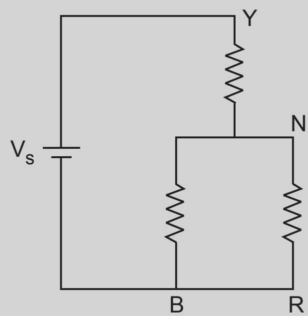
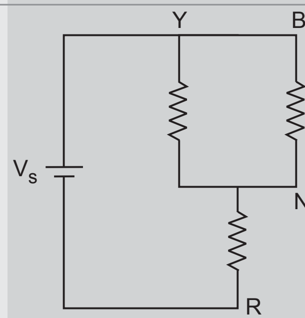
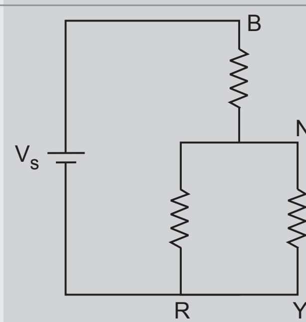
IV	2 3 4		$-V_s$	$-\frac{V_s}{3}$
V	3 4 5		$-V_s$	$-\frac{2V_s}{3}$
VI	4 5 6		0	$-\frac{V_s}{3}$

Table 3.4.1 : Analysis of 3 ϕ inverter (180° conduction)

Based on analysis given in Table 3.4.1, the waveforms are drawn in Fig. 3.4.3. Waveforms in Fig. 3.4.3 (a) are base drives of all the six MOSFETs. Observe that the successive base drives of delayed by 60°. Fig. 3.4.3 (b) shows the load voltage V_{RY}. It has maximum value of $\pm V_s$. It is quasi square wave. Voltages of other lines will be 60° delayed with respect to V_{RY}. All line voltages will have similar waveforms. Fig. 3.4.3 (c) shows phase voltage V_{RN}. It is six step waveform. Its values are $\pm \frac{2V_s}{3}$. The phase voltage V_Y and V_B are also similar to V_R. They have 120° phase shift with respect to each other. For example V_Y is lagging by 120° with respect to V_R. Thus the three phase AC output is generated by the inverter. For resistive loads, the phase current will be similar to phase voltage. Fig. 3.4.3 (f) shows current waveform for 'R' phase.

(See Fig. 3.4.3 on next page).

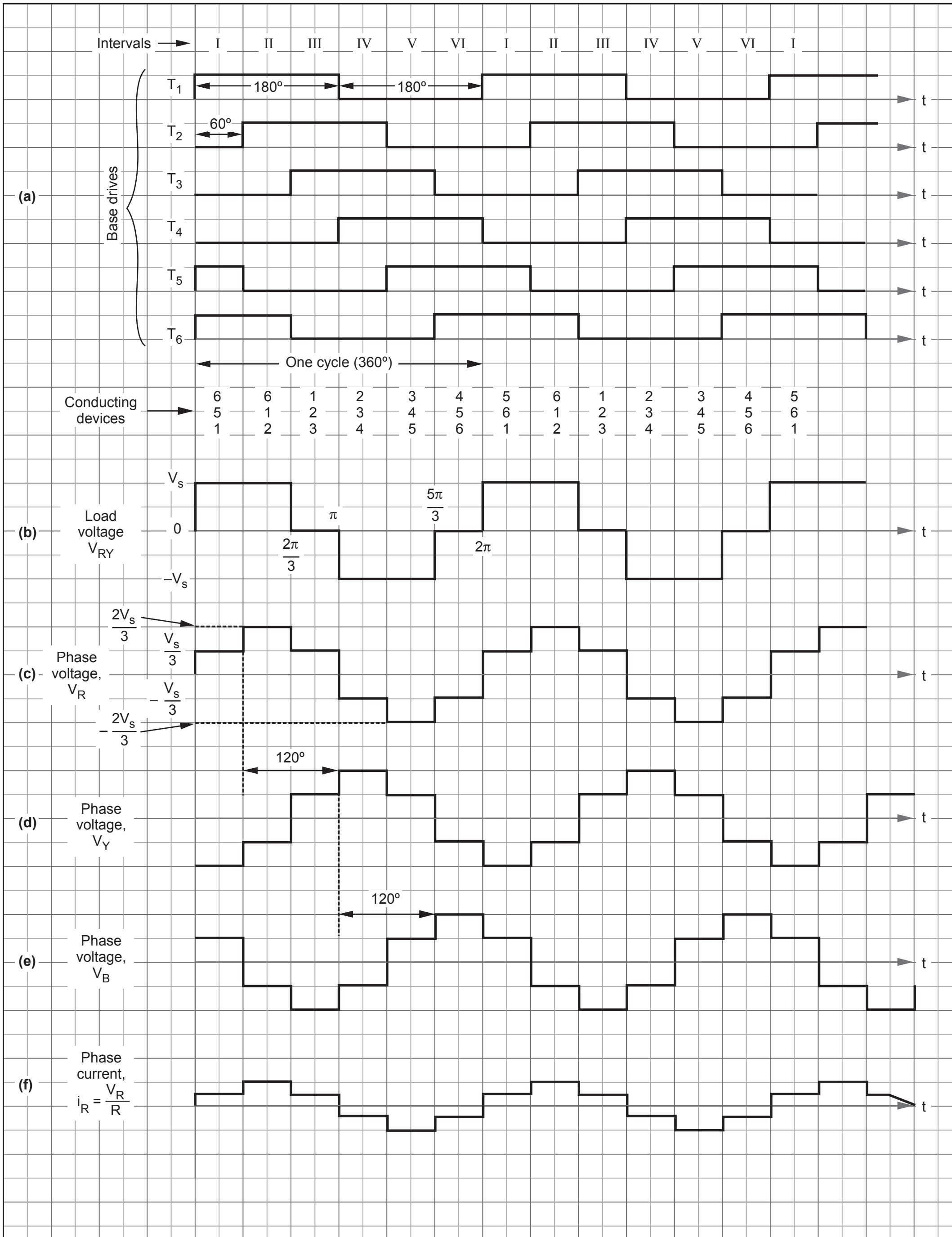


Fig. 3.4.3 Waveforms of 180° mode inverter

3.4.1.1 Mathematical Analysis of Waveforms

The line voltage is quasi square wave. It's rms value can be obtained as,

$$V_{line(rms)} = \left[\frac{1}{2\pi}\int_0^{2\pi} V_{RY}^2 \, d\,\omega\, t\right]^{\frac{1}{2}}$$

From waveforms of Fig. 3.4.3 (b),

$$V_{line(rms)} = \left\{\frac{1}{2\pi}\left[\int_0^{\frac{2\pi}{3}} V_s^2 d\,\omega\, t + \int_{\pi}^{\frac{5\pi}{3}} V_s^2 d\,\omega\, t\right]\right\}^{\frac{1}{2}} = \left\{\frac{1}{2\pi}V_s^2\left[\left(\frac{2\pi}{3}-0\right)+\left(\frac{5\pi}{3}-\pi\right)\right]\right\}^{\frac{1}{2}}$$

$$\therefore \quad \boxed{V_{line(rms)} = V_s\sqrt{\frac{2}{3}}} \qquad \ldots (3.4.1)$$

This equation is applicable to all the six line voltages. Now rms value of phase can be obtained by,

$$V_{ph(rms)} = \frac{V_{line(rms)}}{\sqrt{3}}$$

$$\therefore \quad \boxed{V_{ph(rms)} = \frac{\sqrt{2}}{3}V_s} \qquad \ldots (3.4.2)$$

This equation is applicable to all the three phase voltages.

The line voltage V_{RY} is quasi square wave. It can be expressed by Fourier series. i.e,

$$v_{RY} = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_s}{n\pi}\cos\frac{n\pi}{6}\sin n\left(\omega t+\frac{\pi}{6}\right) \qquad \ldots (3.4.3)$$

Similarly other line voltages can be expressed by Fourier series. Only they will be phase shifted. Above equation shows that line voltage contains only odd harmonics. The fundamental component of line voltage can be obtained by putting n = 1 in above equation i.e.,

$$v_1 = \frac{4V_s}{\pi}\cos\frac{\pi}{6}\sin\left(\omega t+\frac{\pi}{6}\right) \qquad \ldots (3.4.4)$$

$$= \frac{4V_s}{\pi}\cdot\frac{\sqrt{3}}{2}\sin\left(\omega t+\frac{\pi}{6}\right) = \frac{2\sqrt{3}V_s}{\pi}\sin\left(\omega t+\frac{\pi}{6}\right) \qquad \ldots (3.4.5)$$

Thus fundamental component of line voltage is sine wave with phase shift of $\frac{\pi}{6}$. Its peak value is $\frac{2\sqrt{3}V_s}{\pi}$. Hence rms value of fundamental component is,

$$V_{1(rms)} = \frac{V_{1(peak)}}{\sqrt{2}} = \frac{2\sqrt{3}V_s}{\pi} \cdot \frac{1}{\sqrt{2}}$$

$$\therefore \quad \boxed{V_{1(rms)} = 0.7797\ V_s} \qquad \ldots (3.4.6)$$

Example 3.4.1 *A 3 ϕ bridge inverter is operated from 200 V dc supply in 180° mode. Determine i) rms value of line voltage.*
ii) rms value of fundamental component of line voltage.

Solution : i) To obtain rms value of line voltage

The rms value of line voltage is given as,

$$V_{line(rms)} = V_s\sqrt{\frac{2}{3}} \quad \text{by equation (3.4.1)}$$

Here V_s = 200, hence above equation becomes,

$$V_{line(rms)} = 200\sqrt{\frac{2}{3}} = \mathbf{163.3\ V}$$

ii) To obtain rms value of fundamental component of line voltage

It is given by equation (3.4.6) as,

$$V_{1(rms)} = 0.7797\ V_s = 0.7797 \times 200 = \mathbf{156\ V}.$$

3.4.2 120° Conduction Type 3 ϕ Inverter

In the previous subsection we studied 3 ϕ inverter with 180° conduction. In 180° conduction, the base drives are applied for 180° duration. Similarly in 120° mode of conduction, the base drives are applied for 120° duration. The circuit diagram and method of analysis remains same as in 180° mode. The waveforms are shown in Fig. 3.4.5. There are six intervals : I, II, III, IV, V and VI. In each interval two transistors conduct. In interval I, T_1 and T_6 conducts. The equivalent circuit diagram is shown in Fig. 3.4.4.

In the above figure observe that phase 'R' is connected to $+V_s$ through T_1. Similarly phase 'Y' is connected to $-V_s$ through T_6. And phase 'B' is open. Fig. 3.4.4 (b) shows the simplified equivalent circuit. It neglects the drops between the BJTs. Now the phase voltage and line voltages are,

$$V_{RN} = \frac{V_s}{2}$$

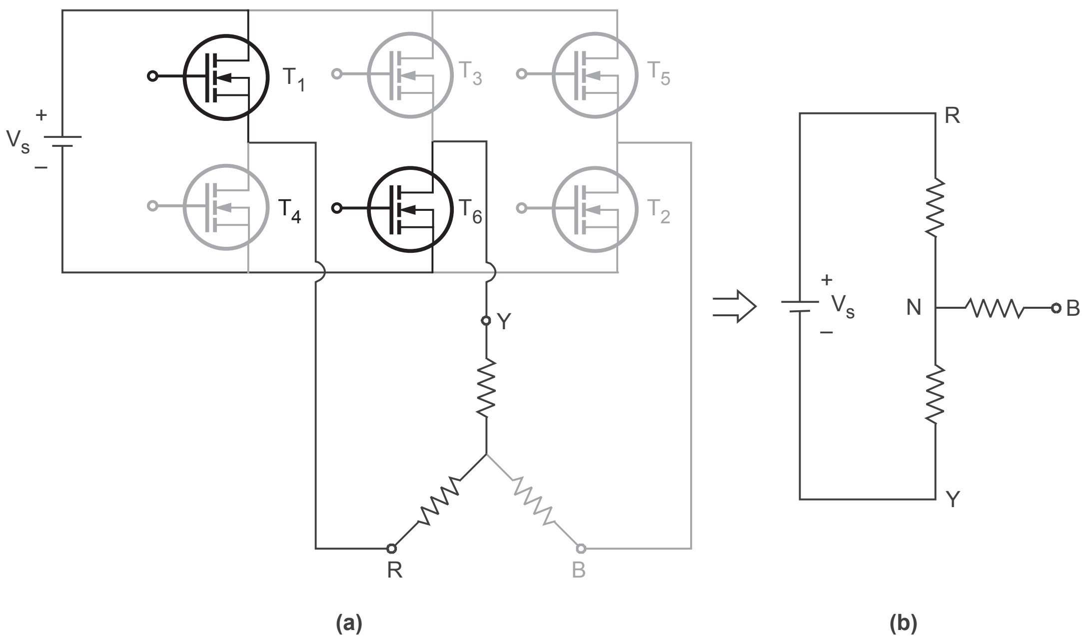


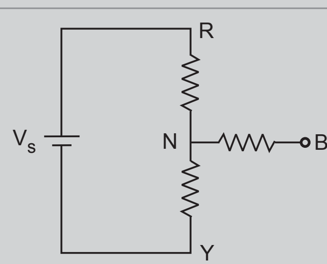
Fig. 3.4.4 Equivalent circuit when T_1 and T_6 conduct in interval I

$$V_{YN} = -\frac{V_s}{2}$$

$$V_{BN} = 0$$

$$V_{RY} = V_s$$

Similarly the voltages are obtained in each interval. Table 3.4.2 lists all the intervals, their equivalent circuits and corresponding line and phase voltages. Based on the analysis of Table 3.4.2, The waveforms are shown in Fig. 3.4.5. (See Fig. 3.4.5 on next page)

Interval	Conducting transistors	Equivalent circuit	Line voltage V_{RY}	Phase voltage V_{RN}
I	6 1		V_s	$\frac{V_s}{2}$

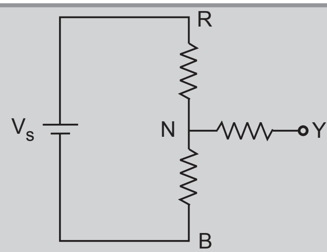
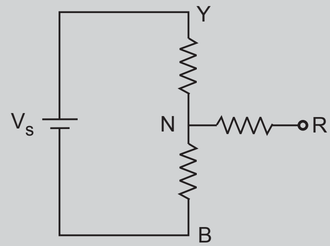
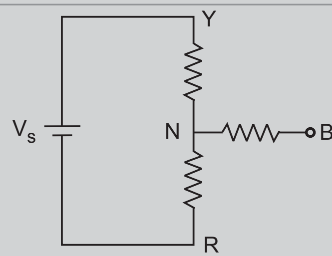
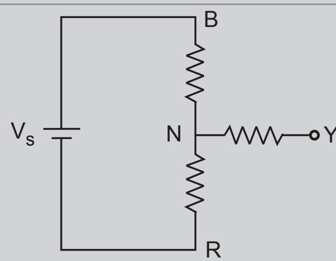
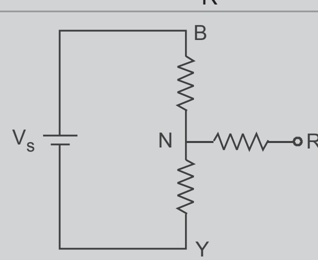
II	1 2		$\frac{V_s}{2}$	$\frac{V_s}{2}$
III	2 3		$-\frac{V_s}{2}$	0
IV	3 4		$-V_s$	$-\frac{V_s}{2}$
V	4 5		$-\frac{V_s}{2}$	$-\frac{V_s}{2}$
VI	5 6		$\frac{V_s}{2}$	0

Table 3.4.2 Analysis of 120° mode of conduction

In the base drives of Fig. 3.4.5 (a), observe that the successive base drives are delayed by 60°. Each BJT conducts for 120° and remains off for 240°. Therefore two devices conduct in any intervals. There are six intervals in one cycle of 360°. These intervals are marked as I, II, III, IV, V and VI. Fig. 3.4.5 (b) shows the line voltage waveform V_{RY} as per calculations in Table 3.4.2. Observe that it is a six step waveform. It has maximum

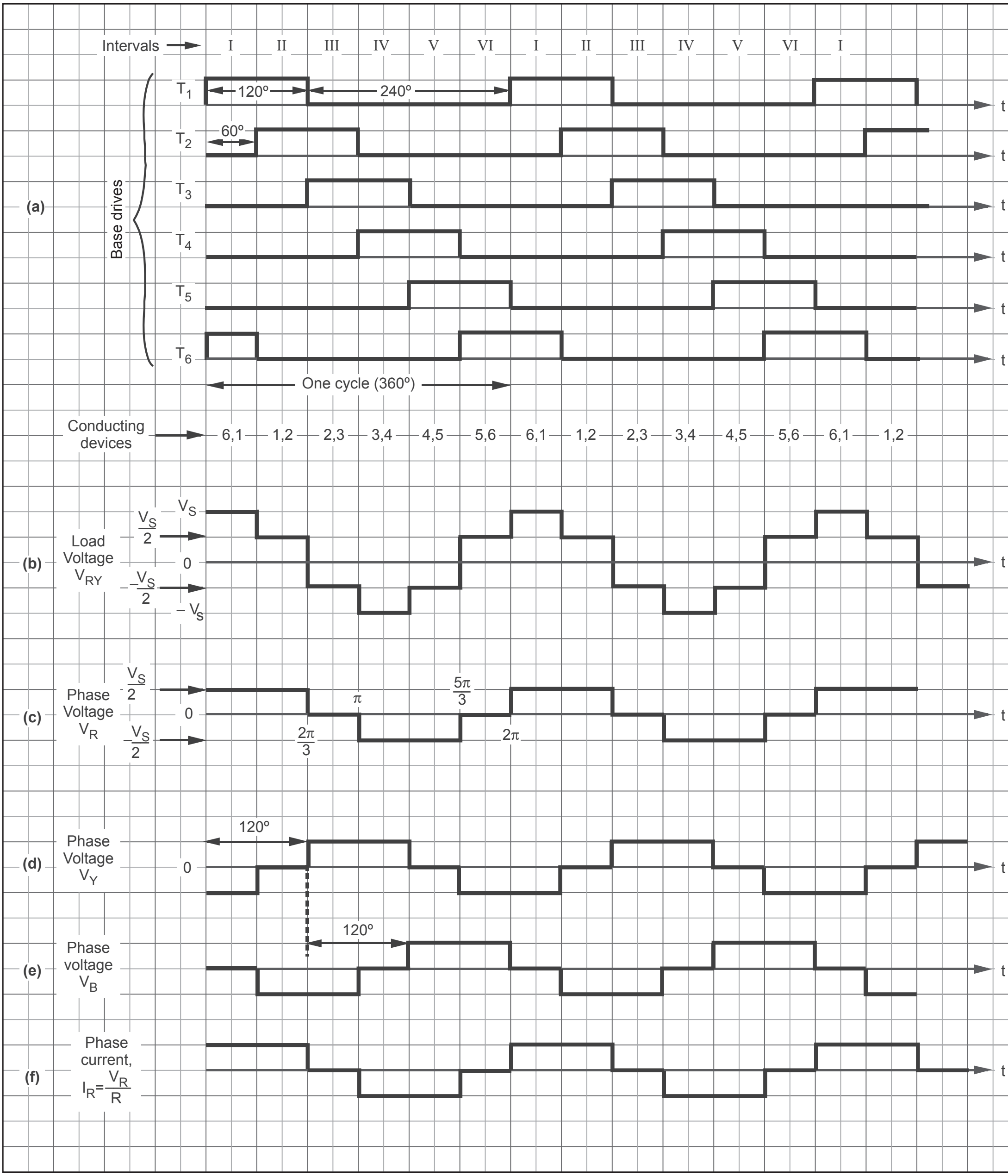


Fig. 3.4.5 Waveforms of 120º mode inverter

values of $\pm V_s$. Similarly other line voltages can be obtained they are phase shifted by 60° with each other. Fig. 3.4.5 (c), (d) and (e) shows the phase voltages. These voltages are quasi square waves. They are phase shifted by 120° with respect to each other. Fig. 3.4.5 (f) shows the phase current through R phase. It's waveform is similar to phase voltage.

3.4.2.1 Mathematical Analysis of 120° Mode Inverter

Fig. 3.4.5 (c) shows the waveform of phase voltage. RMS value of this voltage can be obtained as,

$$V_{ph(rms)} = \left[\frac{1}{2\pi}\int_0^{2\pi} V_R^2 \, d\,\omega\, t\right]^{\frac{1}{2}}$$

$$= \left\{\frac{1}{2\pi}\left[\int_0^{2\pi/3} \left(\frac{V_s}{2}\right)^2 d\,\omega\, t + \int_\pi^{\frac{5\pi}{3}} \left(-\frac{V_s}{2}\right)^2 d\,\omega\, t\right]\right\}^{\frac{1}{2}}$$

$$\therefore \quad \boxed{V_{ph(rms)} = \frac{V_s}{2}\sqrt{\frac{2}{3}}} \qquad \ldots (3.4.7)$$

Then line voltage can be obtained as,

$$V_{line(rms)} = \sqrt{3} V_{ph(rms)} = \sqrt{3}\cdot\frac{V_s}{2}\cdot\sqrt{\frac{2}{3}}$$

$$\therefore \quad \boxed{V_{line(rms)} = \frac{V_s}{\sqrt{2}}} \qquad \ldots (3.4.8)$$

The phase voltages can be expressed by Fourier series. For R-phase we can write,

$$v_R = \sum_{n=1,3,5,\ldots}^{\infty} \frac{2V_s}{n\pi}\cos\frac{n\pi}{6}\sin n\left(\omega t + \frac{\pi}{6}\right) \qquad \ldots (3.4.9)$$

Similarly other phase voltages (120° phase shift) can be represented. Above equation shows that only odd harmonics are prevent.

3.4.3 Comparison of 120° and 180° Modes of Conduction

Table 3.4.3 shows the comparison between the two operating modes of inverters.

Sr. No.	Parameter	180° mode	120° mode
1.	Conduction of the device	Each device conduct for 180°	Each device conducts for 120°
2.	Number of conducting devices in one interval	Three devices conduct in one interval	Two devices conduct in one interval.
3.	Line voltages	Quasi square wave with $\pm V_s$	Six step waveform with $\pm V_s$ and $\pm \frac{V_s}{2}$

4.	Phase voltages	Six step waveform with $\pm \frac{2V_s}{3}$ and $\pm \frac{V_s}{3}$	Quasi square wave with $\pm \frac{V_s}{2}$
5.	Possibility of cross conduction	Cross conduction is possible	Cross conduction is not possible
6.	Utilization of devices	Devices are better utilized	Devices are underutilized
7.	Output power	Output power is higher because of higher voltage levels	Output power is less because of lower voltage levels
8.	$V_{line(rms)}$	$V_s\sqrt{\frac{2}{3}}$	$\frac{V_s}{\sqrt{2}}$
9.	$V_{1(rms)}$	0.7797 V_s	0.6752 V_s

Table 3.4.3

Review Questions

1. *With the help of neat diagram and waveforms explain an operation of 180° mode of 3 φ inverters.* **SPPU : Dec.-06,09, Marks 8, Dec.-08, May-07, Marks 12, Dec.-11, Marks 5, Dec.-07, May-12, Marks 9, April-17 (In Sem), May-17**
2. *Explain 180 dgree conduction method of hree phase voltage source inverter for balanced star connected resistive load.* **SPPU : May-17, Marks 6**
3. *Explain 120° mode of 3φ inverters with the help of waveforms.* **SPPU : May-11, Dec.-06,13, Marks 8, May-07, Marks 12, May-08, Marks 10**
4. *Compare 120° and 180° modes of conduction of inverters.* **SPPU : Dec.-08, May-15, April-17 (In Sem), Marks 6**
5. *With the help of neat circuit diagram and waveform explain the working of 3 φ voltage source inverter R load with 120° conduction mode.* **SPPU : April-19 (In Sem), Marks 6**
6. *Explain 180° conduction mode of three phase inverter for balanced star R load with circuit diagram.* **SPPU : April-15,16, Marks 10, May-19 (End Sem), Marks 6**
7. *What is inverter ? Explain with diagram 3φ voltage controlled inverter with star load (R). Comment on waveforms and duty cycle.* **SPPU : Dec.-15, Marks 7**
8. *Explain with circuit diagram and waveforms three phase inverter with 180 degree conduction mode.* **SPPU : Dec.-16, Marks 7**

3.5 Voltage Control and Harmonic Elemination Techniques

SPPU : Dec.-01,02,07,19, May-07,08,17, April-17,19

The output voltage of the inverter needs to be varied as per load requirement. Whenever the input DC varies, the output voltage can change. Hence these variations needs to be compensated. In case of motor drives the ratio of voltage to frequency $\left(\frac{V}{f}\right)$ is maintained constant. The output voltage and frequency of the inverter is adjusted to keep $\frac{v}{f}$ constant. Similarly, in UPS the output voltage of inverter is to be regulated. These all the reasons indicate that the output voltage of inverter is to be controlled. The pulse width modulation (PWM) techniques are mainly used for voltage control. These techniques are most efficient and they control the drives of the switching devices.

Following are the PWM techniques :

i) Single pulse width modulation

ii) Multiple pulse width modulation

iii) Sinusoidal pulse width modulation

iv) Modified sinusoidal pulse width modulation

v) Phase displacement control.

Out of the above techniques, sinusoidal PWM techniques are most widely used. They control the output voltage as well as reduce the harmonics.

3.5.1 Sources of Harmonics

A power supply should show a perfectly sinusoidal voltage at every residential or industrial location. But, utilities find it difficult to preserve such conditions due to various reasons. The deviation of the voltage and current waveforms from sinusoidal is said to be harmonic distortion. A harmonic component in a power system is defined as a sinusoidal component of a periodic waveform having a frequency that is an integral multiple of the fundamental frequency.

The sources of harmonics in power system are :

- Rectifiers (AC-DC Converters).
- Inverters (DC-AC Converters).
- Choppers(DC-DC Converters).
- Uninterrupted Power Supplies (UPS).
- Switched mode power supplies (SMPS).
- Fluorescent lights (CFL).
- Static VAR compensators.
- Variable frequency motor drives (VFD).
- Power transformer.
- Ballast inductor.
- Cyclo-converters.
- Television sets.

- Personal computers.
- Synchronous machines.
- Induction machines.
- Washing Electric arc furnaces.
- Motor-soft start units.
- Pulse-burst heating.
- Soldering equipment.
- Mercury-vapor or high-pressure sodium lamps.
- Battery chargers.
- Refrigerators.
- Freezers.
- Machines.
- Air-conditioning devices.
- FAX machines.
- Printers.

Harmonics Elimination Techniques :

- Sinusoidal PWM (most common)
- Selected Harmonic Elimination (SHE) PWM
- Space-Vector PWM
- Instantaneous current control PWM
- Hysteresis band current control PWM
- Sigma-delta modulation.

3.5.2 Single Pulse Modulation (SM)

This modulation gives quasi-square wave output.

- Observe that there is single pulse of output voltage during each half cycle.
- The width of the pulse is '2d'. R.M.S. value of output voltage can be controlled by varying the pulse width.

Mathematical analysis

We have done the complete mathematical analysis of quasi-square wave inverter. The same analysis is applicable to single pulse modulation. Following are the relations in terms of 'd'.

$$a_n = 0 \qquad \text{for all 'n'}$$

$$b_n = \frac{4V_s}{n\pi} \sin \frac{n\pi}{2} \sin nd$$

$$= \pm \frac{4V_s}{n\pi} \sin nd \quad \text{for odd n.}$$

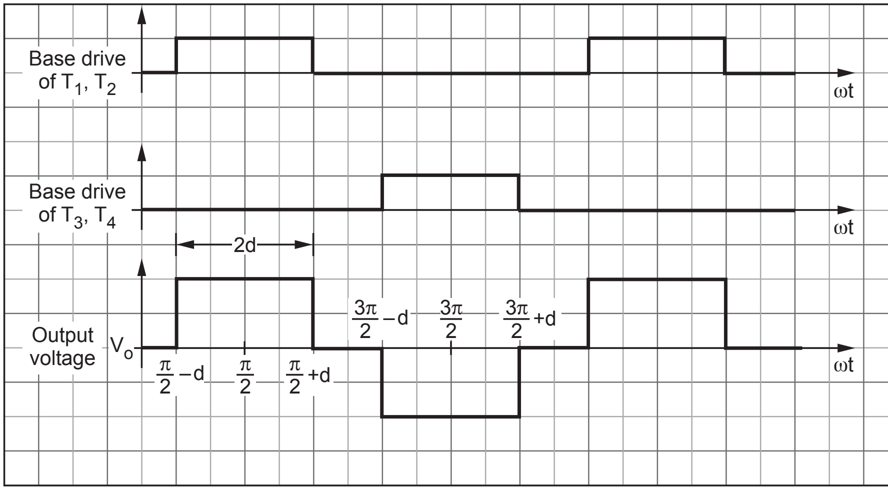


Fig. 3.5.1 Output voltage control using single pulse modulation

$$\therefore \qquad c_n = \sqrt{a_n^2 + b_n^2} = \frac{4V_s}{n\pi} \sin nd$$

$$\phi_n = \tan^{-1} \frac{a_n}{b_n} = 0$$

Fourier series will be,

$$v(\omega t) = \sum_{n=1,3,5,.......}^{\infty} \frac{4V_s}{n\pi} \sin nd \ \sin n\omega t$$

Fundamental component

$$V_{o1(rms)} = \frac{c_1}{\sqrt{2}} = \frac{\frac{4V_s}{\pi} \sin d}{\sqrt{2}}$$

$$= \frac{2\sqrt{2}\ V_s}{\pi} \sin d = 0.9\ V_s \sin d.$$

Generation of single pulse modulation

Fig. 3.5.2 shows how single pulse modulated output is generated.

The ratio of triangular signal amplitude (A_c) and square wave signal amplitude (A_r) is called modulation index. i.e.

$$\text{m} = \frac{A_r}{A_c}$$

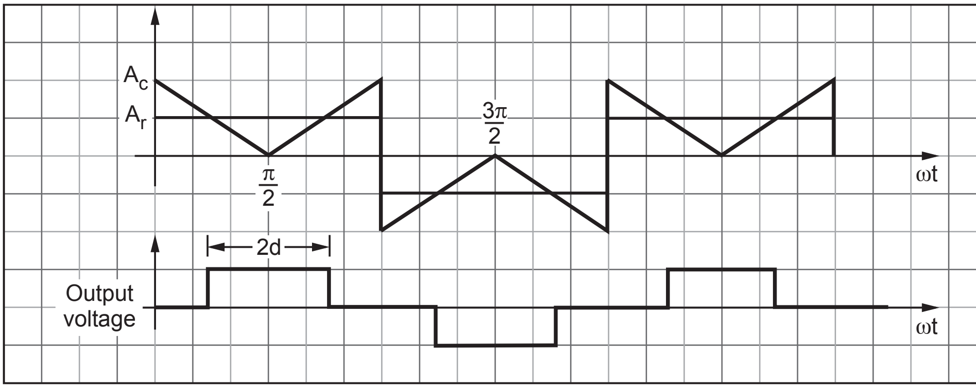


Fig. 3.5.2 Generation of SM output

The width of the pulse can be changed by varying the modulation index.

When m = 1, square wave output is obtained.

3.5.3 Multiple Pulse Width Modulation Technique

Principle : Multiple pulses are used to reduce the harmonic content. The width of all the pulses is same.

Waveforms and explanation

Fig. 3.5.3 shows the waveforms of multiple pulse width modulation.

- Fig. 3.5.3 (a) shows the carrier signal and the reference signal. The carrier signal is the triangular waveform and reference signal is the DC voltage.
- They are compared and the pulsed waveform of Fig. 3.5.3 (b) is obtained. The width of the pulse can be varied by changing the amplitude of DC reference signal. (See Fig. 3.5.3 on next page).
- Fig. 3.5.3 (c) and (d) shows two 50 Hz out of phase masking square waves. The pulsed waveform of Fig. 3.5.3 (b) is ANDed with these masking signals to obtain base drivers.
- Fig. 3.5.3 (e) shows the base drive of T_1 and T_2. And Fig. 3.5.3 (f) shows the base drive of T_3 and T_4.
- Fig. 3.5.3 (g) shows the output waveform of inverter. Observe that there are four pulses in each half cycle.

Mathematical analysis

Let f_c be the frequency of triangular wave and f_0 be the output frequency. Then number of pulses per half cycle is,

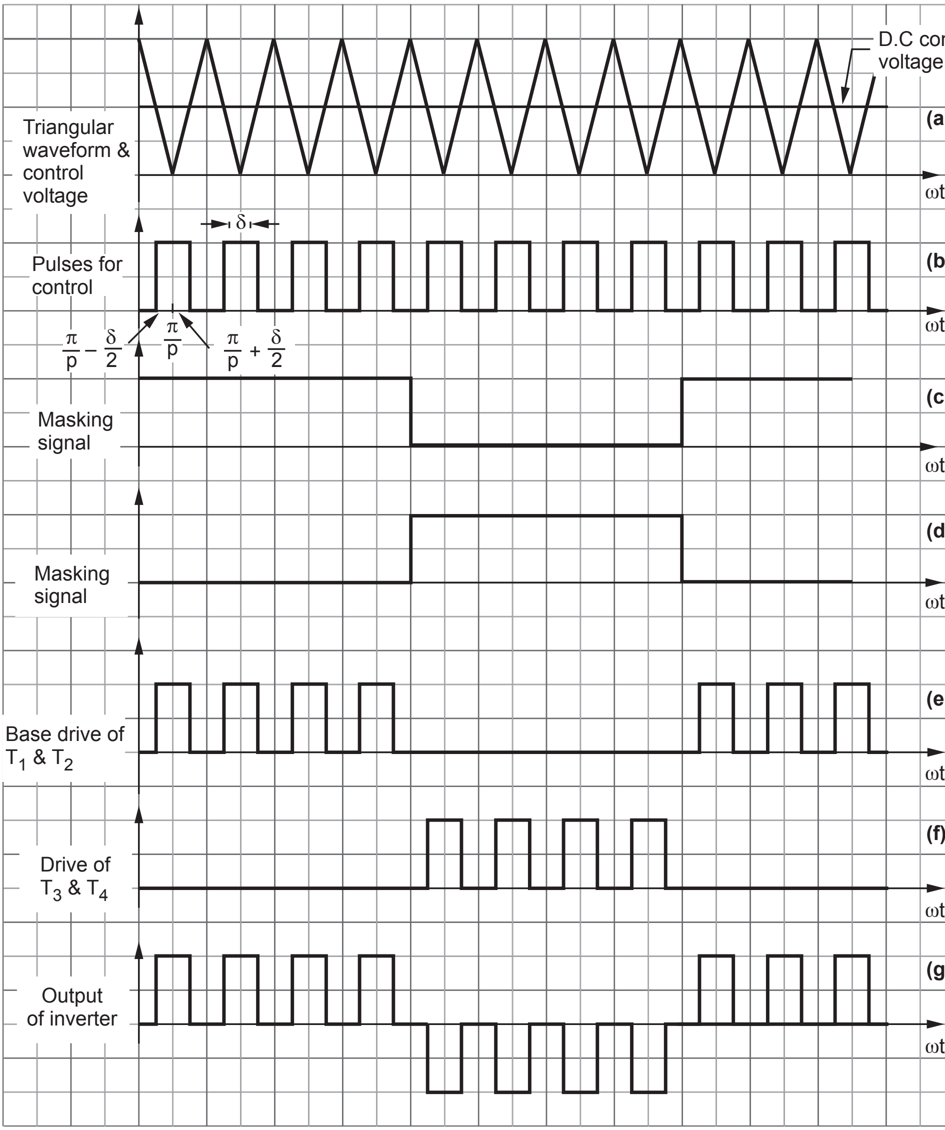


Fig. 3.5.3 Waveforms of multiple pulse width modulation

$$p = \frac{f_c}{2 f_0} = \frac{m_f}{2}$$

Here $m_f = \frac{f_c}{f_0}$ is called frequency modulation ratio. Minimum pulse width is zero, and maximum pulse width will be $\frac{\pi}{p}$.

Output rms value

$$V_{o(rms)} = \left[\frac{1}{T}\int_0^T v^2(\omega t)\, d\omega t\right]^{1/2}$$

Let the period $T = 2\pi$. In this period there are $2p$ pulses of equal width. Consider the first pulse, which is located at $\frac{\pi}{p}$. Then its width is $\frac{\pi}{p}-\frac{d}{2}$ to $\frac{\pi}{p}+\frac{d}{2}$. Let us calculate rms value of first pulse and multiply by 2p to get rms value of complete waveform,

$$V_{o(rms)} = \left[\frac{1}{2\pi}\int_{\frac{\pi}{p}-\frac{d}{2}}^{\frac{\pi}{p}+\frac{d}{2}} V_s^2\, d\omega t\right]^{1/2}$$

$$= \left[\frac{1}{2\pi}\cdot V_s^2\cdot\left(\frac{\pi}{p}+\frac{d}{2}-\frac{\pi}{p}+\frac{d}{2}\right)\right]^{1/2}$$

$$= V_s\sqrt{\frac{pd}{\pi}} \qquad \text{... (3.5.1)}$$

Thus by varying the width 'δ', output rms voltage can be changed.

Advantages

i) Distortion factor is reduced compared to single pulse modulation.

ii) As value of 'p' increases amplitudes of lower harmonics reduces.

Disadvantages

i) With increased number of pulses, switching losses are increased.

ii) Control scheme is complex.

3.5.4 Sinusoidal PWM (SPWM)

The sinusoidal pulse width modulation (PWM) is most widely used method of voltage control in inverters. The width of each pulse is weighted by the amplitude of sine wave at that instant. Fig. 3.5.4 shows the scheme of generating sinusoidal PWM. The carrier signal is a triangular wave of frequency 'f_c' and amplitude 'V_c'. The control signal is a sine wave of frequency 'f' and amplitude 'V_r'. Here 'f' becomes the frequency of the output of inverter. The sine wave and triangular waves are compared and the PWM signal is prepared as shown in Fig. 3.5.4. From this PWM, the drives for the MOSFETs in the inverter are prepared. Fig. 3.5.4 (e) shows the output waveform of the bridge inverter when sine PWM drives are applied. Note that the widths of the pulses are sine weighted. In the waveform of Fig. 3.5.4, there are three pulses per half cycle.

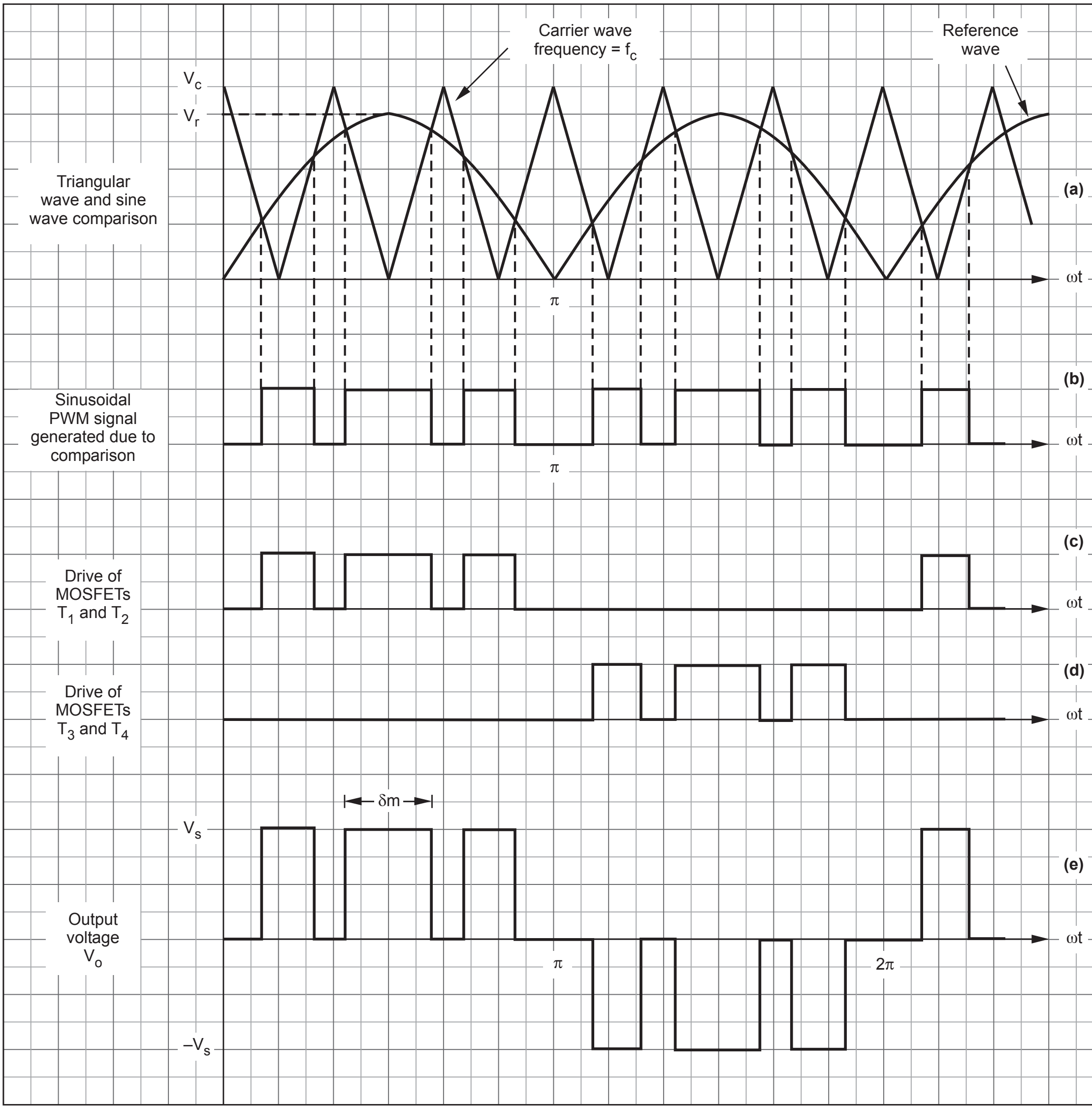


Fig. 3.5.4 Scheme of generating sinusoidal PWM and corresponding inverter output

The widths of the pulses depend upon the amplitude (V_r) of the sine wave. If amplitude is increased, widths increase. The ratio of V_r to V_c is called modulation index. i.e.,

Modulation index, $$m = \frac{V_r}{V_c} \quad \text{... (3.5.2)}$$

The rms value of output voltage of the inverter depends upon widths (δ_m) of the pulses. These widths depend upon modulation index 'm'. Thus modulation index 'm' controls the output voltage of the inverter. The output voltage increases as the modulation index increases. The modulation index can be varied by changing the amplitude of the reference signal (i.e. sine wave). The rms value of the output voltage is given as,

$$V_{o(rms)} = V_s \left[\sum_{m=1}^{p} \frac{\delta_m}{\pi} \right]^{\frac{1}{2}} \qquad \text{... (3.5.3)}$$

Here δ_m is width of the m^{th} pulse

and p is the number of pulses per half cycle.

The number of pulses 'p' depends upon frequency of the carrier i.e. f_c. It is given as,

$$p = \frac{f_c}{2f} = \frac{m_f}{2} \qquad \text{... (3.5.4)}$$

Here $m_f = \frac{f_c}{f}$ is frequency modulation ratio.

The sine PWM (SPWM) eliminates all the harmonics less than $(2p-1)$. For example if there are three pulses per half cycle, then lowest harmonics present will be $(2\times 3-1)=5$. Thus 2^{nd}, 3^{rd} and 4^{th} harmonics will be absent. Thus it is desirable to use more number of pulses to eliminate more harmonics. But more number of pulses increases switching losses in the devices. Hence the optimum value of the pulses is selected.

3.5.5 Modified Sinusoidal PWM (MSPWM)

The widths of the pulses near peak of the sine wave do not change much when modulation index is changed. Hence carrier is suppressed at ± 30° in the neighborhood of peak of sine wave. Such scheme is shown in Fig. 3.5.5. Observe that the triangular wave is present for the period of first 60° and last 60° of the half cycle of sine wave. The middle 60° of the sine wave do not have the triangular wave. Hence the generated PWM have less number of pulses. The rms value is more for the same modulation index. The harmonic content is also reduced. This control scheme also reduces switching losses. The implementation of this scheme is relatively complex than sine PWM. (Refer Fig. 3.5.5 on next page)

3.5.6 Phase Displacement Control

Principle

The two inverters are connected in parallel. Output of one inverter is phase shifted with respect to another inverter. The net output depends upon phase shift between the two inverter outputs.

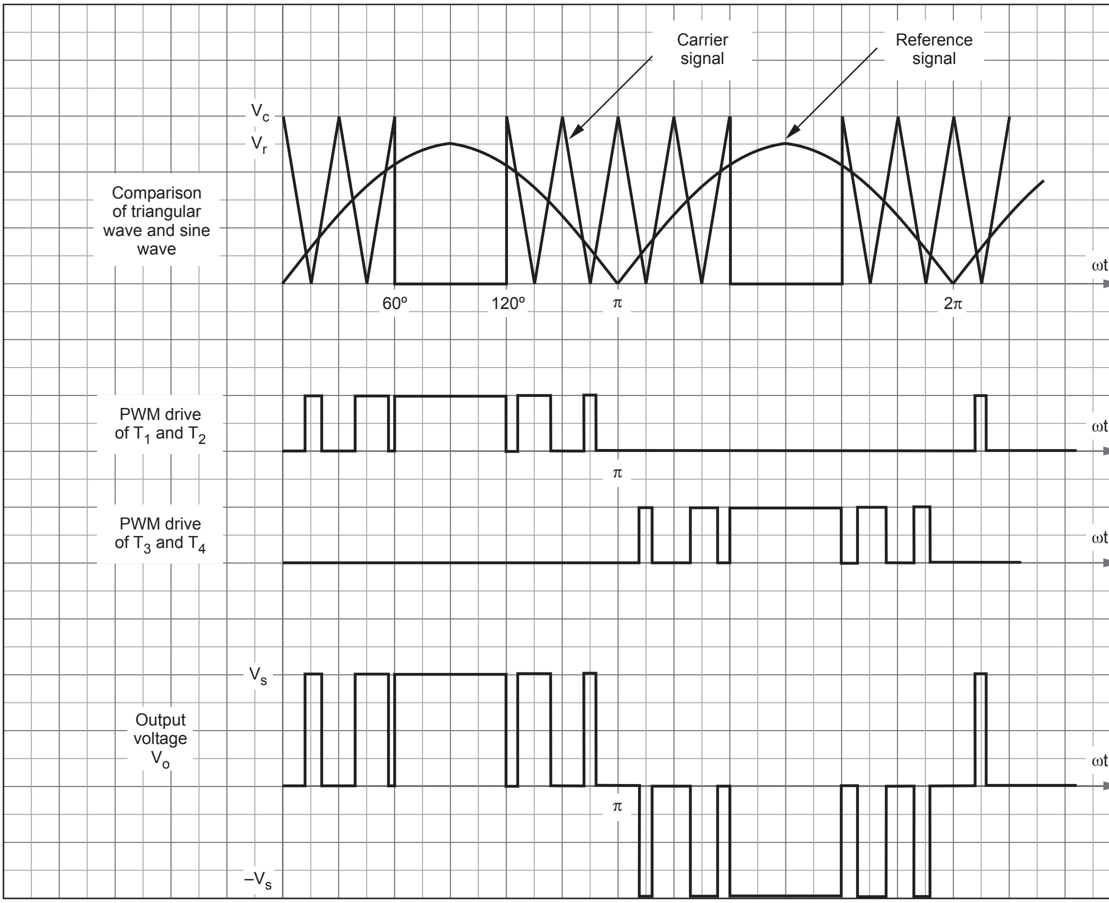


Fig. 3.5.5 Waveforms of modified sinusoidal PWM

Waveforms

Fig. 3.5.6 shows the waveforms of this scheme. Fig. 3.5.6 (a) and (b) shows the output voltage waveforms of inverter – 1 and inverter – 2. The voltage levels of output are $\frac{V_s}{2}$ in both the inverter outputs. Output of second inverter is phase shifted with respect to first inverter by 'β'. The final output is the difference of two inverter outputs. i.e.,

$$v_o = v_{o1} - v_{o2}$$

Note that $v_o = v_s$ when the two inverter outputs are out of phase. Output voltage can be controlled by varying the phase shift 'β'.

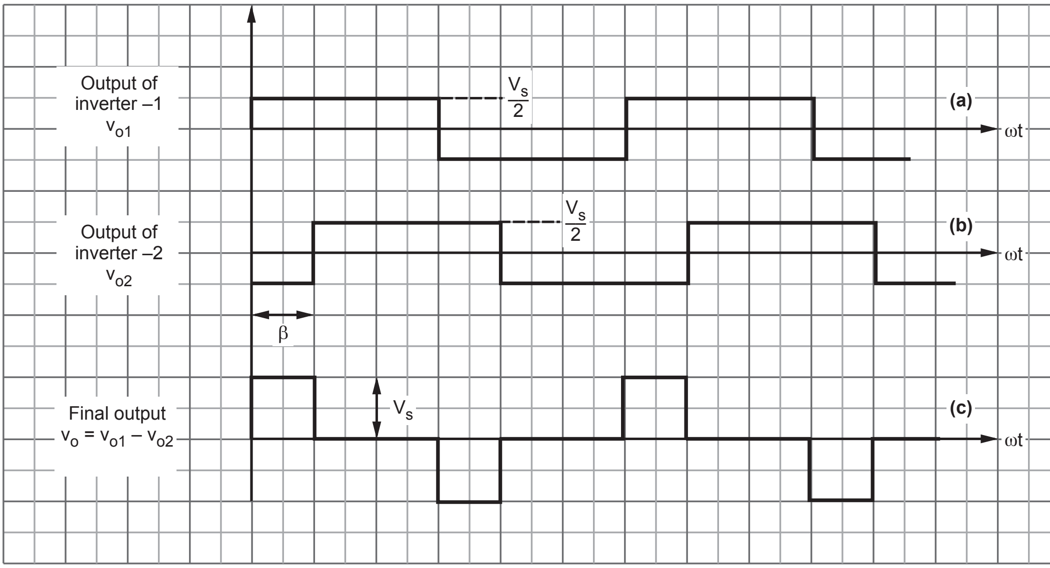


Fig. 3.5.6

3.5.7 Advantages of PWM Inverters

i) Harmonic content of PWM inverters is less compared to square wave inverter for same fundamental voltage.

ii) Voltage control and harmonic reduction can be simultaneously obtained within an inverter.

iii) PWM inverters give sine wave output for motor loads. This is far better than square wave.

iv) V/f ratio can be maintained constant in PWM inverters.

Example 3.5.1 *Derive an expression for rms value of output of the inverter having phase displacement control. Assume that the two inverters are supplied with voltage $V_s/2$.*

Solution : Fig. 3.5.6 (c) shows the waveforms of such inverter control. The rms value is given as,

$$V_{o\,(rms)} = \left[\frac{1}{T}\int_0^T v_o^2(\omega t)\,d\omega t\right]^{1/2} = \left[\frac{1}{\pi}\int_0^{\beta} V_s^2\,d\omega t\right]^{1/2}$$

$$= \left\{\frac{1}{\pi} V_s^2 [\omega t]_o^{\beta}\right\}^{1/2}$$

$$= V_s\sqrt{\frac{\beta}{\pi}} \qquad \dots (3.5.5)$$

And the rms value of fundamental output voltage is given as,

$$V_{o1(rms)} = 2\sqrt{2}V_s \sin\frac{\beta}{2} \quad \ldots (3.5.6)$$

Example 3.5.2 *Considering a single phase bridge inverter, explain the phase displacement method of output voltage control. If the dc voltage is 200 V and the required rms fundamental output voltage is 90 V, determine the delay angle β.*

Solution :

Here $V_s = 200$ V and $V_{o1\,(rms)} = 90$ V

From equation (3.5.6),

$$V_{o1\,(rms)} = 2\sqrt{2}\,V_s \sin\frac{\beta}{2}$$

Putting the values,

$$90 = 2\sqrt{2} \times 200 \sin\frac{\beta}{2}$$

$$\therefore \quad \beta = 18.3^\circ$$

Review Questions

1. *State the various techniques of voltage control in inverters. Explain the sinusoidal PWM technique.* **SPPU : Dec.-01, Marks 10**
2. *Explain the selective elimination of harmonics. How it is done ?*
3. *Write short notes on*
   i) Modified sinusoidal PWM
   ii) Feedback operation in inverter
   iii) Harmonic distortion in inverter. **SPPU : May-08, Marks 8**
4. *What are the advantages of PWM inverters.* **SPPU : Dec.-02,07, Marks 4**
5. *State the need for voltage control and harmonic reduction in invertors.*
6. *List the different switching technique used for single phase inverter to produce a quasi-square wave and explain any one of them.* **SPPU : May-07, Marks 8**
7. *What are voltage control methods of inverter ? Explain any one technique.* **SPPU : May-18 (End Sem) Marks 6**
8. *Explain single pulse PWM and sinusoidal PWM control technique for 1ϕ inverter.* **SPPU : Dec.-18 (End Sem), April-17,19 (In Sem), Marks 7**
9. *Explain 180 degree conduction method of three phase voltage source inverter for balanced star connected resistive load.* **SPPU : May-17, Marks 6**
10. *List out the different voltage control techniques used in inverters ? Explain any one in detail ?* **SPPU : Dec.-19, Marks 6**

3.6 Matrix Inverter or Matrix Converters

SPPU : May-16

Principle

Bidirectional switches are used to achieve conversion of power from AC to AC. There is no DC link. Matrix converters have single stage of conversion.

Matrix Inverter Circuit :

- Fig. 3.6.1 shows 1ϕ matrix converter. The pairs of $S_1 - S_1'$, $S_2 - S_2'$, $S_3 - S_3'$ and $S_4 - S_4'$ form bidirectional switches. These switches have ability to conduct in both the directions.

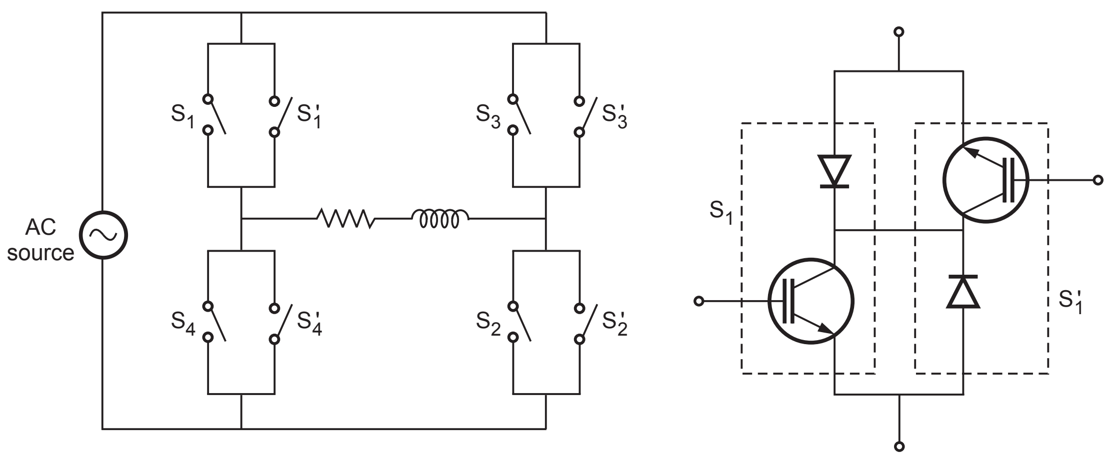


Fig. 3.6.1 Matrix inverter

- Three phase matrix converter uses nine bidirectional switches. Hence such matrix converter can have 2^9 = 512 switching states combinations.
- The switching combinations of matrix converter should be selected in such a way that input phases should never be short circuited and output current should never be interrupted.

Methods of matrix converter control :

The matrix converters can be controlled by following methods :

i) Space vector modulation

ii) Pulse width modulation

iii) Venturi-analysis of function transfer.

Advantages of matrix converters :

i) Sinusoidal input and output waveforms

ii) Minimum higher order harmonics

iii) Inherent bidirectional energy flow capability

iv) Input power factor can be fully controlled

v) Minimal energy storage requirements

vi) Matrix of switching is programmable.

Disadvantages of matrix converters :

i) Maximum voltage transfer ratio is limited to 87 % for sinusoidal input and output waveforms.

ii) More semiconductor devices are required.

iii) Sensitive to disturbances in input voltages.

Review Question

1. *Write short notes on any two : PWM techniques.* **SPPU : May-16, Marks 2**

3.7 Multilevel Inverters, their Topologies and Driver Circuits

The multilevel converters provide output in more than two levels. Conventional inventors have two level output in terms of 0 and V_s volts. But these two level converters are not suitable for all applications due to various reasons.

3.7.1 Need for Multilevel Inverters

1) High power ratings are not achieved by two level inverter.

2) Smithing losses are increased at high frequencies. Multilevel inverters can be designed at low frequencies.

3) High power ratings are obtained with low ratings of devices.

4) Multilevel inverters have reduced harmonic content even at low switching frequencies.

5) Large step up transforms are required to obtain voltages higher then $\pm V_s$.

6) PWM gives reduced harmonic content but higher switching losses.

7) Harmonic content of multilevel inverters reduce significantly if number of levels are increased.

3.7.2 Concept of Multilevel

- Fig. 3.7.1 shows the concept of multilevel. The DC supply V_s has four capacitors C_1, C_2, C_3 and C_4 connected across it. Hence voltage across each capacitor will be $\frac{V_s}{4}$.
- Note that $V_1 = 0$, i.e. voltage at point 'C'. $V_2 = \frac{V_s}{4}$, $V_3 = \frac{V_s}{2}$, $V_4 = \frac{3V_s}{4}$ and $V_5 = V_s$ these voltages are applied to the multilevel inverter.

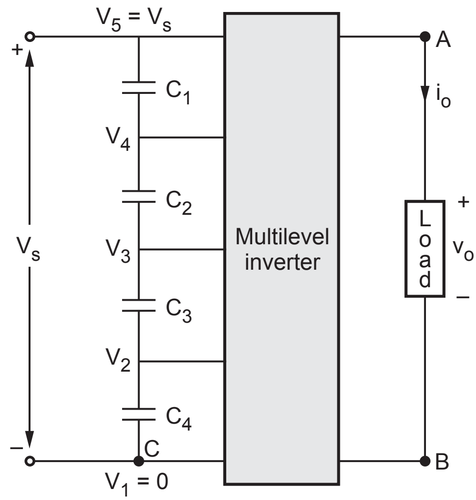


Fig. 3.7.1 Multilevel inverter

- In the positive half cycle the voltage at point 'A' with respect to point 'C' is observed. It is represented as V_{AC} in Fig. 3.7.2.

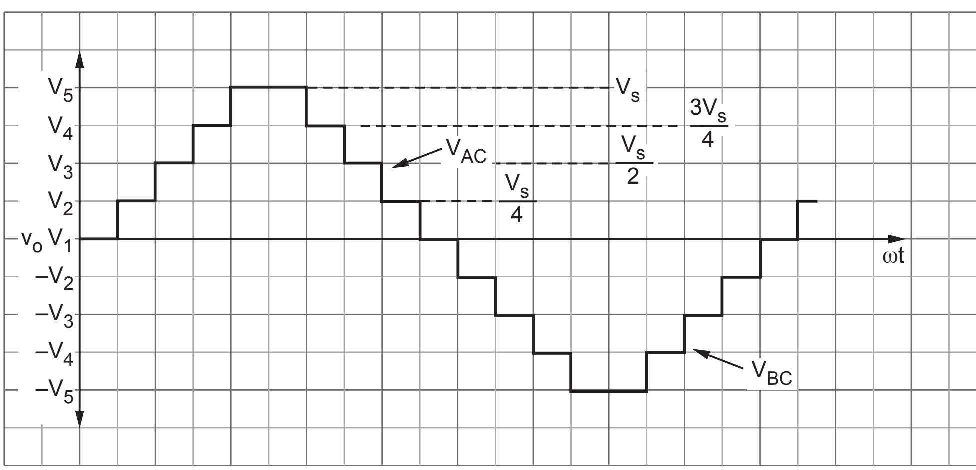


Fig. 3.1.2 Output voltage waveform of 5-level inverter

- Observe that voltages V_1, V_2, V_3, V_4 and V_5 are applied across points A-C. Hence multiple level output is obtained. The switches in multilevel inverter are switched ON/OFF accordingly.
- Similarly voltage V_{BC} forms negative half cycle. The voltage of load point 'B' with respect to 'C' is observed. The voltage level $V_1, -V_2, -V_3, -V_4$ and $-V_5$ are applied depending upon switch ON/OFF positions of inverter. Thus multilevel output waveform is obtained.
- The net output is $v_0 = V_{AB} = V_{AC} - V_{BC}$.

3.7.3 Topologies for Multilevel Inverters

Multilevel inverters can be always 1ϕ or 3ϕ type. The basic topologies are :

1) **Diode clamped multilevel inverter :** The voltage levels are provided by clamping diodes across switches.
2) **Flying capacities multilevel inverter :** The voltage levels are provided by flying capacitors connected across the switches.
3) **Cascaded H - bridges multilevel inverter :** Bridge inverters are connected in cascade and their individual outputs are added upto provide multilevel output.

3.7.4 Diode Clamped Multilevel Inverters

- **Principal :** This type of inverter uses clamping diodes and cascaded DC capacitors to produce multilevel ac output voltages waveform.
- The *m* - level diode clamped multilevel inverter consists of (m–1) capacitors cascaded across the DC supply. It produces '*m*' levels of load phase.

3.7.5 5 - Level Diode Clamped Multilevel Inverter

- Fig. 3.7.3 shows the circuit diagram of 1ϕ five level diode clamped multilevel inverter. In this circuits there are 4 capacitors C_1, C_2, C_3 and C_4. Voltage across each capacitor is $\frac{V_s}{4}$ since all the capacitors have same value.

Thus

$$V_1 = 0 \text{ Volts}$$

$$V_2 = \frac{V_s}{4}, \quad V_3 = \frac{V_s}{2}, \quad V_4 = \frac{3V_s}{4} \quad \text{and} \quad V_5 = V_s \text{volts.}$$

- One leg of the inverter consists of 4 switches (T_1, T_2, T_3 and T_4) on positive side and 4 switches (T_1', T_2', T_3' and T_4') on the negative side. All the switches have antiparallel diodes connected across them.
- $D_1, D_2\ D_3$ and D_1', D_2', D_3' are capacitor voltage clamping diodes. These diodes are responsible for applying appropriate level of voltage across the load. In the circuit diagram $D_2 \times 2$ means two D_2 diodes connected in series. Similarly $D_3' \times 3$ means three D_3' diodes are connected in series. Such series connections of similar clamping diodes reduces the voltage rating required for diodes.
- The load can be inductive. It is connected between points '*A*' and '*B*' of two legs of invertor. Note that $v_0 = V_A - V_B$. If we calculate V_A and V_B with respect to '0' volts (the '0' volts line is named as point '*C*' in Fig. 3.7.1) of DC supply then

$$v_0 = V_{AC} - V_{BC}$$

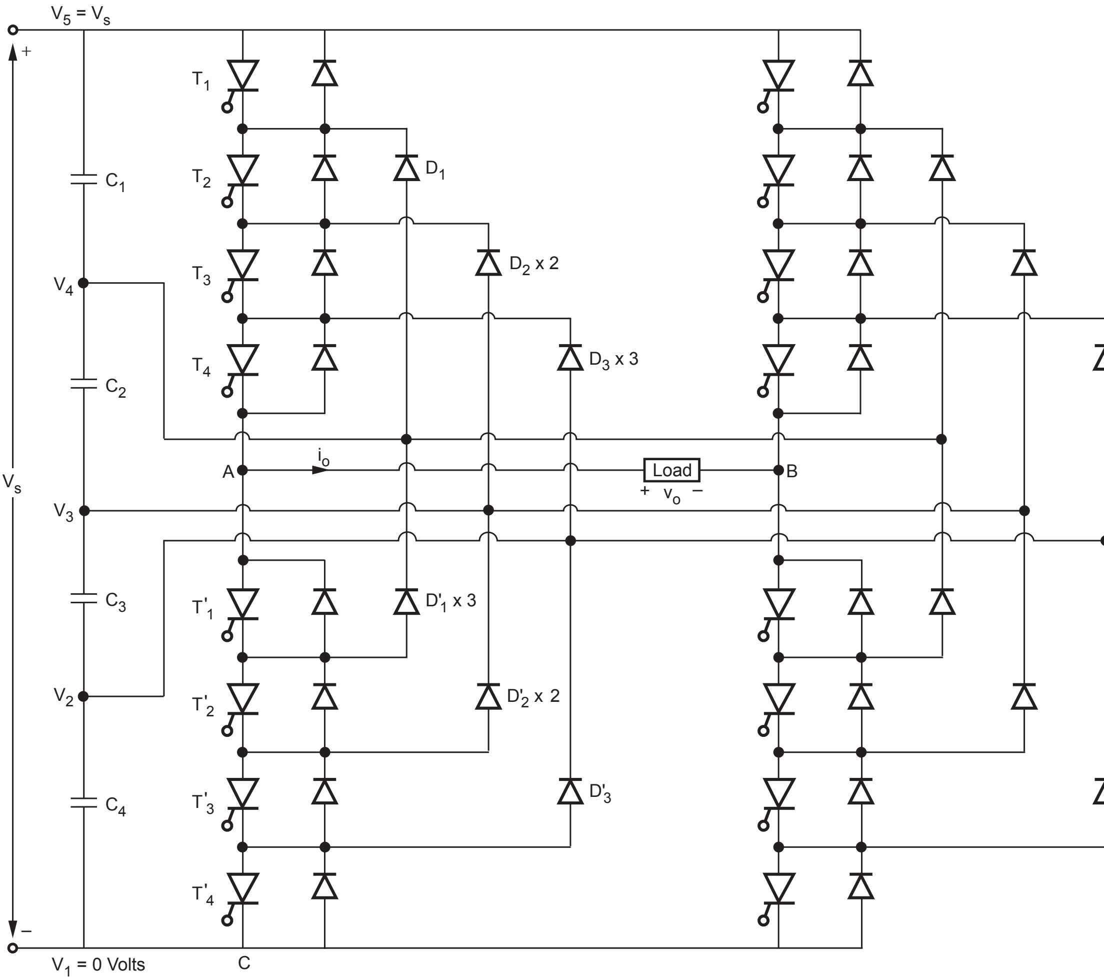


Fig. 3.7.3 5-level diode clamped multilevel inverter

Note that point 'C' is used as a reference to calculate V_A and V_B.

- The load current i_0 flows from point 'A' to 'B'. It is termed as positive current.
- Voltage V_4 is applied at junction of D_1 and $D_1' \times 3$. Similarly V_3 is applied at junction of $D_2 \times 2$ and $D_2' \times 2$. And V_2 is applied at junction of $D_3 \times 3$ and D_3'.
- The other leg of inverter has similar switches, antiparallel diodes and clamping diodes. The capacitor connections are also similarly given. In other words, both the legs of inverter are exactly identical.

Review Questions

1. *Why multilevel inverter is required ?*
2. *Draw the circuit diagram and waveforms of 5 - level diode clamped invertor. Explain its working.*

3.8 Applications of Inverters

SPPU : May-2000

i) Induction motor drives.

ii) Uninterruptible power supplies.

iii) Standby power supplies.

iv) Induction heating.

v) Electronic ballasts.

Review Question

1. *Write applications of an inverter.* **SPPU : May-2000, Marks 2**

3.9 Multiple Choice Questions

Q.1 Inverters converts ______.

a dc power to dc power
b dc power to ac power
c ac power to ac power
d ac power to dc power

Q.2 Single phase half bridge inverters requires ______.

a two wire ac supply
b two wire dc supply
c three wire ac supply
d three wire dc supply

Q.3 The output of a single-phase half bridge inverter on R load is ideally ______.

a a sine wave
b a square wave
c a triangular wave
d constant dc

Q.4 Single-phase full bridge inverters requires ______.

a 4 SCRs and 2 diodes
b 4 SCRs and 4 diodes
c 2 SCRs and 4 diodes
d 2 SCRs and 2 diodes

Q.5 The device which performs dc-ac conversion :

a Inverter
b Rectifier
c Chopper
d Switch

Q.6 The 120° mode of operation of a three phase bridge inverter requires ____________ number of steps.

a 2 b 4

c 6 d 8

Q.7 In case of the 120° mode of operation, ___________ devices conduct at a time.

a 2 b 3

c 4 d none of the mentioned

Q.8 The peak value of the line voltage in case of 120° mode of operation of a three-phase bridge inverter is ______________.

a $V_s/2$ b $3V_s/2$

c $V_s/\sqrt{2}$ d V_s

Q.9 The external control of ac output voltage can be achieved in an inverter by ______________.

a connecting a cyclo-converter

b connecting an ac voltage controller between the output of the inverter and the load

c connecting an ac voltage controller between the dc source and inverter

d connecting an ac voltage controller between the load and the dc source

Q.10 In the PWM method :

a External commutating capacitors are required

b More average output voltage can be obtained

c Lower order harmonics are minimized

d Higher order harmonics are minimized

Q.11 In VSI (Voltage Source Inverters) ______________.

a both voltage and current depend on the load impedance

b only voltage depends on the load impedance

c only current depends on the load impedance

d none of the mentioned

Q.12 _____________ is the measure of the contribution of any individual harmonic to the inverter output voltage.

a THHD

b Distortion factor

c Harmonic factor

d TUF

Q.13 The Total Harmonic Distortion (THD) is the measure of _____________.

a input vs output power factor

b temperature sensitivity

c waveform distortion

d contribution of each harmonic to the total output

Explanations :

Q.1 Explanation : Inverter is a dc to ac converter

Q.2 Explanation : They require two voltage sources $\frac{V_s}{2}$ and $\frac{V_s}{2}$.

Q.3 Explanation : Due to rapid switching on and off of the devices, it seems to be a square wave.

Q.4 Explanation : Full bridge inverters require 4 SCR and 4 diodes along with a two wire dc source

Q.6 Explanation : Like the 180 mode, the 120° mode also requires six steps, each of 60° duration.

Q.7 Explanation : Unlike the 180° mode, in the 120° mode 2 devices are conducting at a time as each conduct for 120°.

Q.8 Explanation : The peak value for 120° mode is V_s. The line voltage waveform is a sine wave with a peak value of V_s (= supply voltage).

Q.9 Explanation : By connecting a AC voltage controller, the ac output from the inverter can be varied and then fed to the load.

Q.10 Explanation : In all the PWM methods, only odd harmonics are present. The lower order harmonics are eliminated along with its output voltage control.

Q.11 Explanation : In VSIs the voltage is independent on the load impedance Z.

Q.12 Explanation : The HF or Harmonic factor is the ratio of the nth harmonic voltage component to the fundamental voltage component. Hence it shows how much a particular harmonic is contributing in the total output of the circuit.

Q.13 Explanation : Lower the value of THD, closer is the waveform to a sine-wave.

Answer Keys for Multiple Choice Questions :

Q.1	b	**Q.2**	d	**Q.3**	b	**Q.4**	b	**Q.5**	a
Q.6	c	**Q.7**	a	**Q.8**	d	**Q.9**	b	**Q.10**	c
Q.11	c	**Q.12**	c	**Q.13**	c				

❑❑❑

Notes

UNIT IV

4 DC to DC Converters

Syllabus

Classification of choppers, Step down chopper for R and RL load and its performance analysis, Step up chopper, various control strategies for choppers, types of choppers (isolated and non isolated) such as type A, B, C, D & E, switch mode power supply (SMPS) viz buck, boost and buck-boost, Fly back, Half and full Bridge isolated and non-isolated interleaved bidirectional topologies, and concept of integrated converter and design of LM3524 based choppers, concept of maximum power point tracking (MPPT).

Contents

4.1 Working Principle of Step Down Chopper

SPPU : Dec.-09,10,13,19, May-10,11,12,15,17,19

Fig. 4.1.1 shows the circuit diagram of the basic step down chopper. The switch (sw) can be a power transistor, SCR, GTO, power MOSFET, IGBT or similar switching device. Normally the drop in the switch is very small and it is neglected. Fig. 4.1.2 shows the waveforms of the stepdown chopper with resistive load.

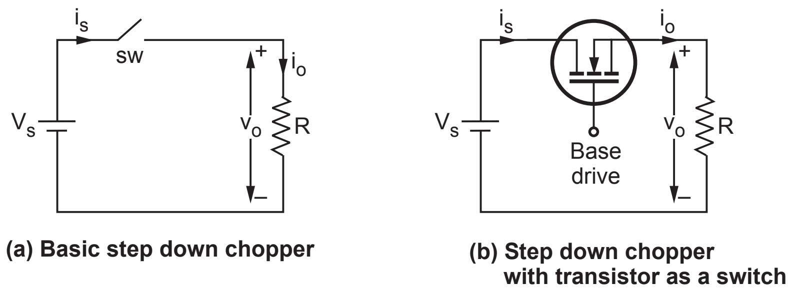


Fig. 4.1.1

Fig. 4.1.2 (a) shows the drive of the switch. In case of power transistor, it will be a base drive. The drive is applied for the period 0 to δT. Hence the switch turns ON for this period and connects supply V_s to the load. Hence $v_o = V_s$ in this period. From δT to T the drive of the switch is removed, hence it turns off. Hence the load voltage is zero. Since the load is resistive, output current will be, $i_o = \frac{v_o}{R}$. Hence the nature of output current is same as output voltage.

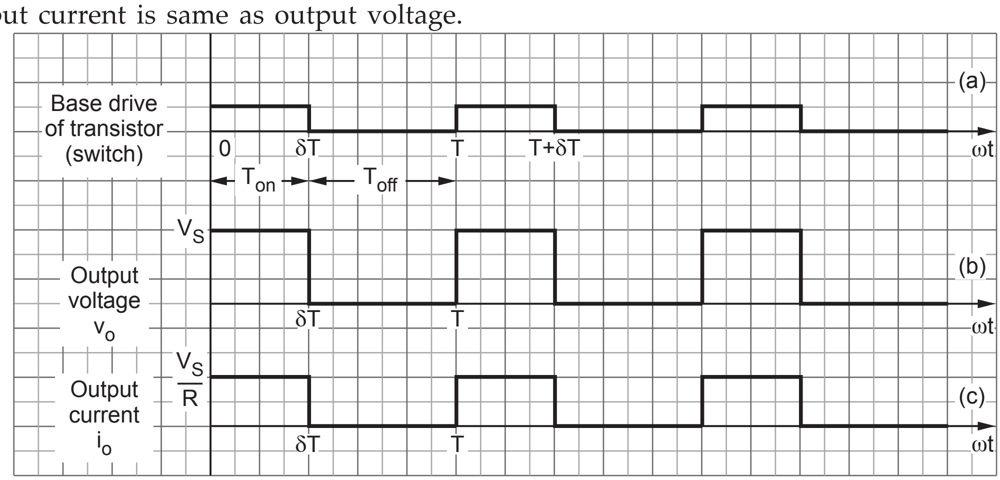


Fig. 4.1.2 Waveforms of the stepdown chopper with resistive load

Examples for Understanding

Example 4.1.1 *For the stepdown chopper having resistive load derive an expression for the following - i) Average output voltage $V_{o(av)}$ ii) rms output voltage $V_{o(rms)}$*

SPPU : Dec.-10, May-12, Marks 4

Solution : i) To obtain $V_{o(av)}$

The average value is given as,

$$V_{o(av)} = \frac{1}{T}\int_0^T v_o(t)\, dt$$

In the output voltage waveform of Fig. 4.1.2 observe that $v_o = V_s$ from 0 to δT, rest of the time v_o is zero. Hence above equation can be written as,

$$V_{o(av)} = \frac{1}{T}\int_0^{\delta T} V_s\, dt = \frac{V_s}{T}\int_0^{\delta T} dt = \frac{V_s}{T}\cdot \delta T$$

$$\therefore \quad V_{o(av)} = \delta V_s \qquad \text{... (4.1.1)}$$

Here $\delta = \frac{T_{on}}{T}$ is called the *duty cycle of the chopper. The value of duty cycle lies between* $0 \le \delta \le 1$.

ii) To obtain $V_{o(rms)}$

The rms value of output is given as,

$$V_{o(rms)} = \left[\frac{1}{T}\int_0^T v_o^2(t)\, dt\right]^{\frac{1}{2}}$$

We know from Fig. 4.1.2 that $v_o = V_s$ from 0 to δT (i.e. when the transistor switch is on). Hence above equation becomes,

$$V_{o(rms)} = \left[\frac{1}{T}\int_0^{\delta T} V_s^2\, dt\right]^{\frac{1}{2}} = \left[\frac{V_s^2}{T}\int_0^{\delta T} dt\right]^{\frac{1}{2}} = \left[\frac{V_s^2}{T}\cdot \delta T\right]^{\frac{1}{2}}$$

$$\therefore \quad V_{o(rms)} = \sqrt{\delta}\, V_s \qquad \text{... (4.1.2)}$$

Example 4.1.2 *Explain the basic principle of step-down chopper and write down the expressions for - i) Average output voltage ii) Output power iii) Effective input resistance in terms of chopper duty cycle.*

Solution : i) Average output voltage

It is derived in previous example. i.e.,

$$\mathrm{V_{o(av)}} = \delta V_s$$

Here $\delta = \frac{T_{on}}{T}$ is called the duty cycle of the chopper.

ii) Output power

The load power can be calculated as,

$$P_o = \frac{1}{T}\int_0^{\delta T} \frac{v_o^2}{R}\,dt = \frac{1}{T}\int_0^{\delta T} \frac{(V_s - V_{ch})^2}{R}$$

$$= \frac{1}{T}\cdot\frac{(V_s - V_{ch})^2}{R}\int_0^{\delta T} dt = \frac{1}{T}\cdot\frac{(V_s - V_{ch})^2}{R}\cdot\delta T$$

$$= \frac{\delta (V_s - V_{ch})^2}{R}$$

If the chopper is lossless, then $V_{ch} = 0$ and output power will be,

$$P_o = \frac{\delta V_s^2}{R}$$

iii) Effective input resistance

Fig. 4.1.3 shows that the average current flowing from the input is basically output average current, i.e. $I_{o(av)}$. The input voltage is supply voltage V_s. Hence effective input resistance will be,

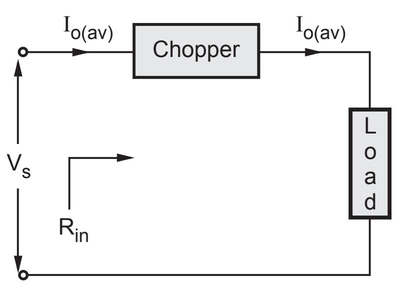


Fig. 4.1.3 Effective input resistance

$$R_{in} = \frac{V_s}{I_{o(av)}}$$

Putting for $I_{o(av)} = \frac{V_{o(av)}}{R}$ in above equation,

$$R_{in} = \frac{V_s}{\frac{V_{o(av)}}{R}} = R\cdot\frac{V_s}{V_{o(av)}}$$

Since $\delta = \frac{V_{o(av)}}{V_s}$, above equation becomes,

$$R_{in} = \frac{1}{\delta}R$$

This is an expression for effective input resistance.

Example 4.1.3 *For a chopper shown below, DC source voltage is 230 V, load resistance is 10 Ω. Consider the voltage drop of 2 V across chopper when it is on. For a duty cycle of 0.4 calculate, i) Average and rms value of output voltage ii) Chopper efficiency*

SPPU : Dec.-13, Marks 4

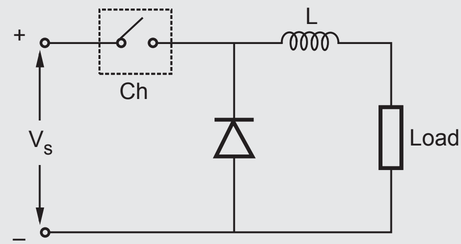


Fig. 4.1.4 Chopper circuit

Solution : The given data is,

$$V_s = 230 \text{ V}, R = 10\ \Omega, V_{ch} = 2 \text{ V}, \delta = 0.4$$

It is a step down chopper. The inductance filter is present. We will consider that the load is fairly resistive.

i) To obtain average and rms values

The average value is given by equation (4.1.1) as,

$$V_{o(av)} = \delta V_s$$

This equation neglects the drop in chopper. Considering the drop, above equation will be,

$$V_{o(av)} = \delta(V_s - V_{ch}) = 0.4\,(230 - 2) = 91.2 \text{ V}$$

The rms value is given by equation (4.1.2) as,

$$V_{o(rms)} = \sqrt{\delta}\, V_s$$

Considering the voltage drop across chopper,

$$V_{o(rms)} = \sqrt{\delta}\,(V_s - V_{ch}) = \sqrt{0.4}\,(230 - 2) = 144.2 \text{ V}$$

ii) To obtain chopper efficiency

The load power can be calculated as,

$$P_o = \frac{1}{T}\int_0^{\delta T} \frac{v_o^2}{R}\, dt = \frac{1}{T}\int_0^{\delta T} \frac{(V_s - V_{ch})^2}{R}\, dt$$

$$= \frac{1}{T}\frac{(V_s - V_{ch})^2}{R}\int_0^{\delta T} dt = \frac{1}{T}\cdot\frac{(V_s - V_{ch})^2}{R}\cdot \delta T$$

$$= \frac{\delta (V_s - V_{ch})^2}{R} \qquad \text{... (4.1.3)}$$

Putting values in above equation,

$$P_o = \frac{0.4(230-2)^2}{10} = 2079.36 \text{ W}$$

The supply power (input power) can be calculated as,

$$P_s = \frac{1}{T}\int_0^{\delta T} v_s \; i_s \, dt$$

In the Fig. 4.1.2, observe that $i_s = i_o$ and $v_s = V_s$. Hence above equation becomes,

$$P_s = \frac{1}{T}\int_0^{\delta T} V_s \; i_o \, dt = \frac{1}{T}\int_0^{\delta T} V_s\left(\frac{V_s - V_{ch}}{R}\right) dt$$

$$= \frac{1}{T}\cdot V_s \cdot \frac{(V_s - V_{ch})}{R}\int_0^{\delta T} dt = \frac{1}{T}\cdot V_s \cdot \frac{V_s - V_{ch}}{R}\cdot \delta T$$

$$= \delta V_s \cdot \frac{V_s - V_{ch}}{R} \qquad \text{... (4.1.4)}$$

Putting the values,

$$P_s = 0.4 \times 230 \times \frac{230-2}{10} = 2097.6 \text{ W}$$

Therefore efficiency of the chopper is,

$$\eta = \frac{\text{Load power (output power)}}{\text{Supply power(input power)}} = \frac{2079.36}{2097.6} = 0.9913 \text{ or } 99.13 \text{ \%}$$

Here note that efficiency is very high since voltage drop in the chopper is very small.

4.1.1 Chopper Control Techniques

The chopper can be operated as constant frequency or variable frequency. These are also called as Time Ratio Control (TRC) techniques.

1. Constant frequency operation :

The chopper frequency is kept constant. Hence total period T remains constant. T_{on} and T_{off} both are varied to vary the duty cycle. The advantage is that the filter components are easy to design. Fig. 4.1.5 (a) and (b) shows the waveforms of this operation.

2. Variable frequency operation :

The frequency of the chopper varies when duty cycle is to be varied. When T_{on} is varied T_{off} is kept constant and vice versa. The filter design is difficult for this type of chopper. Fig. 4.1.5 (c) and (d) shows the waveforms of this operation. In this figure T_{on} is kept constant and T_{off} is varied. This also varies 'T'.

3. Current limit control :

In this type of control, the output current is sensed. When the current exceeds $i_{0(\max)}$, the chopper is turned off; when output current reduces below $i_{o(\min)}$, the chopper is turned on. Fig. 4.1.5 (e) and (f) shows the waveforms for this operation.

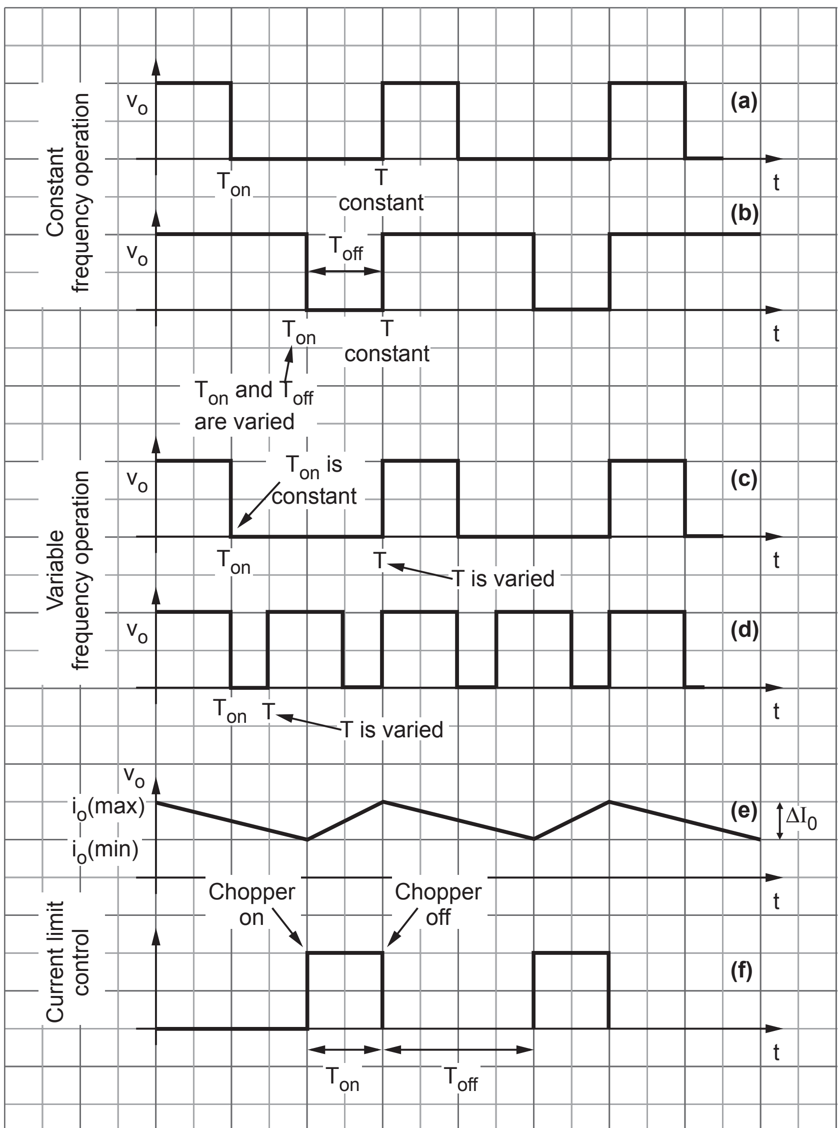


Fig. 4.1.5 Chopper control schemes

Example 4.1.4 *A step down DC chopper has a resistive load of R = 15 Ω and input voltage V_s = 200 V. When the chopper remains on, its voltage drop is 2.5 V. The chopper frequency is 1 kHz. If the duty cycle is 50 % determine : i) Average output voltage ii) r.m.s output voltage iii) Chopper efficiency.* **SPPU : May - 11, Marks 6**

Solution : Given data :

R = 15 Ω, V_s = 200 V, V_{ch} = 2.5 V, f = 1000 Hz, δ = 0.5

i) Average output voltage

$$V_{o(av)} = \delta(V_s - V_{ch}) = \sqrt{0.5}\,(200 - 2.5) = 98.75V$$

ii) RMS output voltage

$$V_{o(rms)} = \sqrt{\delta}\,(V_s - V_{ch})$$

$$= \sqrt{0.5}\,(200 - 2.5) = 139.65\ V$$

iii) Chopper efficiency

$$P_o = \frac{\delta(V_s - V_{ch})^2}{R},\quad P_s = \delta V_s \cdot \frac{V_s - V_{ch}}{R}$$

$$\therefore \quad \eta = \frac{P_o}{P_s} = \frac{\delta(V_s - V_{ch})^2 | R}{\delta V_s (V_s - V_{ch}) | R}$$

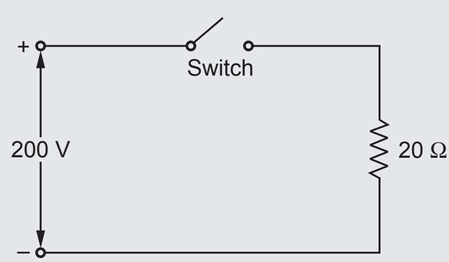
$$= \frac{V_s - V_{ch}}{V_s} = \frac{200 - 2.5}{200} = 0.9875$$

or $\quad \eta = 98.75\ \%$

Example 4.1.5 *Considering the switch to be ideal in the circuit shown below determine :*

i) The duty cycle, for which the output average dc voltage and rms voltage are equal.

ii) The chopper efficiency



Solution : i) To obtain duty cycle

Average voltage is given as,

$$V_{o(av)} = \delta V_s$$

And rms voltage is given as,

$$V_{o(rms)} = \sqrt{\delta}\,V_s$$

Here not that $V_{o(av)} = V_{o(rms)}$ if $\sqrt{\delta} = \delta$. This is possible only for

$$\delta = 1$$

ii) Chopper efficiency

The switch is ideal. Hence there are no losses in the chopper. Therefore efficiency of the chopper is 100 %.

Example 4.1.6 *A type A step down chopper operates from a battery whose fully-charged and end of discharge voltage are 26 V and 22 V, respectively. If the required output voltage varies from 10 V to 14 V, calculate the range of variation of the chopper duty cycle.*

Solution :

$$V_{s(\max)} = 26 \text{ V}, \quad V_{s(\min)} = 22 \text{ V}$$

$$V_{o(\max)} = 14 \text{ V}, \quad V_{o(\min)} = 10 \text{ V}$$

$$V_{o(\min)} = \delta_{\min} V_{s(\max)}$$

$$10 = \delta_{\min} \times 26 \quad \Rightarrow \quad \delta_{\min} = 0.384 \text{ or } 38.4 \text{ \%}$$

and $$V_{o(\max)} = \delta_{\max} V_{s(\min)}$$

$$14 = \delta_{\max} \times 22 \quad \Rightarrow \quad \delta_{\max} = 0.636 \text{ or } 63.6 \text{ \%}$$

Thus duty cycle range will be, 38.4 % to 63.6 %

Example 4.1.7 *A transistor chopper is shown in Fig. 4.1.6. If the DC supply of 120 V is applied and the transistor is switched by applying periodic base pulses of voltage varying between 0 to 1 V, sketch the load voltage with reference to the input base pulses. Calculate i) Average/DC output voltage, and ii) Average load current assuming the chopper frequency as 200 Hz, duty cycle of operation as 33.33 %, and load resistance of 10 Ω.*

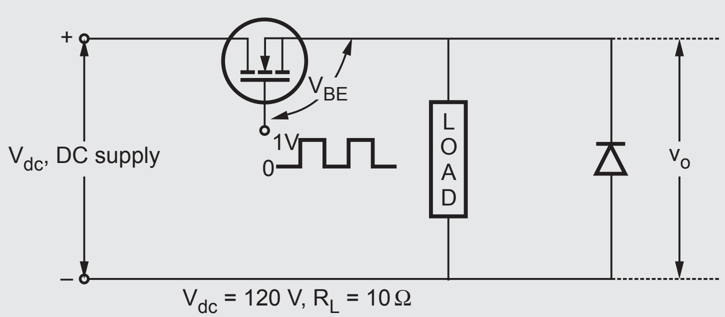


Fig. 4.1.6 Chopper circuit

Solution : This is a stepdown chopper. The base drive and load voltage waveforms are shown in the Fig. 4.1.2. The average value of output is derived in equation (4.1.1) as,

$$V_{o\,(av)} = \delta V_s$$

i) Average output voltage $V_{o(av)}$

Here the given data is,

$$V_s = V_{dc} = 120 \text{ V}$$

$$\delta = 33.33 \% = 0.3333 = \frac{1}{3}$$

$$R = 10 \ \Omega$$

Hence average output voltage will be,

$$V_{o(av)} = \delta V_s = \frac{1}{3} \times 120 = 40 \text{ V}$$

ii) Average output current $I_{o(av)}$

Since the load is resistive, averge load current will be,

$$I_{o(av)} = \frac{V_{o(av)}}{R} = \frac{40}{10} = 4 \text{ A}$$

Example 4.1.8 *With the aid of basic circuit and waveform explain the basic principles of operation of a step-down chopper with resistive load. Obtain expressions for i) DC output voltage ii) Output power and iii) Chopper efficiency*

Solution : i) DC output voltage

The DC output voltage is given by equation (4.1.1) as,

$$V_{o(av)} = \delta V_s$$

ii) Output power

Since the drop in chopper switch is not given, we will consider ideal switch. Hence output power as calculated in example (4.1.2) will be,

$$P_o = \frac{\delta V_s^2}{R}$$

iii) Chopper efficiency

The supply power to the chopper is given by equation (4.1.4).

$$P_s = \delta V_s \cdot \frac{V_s - V_{ch}}{R}$$

Since chopper is lossless,

$$P_s = \delta V_s \cdot \frac{V_s}{R} = \frac{\delta V_s^2}{R}$$

Chopper efficiency is,

$$\eta = \frac{P_o}{P_s} = \frac{\delta V_s^2 / R}{\delta V_s^2 / R} = 1$$

The efficiency is 100 % since chopper is lossless.

Example 4.1.9 *A step down chopper is used to charge a 120 V DC battery bank through a smoothing reactor and current limiting resistor. The internal resistance of the battery bank is 0.2 Ω and the winding resistance of the reactor is 0.3 Ω. The DC supply to the chopper is via the rectified and filtered mains having a nominal value of 325 V DC.*

Calculate - (i) Value of the current limiting resistor required for a nominal charging current of 20 A if the nominal duty cycle is 60 %.

(ii) Maximum and minimum duty cycles to maintain the current constant if the chopper DC supply voltage varies by ± 15 %.

Solution : i) To obtain current limiting resistor

When the switch is 'ON' full voltage of 325 V appears across the output as shown in Fig. 4.1.7.

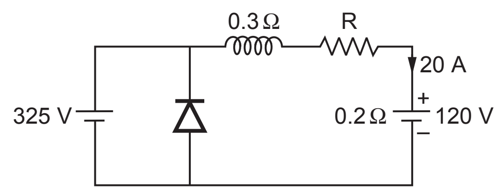


Fig. 4.1.7 Chopper

From this circuit we can write,

$$325 = (0.3 + R + 0.2) \times 20 + 120$$

$$\therefore \quad R = 9.75\ \Omega$$

ii) Maximum and minimum duty cycles

$$V_{s(\max)} = 325 + 15\% \text{ of } 325 = 325 + 325 \times 0.15 = 373.75$$

$$V_{s(\min)} = 325 - 15\% \text{ of } 325 = 325 - 325 \times 0.15 = 276.25$$

$$I = \frac{\delta_{\max} V_{s(\min)}}{R}$$

$$20 = \frac{\delta_{\max} \times 276.25}{9.75} \Rightarrow \quad \delta_{\max} = 0.7 \text{ or } 70\ \%$$

and

$$I = \frac{\delta_{\min} V_{s(\max)}}{R}$$

$$20 = \frac{\delta_{\max} \times 373.75}{9.75} \Rightarrow \delta_{\min} = 0.52 \text{ or } 52\ \%$$

Examples for Practice

Example 4.1.10 *In a DC chopper the average load current is 30 A. The chopping frequency is 250 Hz and supply voltage is 110 volts. Calculate ON and OFF periods, if the load resistance is 2 Ω.* **SPPU : May 17**

[Ans. : T_{on} = 2.18 msec, T_{off} = 1.818 msec]

Example 4.1.11 *A chopper has supply voltage of 220 V, load resistance $R = 10\ \Omega$ and operating frequency of 1 kHz. The duty cycle is 50 % Determine,*
(i) Average and rms output voltage (ii) Output power.

[Ans. : $V_{o(av)}$ = 110 V, $V_{o(rms)}$ = 155.56 V, P_o = 2420 W]

Example 4.1.12 *A chopper circuit is operating on TRC at a frequency of 2 kHz on a 460 V supply of the load voltage of 350 V. Calculate the conduction period of the thyristor in each cycle.* **[Ans. : T_{on} = 380 μ sec]**

Example 4.1.13 : *A step down (type - A) chopper feeds a resistive load of 10 Ω from 100 V DC supply. Calculate the duty cycle required so that the average power dissipation in the load is 100 W.* **[Ans. : δ = 0.1 or 10 %]**

Example 4.1.14 : *For step down type A chopper, input voltage is 600 V DC. It supplies a load of 10 Ω at 25 % duty cycle. Find average output voltage, average output cycle. Find average output voltage, average output current, RMS value of output voltage and ripple factor.*
[Ans. : $V_{o(av)}$= 150 V, $I_{o(av)}$ = 15 A, $V_{o(rms)}$ = 300 V, RF = 1.732]

Example 4.1.15 : *The step down chopper with resistive load of R = 10 Ω and the I/P voltage V_s 220 V, when the chopper switch remains on, its voltage drop is V_{ch} = 2 V and chopping frequency is F = 1 kHz. If the duty cycle is 50 %. Determine i) The average output voltage. ii) RMS output voltage. iii) Chopper efficiency.* **[Hints and Ans. : $V_{o(av)}$ = 109 V, $V_{o(rms)}$ = 154 V, P_o = 2376 W, P_i = 2398 W, η = 99 %]**

Review Questions

1. *Draw the circuit diagram and explain the operation of step down chopper with the help of waveforms.* **SPPU : May-10,12, Marks 6**
2. *Explain control strategies used for chopper.* **SPPU : Dec.-10, Marks 5, May-11,15,17 Marks 6**
3. *Explain the time ratio control and current limit control used for DC chopper.* **SPPU : Dec.-09, May-10, 17 Marks 6**
4. *Explain the operation of step down chopper with circuit diagram and derive an expression for its output voltage in terms of chopping frequency.* **SPPU : May-19, Marks 8**
5. *Draw and explain step down chopper for R-load with circuit diagram and wave forms. Derive expression for avg output voltage ?* **SPPU : Dec.-19, Marks 8**

4.2 Step Down Chopper with RL Load

SPPU : Dec.-10

Normally the choppers are used to drive the DC motors. These motors are considered as RL (inductive) load. Fig. 4.2.1 shows the circuit diagram of stepdown chopper having inductive load.

Transistor is used as a switch. It can be MOSFET, GTO, IGBT or SCR also. Since the load is inductive, freewheeling diode D_{FW} is used in the circuit. Normally the

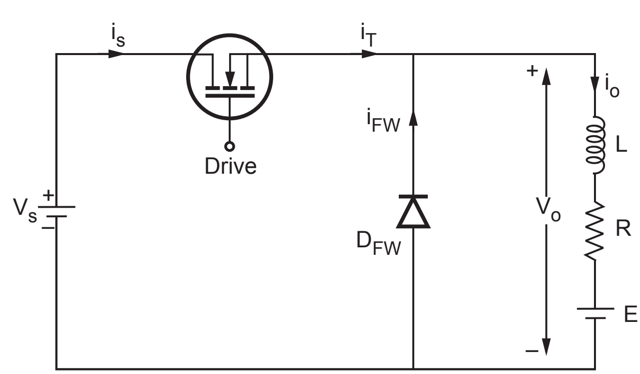


Fig. 4.2.1 Stepdown chopper with RL load

inductive loads are motors. Hence back emf 'E' is also shown in the circuit diagram as a part of load. Such loads are also called as 'RLE' load.

4.2.1 Continuous Load Current

Fig. 4.2.2 shows the waveforms of this circuit. The switch is turned 'on' for 0 to δT. Here 'δ' is the duty cycle of the chopper. The output voltage is equal to supply voltage $(v_o = v_s)$ when the switch is 'ON'. The equivalent circuit-I in Fig. 4.2.2 shows the current flow when the switch is on. The output current is assumed continuous. At δT, the output current reaches to maximum value I_{max}.

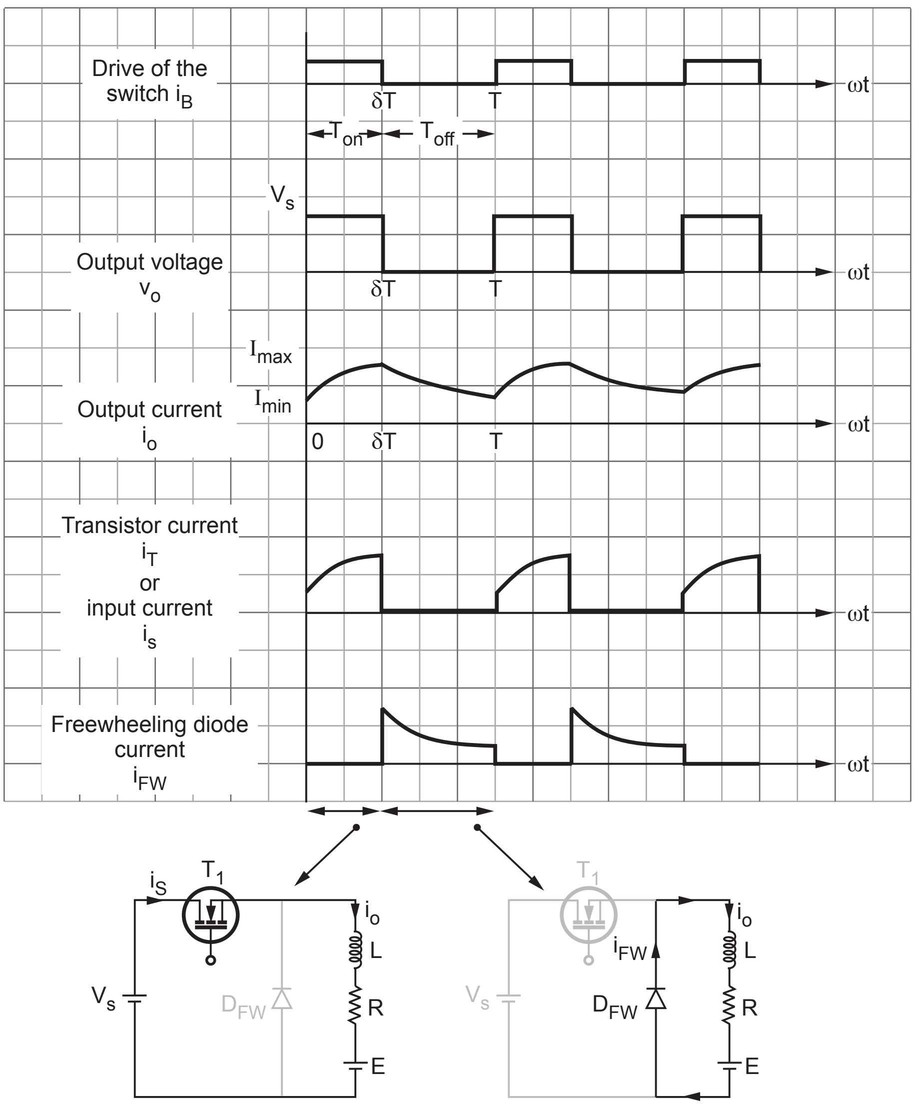


Fig. 4.2.2 Waveforms of step down chopper for inductive load (continuous load current)

From δT to T the switch is 'OFF'. At δT, the output current is at I_{max}. When the switch is turned off, the load inductance tries to maintain the output current in the same direction. This current flows through the freewheeling diode D_{FW}. The equivalent circuit-II in Fig. 4.2.2 shows this situation. The freewheeling diode is forward biased due to load inductance voltage $L\frac{di_o}{dt}$. Output voltage is zero when freewheeling diode conducts. In Fig. 4.2.2, observe that input current i_s flows only when switch (transistor conducts). Hence i_s and switch current i_T are same. The values of I_{max} and I_{min} depends upon the load inductance.

4.2.2 Discontinuous Load Current

If the inductance of the load is small then load current may be discontinuous. The waveforms of step down chopper for inductive load with discontinuous load current are shown in Fig. 4.2.3. The load current increases from zero when the switch is turned 'on'. The current reaches to 'I_{max}' at δT. The switch is turned off at δT. From δT to T, the switch is 'off'. The freewheeling diode conducts from δT to t_1. At t_1, the load current becomes zero. The load inductance supplies the energy from δT to t_1 (i.e. freewheeling). The load current is zero from t_1 to T. Thus the load current is discontinuous. (See Fig. 4.2.3 on next page.)

The output voltage is equal to supply voltage when the switch conducts. Hence $v_o = V_s$ from 0 to δT. The output voltage is zero when the switch is off. Here note that the load current is discontinuous if load inductance is small.

Examples for Understanding

Example 4.2.1 *Derive an expression for peak to peak value of load current (i.e. ripple) for continuous load current in RLE (i.e. inductive) load.*

Solution : This is continuous mode of operation. Hence we will use the waveforms of Fig. 4.2.2. We have to obtain the expressions for I_{max} and I_{min}. Let us call the current $i_1(t)$ from 0 to δT and $i_2(t)$ from δT to T. This is shown in Fig. 4.2.4 for convenience.

Let us consider the period from 0 to δT when the switch is 'on'. Current $i_1(t)$ flows in the loop formed by supply switch and load. This is shown in equivalent circuit-I in Fig. 4.2.2. By KVL to this loop,

$$V_s = L\frac{d\,i_1(t)}{dt} + R\,i_1(t) + E$$

Here we have neglected the drop in the switch (transistor). At $t = 0$, $i_1(t) = I_{min}$. Hence solution of above equation will be,

$$i_1(t) = I_{min}\,e^{-t\frac{R}{L}} + \frac{V_s - E}{R}\left(1 - e^{-t\frac{R}{L}}\right) \quad \text{... (4.2.1)}$$

Now let us consider the period from δT to T, when the switch is 'off'. The load current is called $i_2(t)$ in this period (See Fig. 4.2.4). The freewheeling diode conducts in this period. Refer to equivalent circuit-II in Fig. 4.2.2. By KVL to the loop formed by freewheeling diode and load,

$$L \frac{d\, i_2(t)}{dt} + R\ i_2(t) + E = 0$$

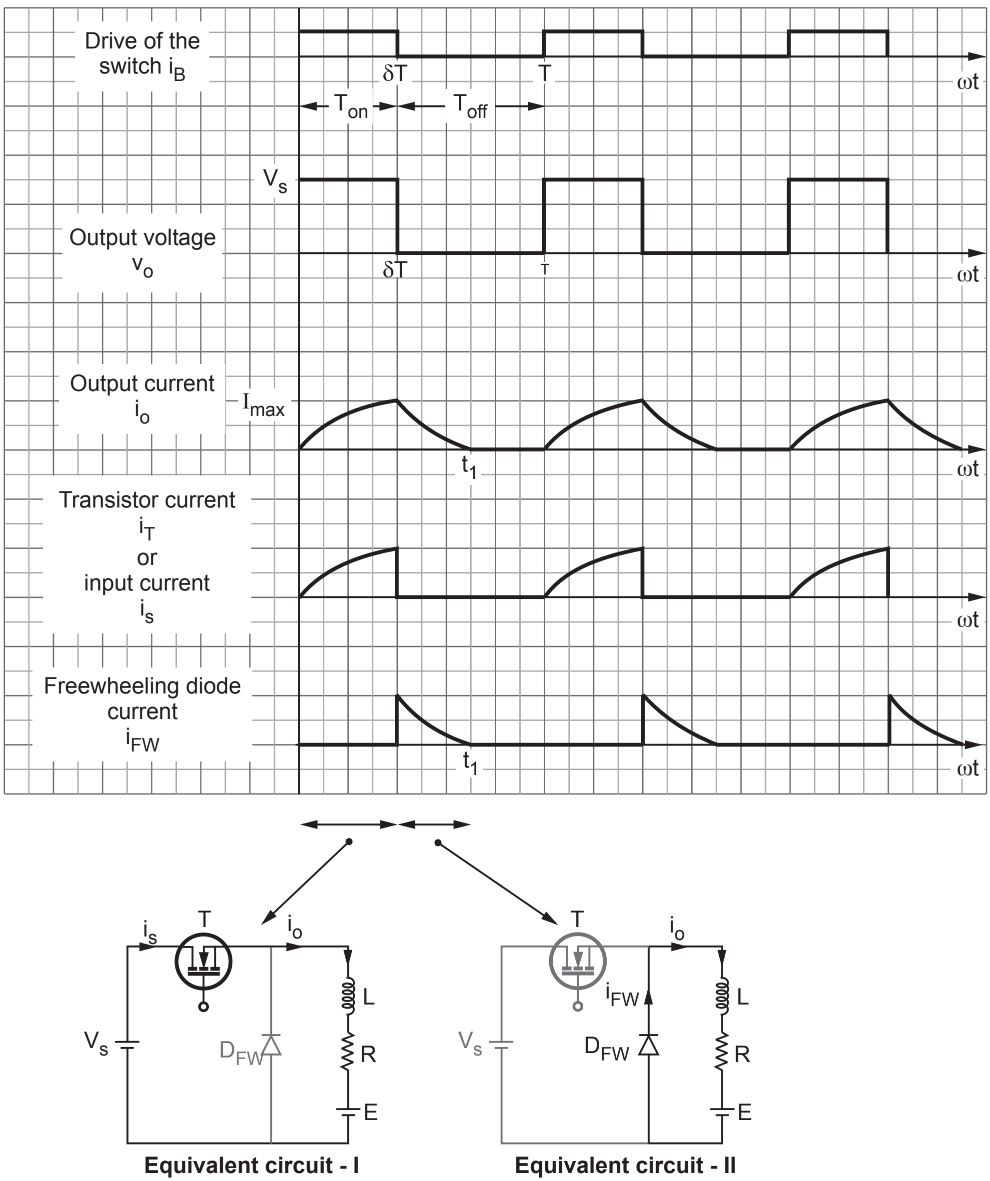


Fig. 4.2.3 Waveforms of stepdown chopper for inductive load (discontinuous load current)

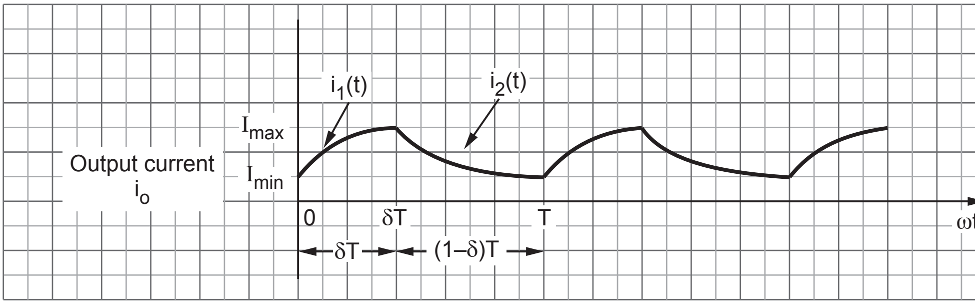


Fig. 4.2.4 Output current waveform for inductive load

As shown in Fig. 4.2.4, $i_2(t)$ is equal to I_{max} initially. Hence solution of above equation gives $i_2(t)$ as follows :

$$i_2(t) = I_{max}\, r^{-t\frac{R}{L}} - \frac{E}{R}\left(1-e^{-t\frac{R}{L}}\right) \qquad \text{... (4.2.2)}$$

Here note that we have considered δT as the time origin for $i_2(t)$. As shown in Fig. 4.2.4 $i_2(t)$ conducts for the period of $(1-\delta)T$. Hence it is clear that after the period of $(1-\delta)T$, $i_2(t)$ reaches to I_{min} as shown in Fig. 4.3.4. i.e., with $t=(1-\delta)T$, $i_2(t)=I_{min}$. Hence equation (4.3.2) becomes,

$$I_{min} = I_{max}\, e^{-(1-\delta)T\frac{R}{L}} - \frac{E}{R}\left(1-e^{-(1-\delta)T\frac{R}{L}}\right) \qquad \text{... (4.2.3)}$$

Now consider equation (4.2.1) for $i_1(t)$. In Fig. 4.2.4 observe that $i_1(t)=I_{max}$ at $t=\delta T$. Hence equation (4.2.1) becomes,

$$I_{max} = I_{min}\, e^{-\delta T\frac{R}{L}} + \frac{V_s-E}{R}\left(1-e^{-\delta T\frac{R}{L}}\right) \qquad \text{... (4.2.4)}$$

The above equation and equation (4.2.3) gives the maximum and minimum values of load current.

The peak to peak load current can be obtained by,

$$I_{o(p-p)} = I_{max} - I_{min}$$

Putting from equation (4.2.3) and equation (4.2.4) and after simplification we get,

$$I_{o(p-p)} = \frac{V_s}{R}\,\frac{1-e^{-\delta T\frac{R}{L}}+e^{-T\frac{R}{L}}-e^{-(1-\delta)T\frac{R}{L}}}{1-e^{-T\frac{R}{L}}} \qquad \text{... (4.2.5)}$$

This equation gives peak to peak ripple in the load current.

Example 4.2.2 *Derive an expression for average and rms value of the load voltage for the step down chopper having inductive load.*

Solution : The waveform of output voltage is shown in Fig. 4.2.2 for inductive load when the load current is continuous. Fig. 4.2.3 shows the output voltage waveform for inductive load when the load current is discontinuous. And Fig. 4.1.2 shows the output voltage waveform for the stepdown chopper for resistive load. Note that the output voltage waveform is exactly same in all these cases. Hence their rms and average values must be same. Hence average value of stepdown chopper for inductive load can be given by equation (4.1.1) as,

$$V_{o(av)} = \delta V_s \qquad \text{... (4.2.6)}$$

Here $\delta = \frac{T_{on}}{\mathrm{T}}$ is called duty cycle of the chopper. Similarly rms value of the output voltage for inductive load can be obtained from equation (4.1.2) as,

$$V_{o(rms)} = \sqrt{\delta}\, V_s \qquad \text{... (4.2.7)}$$

Example 4.2.3 *Prove that maximum ripple occurs in the output current of stepdown chopper when duty cycle is 0.5. And the value of maximum ripple current is given as.*

$$I_{o\,\max(p-p)} = \frac{V_s}{R}\, tanh\, \frac{TR}{4L}$$

Solution : The peak to peak ripple in the load current is given by equation (4.2.5) as,

$$I_{o(p-p)} = \frac{V_s}{R}\,\frac{1-e^{-\delta T\frac{R}{L}}+e^{-T\frac{R}{L}}-e^{-(1-\delta)T\frac{R}{L}}}{1-e^{-T\frac{R}{L}}} \qquad \text{... (4.2.8)}$$

For the maximum value of $I_{o(p-p)}$ with respect to duty cycle δ, we have to set the following condition,

$$\frac{d}{d\delta} I_{o(p-p)} = 0$$

That is differentiate peak to peak ripple current with respect to duty cycle δ. Then differentiating equation (4.2.8) with respect to δ and equating to zero we get,

$$e^{-\delta T\frac{R}{L}} - e^{-(1-\delta)T\frac{R}{L}} = 0$$

$$\therefore \quad e^{-\delta T\frac{R}{L}} = e^{-(1-\delta)T\frac{R}{L}}$$

$$\therefore \quad \delta T\frac{R}{L} = (1-\delta)T\frac{R}{L}$$

$$\therefore \quad \delta = \frac{1}{2} = 0.5$$

This shows that at duty cycle $\delta = 0.5$, the peak to peak value of ripple current is maximum. Hence by putting $\delta = 0.5$ equation (4.2.8) becomes,

$$I_{o\,\max(p-p)} = \frac{V_s}{R}\,\frac{1-e^{-0.5\,T\frac{R}{L}} + e^{-T\frac{R}{L}} - e^{-(1-0.5)\,T\frac{R}{L}}}{1-e^{-T\frac{R}{L}}}$$

On simplifying the above equation,

$$I_{o\,\max(p-p)} = \frac{V_s}{R}\,tanh\left(\frac{TR}{4L}\right) \quad \text{... (4.2.9)}$$

Note that the above equation is derived only for continuous load current.

Example 4.2.4 *Derive an expression for the load current of the stepdown chopper with inductive load having discontinuous load current. Also obtain the time at which the load current becomes zero.*

Solution : The waveforms of step down chopper for inductive load (discontinuous mode) are shown in Fig. 4.2.3 The equivalent circuits are similar to those in Fig. 4.2.2. Hence the equations derived in example 4.2.1 are also applicable to discontinuous mode. Here $I_{\min} = 0$, since load current is discontinuous. Hence equation (4.2.1) will be,

$$i_1(t) = \frac{V_s - E}{R}\left(1-e^{-t\frac{R}{L}}\right) \quad \text{... (4.2.10)}$$

This is the equation for the load current from 0 to δT, i.e. when the switch is 'on'. Equation (4.2.2) gives the load current when the chopper switch is 'off'. i.e.,

$$i_2(t) = I_{\max}\,e^{-t\frac{R}{L}} - \frac{E}{R}\left(1-e^{-t\frac{R}{L}}\right) \quad \text{... (4.2.11)}$$

This current goes to at $t = t_1$ (See Fig. 4.2.3), hence above equation becomes,

$$0 = I_{\max}\,e^{-t_1\frac{R}{L}} - \frac{E}{R}\left(1-e^{-t_1\frac{R}{L}}\right)$$

$$I_{\max}\,e^{-t_1\frac{R}{L}} = \frac{E}{R}\left(1-e^{-t_1\frac{R}{L}}\right)$$

$$\therefore \left(I_{\max}+\frac{E}{R}\right)e^{-t_1\frac{R}{L}} = \frac{E}{R}$$

$$\therefore \qquad e^{-t_1\frac{R}{L}} = \frac{\frac{E}{R}}{I_{\max}+\frac{E}{R}}$$

$$\therefore \qquad -t_1 \frac{R}{L} = ln\left[\frac{\frac{E}{R}}{I_{max} + \frac{E}{R}}\right]$$

$$\therefore \qquad t_1 = \frac{L}{R} ln\left[\frac{I_{max} + \frac{E}{R}}{\frac{E}{R}}\right]$$

$$\therefore \qquad t_1 = \frac{L}{R} ln\left(1 + \frac{RI_{max}}{E}\right) \qquad \text{... (4.2.12)}$$

This equation gives the time at which the load current will be zero or discontinuous.

Example 4.2.5 *With the help of a neat circuit diagram and relevant waveforms, explain the operation of a step-down (type A) chopper feeding an active (RLE) load, if the load current is ripple free, obtain an expression for the average supply current in terms of the duty cycle.*

Solution : Fig. 4.2.5 shows an equivalent circuit of the chopper.

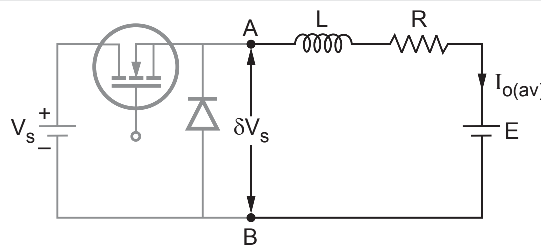


Fig. 4.2.5 Chopper with active load

The average voltage applied across the load points A-B is δV_s. Hence writing KVL to the load loop,

$$L\frac{di_o(t)}{dt} + RI_{o(av)} + E = \delta V_s$$

Here $\qquad i_o(t) = I_{o(av)}$ i.e. constant and ripple free.

Hence $\qquad \dfrac{di_o(t)}{dt} = 0.$

$$\therefore \qquad RI_{o(av)} + E = \delta V_s$$

$$\therefore \qquad I_{o(av)} = \frac{\delta V_s - E}{R}$$

This is the average supply current in terms of duty cycle 'δ'.

Example 4.2.6 *A chopper circuit drives an inductive load from 200 V DC supply. Given the load resistance as 4 Ω, the average load current as 30 A and operating frequency is 400 Hz. Compute the ON period and OFF period of the chopper. Also determine the duty cycle of the chopper.*

Solution : Given data :

Supply voltage $V_s = 200\ V$, Load resistance $R = 4\ \Omega$

Output current $I_{o\,(av)} = 30\ A$, Frequency $f = 400\ Hz$

i) To obtain $V_{o\,(av)}$

Output average voltage is given as

$$V_{o\,(av)} = R \times I_{o\,(av)} = 4 \times 30 = 120\ \text{V}$$

ii) To obtain δ

We know that

$$V_{o\,(av)} = \delta\, V_s$$

$$\therefore \quad \delta = \frac{V_{o(av)}}{V_s} = \frac{120\ \text{V}}{200\ \text{V}} = 0.6$$

iii) To obtain T_{on} and T_{off}

We know that,

$$\delta = \frac{T_{on}}{T} = T_{on} \times f$$

$$\therefore \quad T_{on} = \frac{\delta}{f} = \frac{0.6}{400} = 1.5\ \text{ms}$$

and $$T = T_{on} + T_{off}$$

$$\therefore \quad T_{off} = T - T_{on} = \frac{1}{f} - T_{on}$$

$$= \frac{1}{400} - 1.5 \times 10^{-3} = 1\ \text{ms}$$

Example 4.2.7 *A DC chopper has a resistive load of 20 Ω and input voltage $V_s = 220\ V$. When the chopper is on, its voltage drop is 1.5 V and chopping frequency is 10 kHz. If duty cycle is 80 % determine the average output voltage, rms output voltage and chopper on time.*

Solution : Given data :

Supply voltage $V_s = 220$, Drop in switch $V_T = 1.5\ \text{V}$

Frequency f = 10 kHz, Duty cycle $\delta = 0.8$

Load resistance $R = 20\ \Omega$

i) To determine $V_{o\,(av)}$

$V_{o\,(av)}$ is given as,

$$V_{o(av)} = \delta\, V_s$$

Considering the drop in the switch,

$$V_{o\,(av)} = \delta\,(V_s - V_T) = 0.8\,(220 - 1.5) = 174.8$$

ii) To determine $V_{o(rms)}$

$V_{o(rms)}$ is given as,

$$V_{o(rms)} = \sqrt{\delta}\, V_s$$

Considering drop in the switch,

$$V_{o(rms)} = \sqrt{\delta}\,(V_s - V_T)$$

$$= \sqrt{0.8}\,(220 - 1.5) = 195.4 \text{ V}$$

iii) To determine T_{on}

Duty cycle is given as,

$$\delta = \frac{T_{on}}{T} = f\, T_{on}$$

$$\therefore \quad T_{on} = \frac{\delta}{f} = \frac{0.8}{10000} = 80 \;\; \mu\, sec$$

Example 4.2.8 *A chopper is supplying an inductive load with a freewheeling diode. The load inductance is 5H and resistance is 10Ω. The input to the chopper is 200 V and the chopper frequency is 100 Hz. The ON to OFF time ratio is 2 : 3 calculate*

i) Average load current ii) Limits between which current fluctuates.

Solution : Given data :

Supply voltage, V_s = 200 V

Frequency, f = 100 Hz

$$\text{ON/OFF ratio} = \frac{2}{3}$$

$$\text{Duty cycle,} \quad \delta = \frac{2}{2+3} = 0.4$$

Resistance, R = 10 Ω

Inductance, L = 5 H

i) To obtain load current

The average value of output voltage is given as,

$$V_{o(av)} = \delta\, V_s = 0.4 \times 200 = 80 \text{ V}$$

Average load current will be,

$$I_{o(av)} = \frac{V_{o(av)}}{R} = \frac{80}{10} = 8 \text{ A}$$

ii) To obtain I_{min} and I_{max}

I_{min} is given by equation (4.2.3) as,

$$I_{min} = I_{max}\; e^{-(1-\delta)T\frac{R}{L}} - \frac{E}{R}\left(1 - e^{-(1-\delta)T\frac{R}{L}}\right)$$

Here $E = 0$, hence above equation will be,

$$I_{min} = I_{max}\; e^{-(1-\delta)\,T\,\frac{R}{L}}$$

Putting the values with $T = \frac{1}{f} = \frac{1}{100}$,

$$I_{min} = I_{max}\; e^{-(1-0.4)\,\frac{10}{100\times 5}}$$

$$= 0.98807\; I_{max} \qquad \text{... (4.2.13)}$$

I_{max} is given by equation (4.2.4) as,

$$I_{max} = I_{min}\; e^{-\delta T\frac{R}{L}} + \frac{V_s - E}{R}\left(1 - e^{-\delta T\frac{R}{L}}\right)$$

Since $E = 0$, $I_{max} = I_{min}\; e^{-\delta T\frac{R}{L}} + \frac{V_s}{R}\left(1 - e^{-\delta T\frac{R}{L}}\right)$

$$= I_{min}\; e^{-0.4\,\frac{10}{100\times 5}} + \frac{200}{10}\left(1 - e^{-0.4\times\frac{10}{100\times 5}}\right)$$

$$= I_{min} \times 0.99203 + 0.15936$$

Putting the value of I_{min} (equation 4.2.13) in above equation,

$$I_{max} = 0.98807\; I_{max} \times 0.99203 + 0.15936$$

$$\therefore \quad I_{max} = 8.0465 \text{ A}$$

And I_{min} will be (from equation 4.2.13),

$$I_{min} = 0.98807\; I_{max} = 0.98807 \times 8.0465 = 7.9505 \text{ A}$$

$I_{o(av)}$ can also be calculated as,

$$I_{o(av)} = \frac{I_{max}+I_{min}}{2} = \frac{8.0465+7.9505}{2} = 7.9985 \text{ A}$$

Example 4.2.9 *A chopper is feeding an R-L load as shown in the Fig. 4.2.6. $V_s = 220$ V, $R = 5\ \Omega$, $L = 7.5$ mH, f = 1 kHz, δ = 0.5 and E = 0 volts. Calculate -*

i) Minimum instantaneous load current, I_{min}

ii) Peak instantaneous load current, I_{max}

iii) Maximum peak to peak load ripple current.

iv) Average value of load current, $I_{o(av)}$

v) rms load current $I_{o(rms)}$

vi) Effective input resistance R_i seen by the source.

vii) rms chopper current, $I_{T(rms)}$

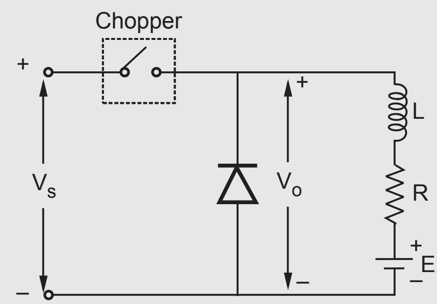


Fig. 4.2.6

Solution : The given data is

$$V_s = 220 \text{ V}$$

$$R = 5\ \Omega$$

$$L = 7.5 \text{ mH}$$

$$f = 1 \text{ kHz} \qquad \therefore \quad T = \frac{1}{f} = 0.001$$

$$\delta = 0.5$$

$$E = 0$$

i) and ii) To obtain I_{min} and I_{max}

The expressions for I_{min} and I_{max} are given by equation (4.2.3) and equation (4.2.4) Putting values in equation (4.2.3),

$$I_{min} = I_{max}\, e^{-(1-0.5)\times 0.001\times \frac{5}{7.5\times 10^{-3}}} - \frac{0}{R}\left[1-e^{-(1-0.5)\times 0.001\times \frac{5}{7.5\times 10^{-3}}}\right]$$

$$\therefore \quad I_{min} = 0.7165\ I_{max} + 0 \qquad \text{.... (4.2.14)}$$

Similarly putting values in equation (4.2.4) we get,

$$I_{max} = I_{min}\, e^{-0.5\times 0.001\times \frac{5}{7.5\times 10^{-3}}} + \frac{220-0}{5}\left[1-e^{-0.5\times 0.001\times \frac{5}{7.5\times 10^{-3}}}\right]$$

$$= 0.7165\ I_{min} + 12.4726 \qquad \text{... (4.2.15)}$$

Solving equation (4.2.14) and above equation we get,

$$I_{max} = 25.63 \text{ A and } I_{min} = 18.36 \text{ A}$$

iii) Maximum peak to peak ripple in load current

The ripple in load current is,

$$I_{o(p-p)} = I_{max} - I_{min} = 25.63 - 18.36 = 7.27 \text{ A}$$

Maximum peak to peak ripple in load current is given by equation (4.2.9),

$$I_{o\,max(p-p)} = \frac{V_s}{R}\tan h\left(\frac{TR}{4L}\right) = \frac{220}{5}\tan h\left(\frac{0.001\times 5}{4\times 7.5\times 10^{-3}}\right)$$

$$= 7.266 \text{ A}$$

Thus the maximum ripple is 7.266 ≈ 7.27 A since $\delta = 0.5$.

iv) Average value of load current

The average value of load current is approximately given as,

$$I_{o(av)} = \frac{I_{max} + I_{min}}{2}$$

$$= \frac{25.63 + 18.36}{2} = 21.995 \approx 22 \text{ A.}$$

v) rms load current

The rms load current is given as,

$$I_{o(rms)} = \left\{ I_{min}^2 + \frac{I_{o(p-p)}^2}{3} + I_{min}\, I_{o(p-p)} \right\}^{1/2} \quad \text{... (4.2.16)}$$

Putting values,

$$I_{o(rms)} = \left\{ 18.36^2 + \frac{7.27^2}{3} + 18.36 \times 7.27 \right\}^{1/2} = 22.095 \text{ A}$$

vi) Effective input resistance

The average source current can be calculated from average load current as

$$I_{s(av)} = \delta I_{o(av)}$$

$$= 0.5 \times 22 = 11 \text{ A}$$

$$\therefore \qquad \text{Input resistance } R_i = \frac{V_s}{I_{s(av)}}$$

$$= \frac{220}{11} = 20\ \Omega$$

vii) rms chopper current

The rms chopper current can be calculated as (See Fig. 4.2.3),

$$I_{T(rms)} = \left\{\frac{1}{T}\int_0^{\delta T} i^2(t)\,dt\right\}^{1/2} = \sqrt{\delta}\left\{I_{\min}^2 + \frac{I_{o(p-p)}^2}{3} + I_{\min} I_{o(p-p)}\right\}^{1/2}$$

$$= \sqrt{0.5}\left\{18.36^2 + \frac{7.27^2}{3} + 18.36 \times 7.27\right\}^{1/2} = 15.62\ \text{A}$$

This value can also be calculated as,

$$I_{T(rms)} = \sqrt{\delta}\ I_{o(rms)} = \sqrt{0.5} \times 22.095$$

$$= 15.62\ \text{A}$$

Example 4.2.10 *An SCR chopper is supplying an inductive load with R = 10 Ω and L = 2 H. The DC supply to the chopper is 200 V. If the chopper is operating at a frequency of 200 Hz and ON/OFF time ratio of chopper is 2 : 3, calculate,*
i) Maximum and minimum values of load current in one cycle of chopper operation under steady state conditions. ii) Average load current

Solution : Given data

Load resistance, R = 10 Ω

Load inductance, L = 2 H

Supply voltage, V_s = 200 V

Chopper frequency, f = 200 Hz, hence $T = \frac{1}{200}$

ON/OFF ratio = 2 : 3

$$\therefore \qquad \delta = \frac{T_{on}}{T_{on} + T_{off}} = \frac{2}{2+3} = \frac{2}{5} = 0.4$$

i) To obtain I_{min} and I_{max}

From equation (4.2.3),

$$I_{min} = I_{\max} e^{-(1-\delta) T \frac{R}{L}} - \frac{E}{R}\left(1 - e^{-(1-\delta) T \frac{R}{L}}\right)$$

Here, $E = 0$, hence above equation becomes,

$$I_{min} = I_{max} e^{-(1-0.4)\cdot\frac{1}{200}\cdot\frac{10}{2}}$$

$$= 0.98511\, I_{max} \quad \ldots (4.2.17)$$

Similarly from equation (4.2.4),

$$I_{max} = I_{min} e^{-\delta T \frac{R}{L}} + \frac{V_s - E}{R}\left(1 - e^{-\delta T \frac{R}{L}}\right)$$

$$= I_{min} e^{-0.4\cdot\frac{1}{200}\cdot\frac{10}{5}} + \frac{200-0}{10}\left(1 - e^{-0.4\cdot\frac{1}{200}\cdot\frac{10}{5}}\right)$$

$$= 0.996\, I_{min} + 0.07984 \quad \ldots (4.2.18)$$

Putting for I_{min} from equation (4.2.17) in above equation,

$$I_{max} = 0.996\,(0.98511\, I_{max}) + 0.07984$$

$$\therefore \quad I_{max} = 4.24 \text{ A}$$

Similarly from equation (4.2.17) we can get I_{min} as,

$$I_{min} = 0.98511\, I_{max}$$

$$= 0.98511 \times 4.24 = 4.1768 \text{ A}$$

ii) To obtain average load current

The average load current is given as,

$$I_{o(av)} = \frac{I_{max} + I_{min}}{2} = \frac{4.24 + 4.1768}{2} = 4.2 \text{ A}$$

Example 4.2.11 *For the chopper circuit shown in Fig. 4.2.7, the duty cycle, k = 0.5 and chopping frequency f = 5 kHz. Determine*

i) Minimum instantaneous load current

ii) Peak instantaneous load current

iii) Maximum peak to peak current in the load

iv) Average load current

v) Rms load current

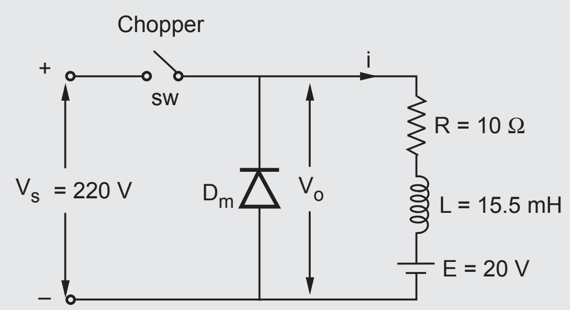


Fig. 4.2.7 Chopper of example 4.2.11

Solution : The given data is,

Supply voltage, $V_s = 220\ V$

Duty cycle, $\delta = 0.5$

Chopper frequency, $f = 5000\ Hz.$

Hence $T = \frac{1}{5000}$

Load resistance, $R = 10\ \Omega$

Load inductance, $L = 15.5\ mH$

and $E = 20\ V$

i) and ii) To obtain I_{max} and I_{min}

From equation (4.2.3) I_{min} is given as,

$$I_{min} = I_{max} e^{-(1-\delta)T\frac{R}{L}} - \frac{E}{R}\left[1-e^{-(1-\delta)T\frac{R}{L}}\right]$$

Putting values in above equation,

$$I_{min} = I_{max} e^{-(1-0.5)\cdot\frac{1}{5000}\cdot\frac{10}{15.5\times10^{-3}}} - \frac{20}{10}\left[1-e^{-(1-0.5)\cdot\frac{1}{5000}\cdot\frac{10}{15.5\times10^{-3}}}\right]$$

$$= 0.9375\ I_{max} - 0.12496 \qquad \text{... (4.2.19)}$$

From equation (4.2.4) I_{max} is given as,

$$I_{max} = I_{min} e^{-\delta T\frac{R}{L}} + \frac{V_s - E}{R}\left(1-e^{-\delta T\frac{R}{L}}\right)$$

Putting values in above equation,

$$I_{max} = I_{min} e^{-0.5\cdot\frac{1}{5000}\cdot\frac{10}{15.5\times10^{-3}}} + \frac{220-20}{10}\left(1-e^{-0.5\cdot\frac{1}{5000}\cdot\frac{10}{15.5\times10^{-3}}}\right)$$

$$= 0.9375\ I_{min} + 1.2495$$

Putting for I_{min} from equation (4.2.19) in above equation,

$$I_{max} = 0.9375\ (0.9375\ I_{max} - 0.12496) + 1.2495 = 9.351\ A$$

Putting this value of I_{max} in equation (4.2.19) we get,

$$I_{min} = 0.9375\ (9.351) - 0.12496 = 8.642\ \text{A}$$

iii) Maximum peak to peak current in the load

Maximum peak to peak current in the load is given as,

$$I_{o(p\text{-}p)} = I_{max} - I_{min} = 9.351 - 8.642 = 0.709\ \text{A}$$

iv) To obtain average load current

Average load current is given as,

$$I_{o(av)} = \frac{I_{max} + I_{min}}{2} = \frac{9.351 + 8.642}{2} = 8.996 \approx 9\text{A}$$

Average load current can also be obtained by following equation,

$$I_{o(av)} = \frac{V_{o(av)}}{R} = \frac{\delta V_s - E}{R} = \frac{0.5 \times 220 - 20}{10} = 9\ \text{A}$$

v) RMS load current

The rms value of load current is given by equation 4.3.16 as,

$$I_{o(rms)} = \left[I_{min}^2 + \frac{I_{o(p-p)}^2}{3} + I_{min} I_{o(p-p)} \right]^{\frac{1}{2}}$$

Putting values in above equation,

$$I_{o(rms)} = \left[(8.642)^2 + \frac{(0.709)^2}{3} + 8.642 \times 0.709 \right]^{\frac{1}{2}} = 8.9988 \approx 9\ \text{A}$$

Example 4.2.12 *A step-up chopper feeds DC motors from 100 V DC supply. If the armature resistance is 1 Ω and the motor back emf is 50 V, calculate the range of duty cycles to obtain no-load to full load armature current variation of 2 A to 20 A. Assume the current to be ripple free.*

Solution : Given : V_s=100 V, R_a = 1 Ω, E_b = 50 Ω

$$I_{o(\min)} = 2\ \text{A}, \quad I_{o(\max)} = 20\ \text{A}$$

$$V_{o\,(av)(\min)} = E_b + I_{o(\min)} R_a = 50 + 2 \times 1 = 52\ \text{V}$$

and $$V_{o(av)(\max)} = E_b + I_{o(\max)} R_a = 50 + 20 \times 1 = 70\ \text{V}$$

$$\therefore \quad \delta_{\min} = \frac{V_{o(av)\min}}{V_s} = \frac{52}{100} = 0.52 \text{ or } 52\ \%$$

$$\therefore \quad \delta_{\max} = \frac{V_{o(av)\max}}{V_s} = \frac{70}{100} = 0.7 \text{ or } 70\ \%$$

Example 4.2.13 *A step-down chopper feeds a level load for a 200 V DC supply. If the resistance of the level load is 10 Ω, calculate the range of average and rms values of the supply current for duty cycle variation of 25 % to 75 %.*

Solution : Given : $V_s = 200\ V$, R = 10 Ω, $\delta_1 = 25\,\%$ and $\delta_2 = 75\,\%$.

Average value of supply current

If we assume that the output current is constant and ripple free, then supply current waveform will be as shown in Fig. 4.2.8. This waveform is drawn with the help of Fig. 4.2.2.

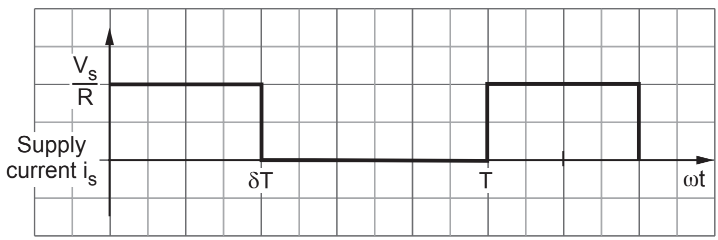


Fig. 4.2.8 Supply current waveform

Average value of supply current will be,

$$I_{s(av)} = \frac{1}{T}\int_0^T i_s(\omega t)\, d\omega\, t = \frac{1}{T}\int_0^{\delta T} \frac{V_s}{R}\, d\omega\, t = \frac{V_s}{R}\cdot\frac{\delta T}{T} = \frac{\delta V_s}{R}$$

For δ = 25 %, $\quad I_{s(av)} = \frac{0.25 \times 200}{10} = 5\ \text{A}$

For δ = 75 %, $\quad I_{s(av)} = \frac{0.75 \times 200}{10} = 15\ \text{A}$

RMS value of supply current

RMS value of supply current will be,

$$I_{s(rms)} = \left[\frac{1}{T}\int_0^T i_s^2(\omega t)\, d\omega\, t\right]^{\frac{1}{2}} = \left[\frac{1}{T}\int_0^{\delta T}\left(\frac{V_s}{R}\right)^2 d\omega\, t\right]^{\frac{1}{2}} = \frac{\sqrt{\delta}\, V_s}{R}$$

For δ = 25 %, $\quad I_{s(rms)} = \frac{\sqrt{0.25} \times 200}{10} = 10\ \text{A}$

For δ = 75 %, $\quad I_{s(rms)} = \frac{\sqrt{0.75} \times 200}{10} = 17.32\ \text{A}$

Review Question

1. *Explain the operation of step down chopper for inductive load with the help of waveforms.*

SPPU : Dec.-10, Marks 6

4.3 Step-up Chopper

SPPU : Dec.-09,10,11,13,18, May-15,18

In the previous section we studied step down chopper. The average value of output voltage $V_{o(av)}$ is always less than or equal to supply voltage V_s in step down chopper. In the step-up chopper $V_{o(av)} \geq V_s$.

Fig. 4.3.1 shows the circuit diagram of the step-up chopper. Observe that there is an inductance in series with the supply V_s. A switch (transistor GTO, MOSFET etc) is connected across inductance and supply. A filter capacitor C is used across the load to make v_o smooth. The diode D_1 blocks the reverse flow of output current when switch is turned 'on'. Fig. 4.3.2 shows the waveforms of this step-up chopper. The drive of the switch is shown at the begining. The transistor is turned on from 0 to δT. Hence current flows through the inductance from the supply. The inductance current rises and inductance stores the energy from the supply. The equivalent circuit-I in Fig. 4.3.2 shows this operation. Note that the drop in the inductance is $L \frac{d\,i_L}{dt}$ with the polarity shown. The voltage $v_{AB} = 0$ since transistor is conducting. Fig. 4.3.2 also show the output voltage and current waveforms. Here we have assumed that the output voltage and current are continuous and ripple-free. The capacitor maintains the voltage 'v_o' and supplies the current 'i_o' when transistor is 'on'. Hence the diode D_1 is reverse biased and it does not conduct.

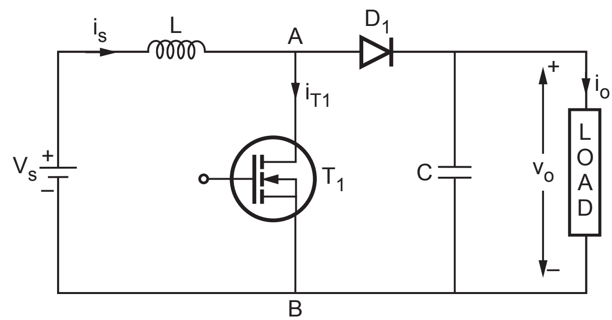


Fig. 4.3.1 Step-up chopper having transistor as a switch

At δT transistor (switch) is turned off. Hence the inductance generates a large voltage $L \frac{d\,i_L}{dt}$ to maintain the current i_L in the same direction. Note the polarity of inductance voltage in equivalent circuit-II of Fig. 4.3.2. The diode D_1 is forward biased and it starts conducting. Thus the output voltage will be

$$v_o = V_s + L \frac{d\,i_L}{dt}$$

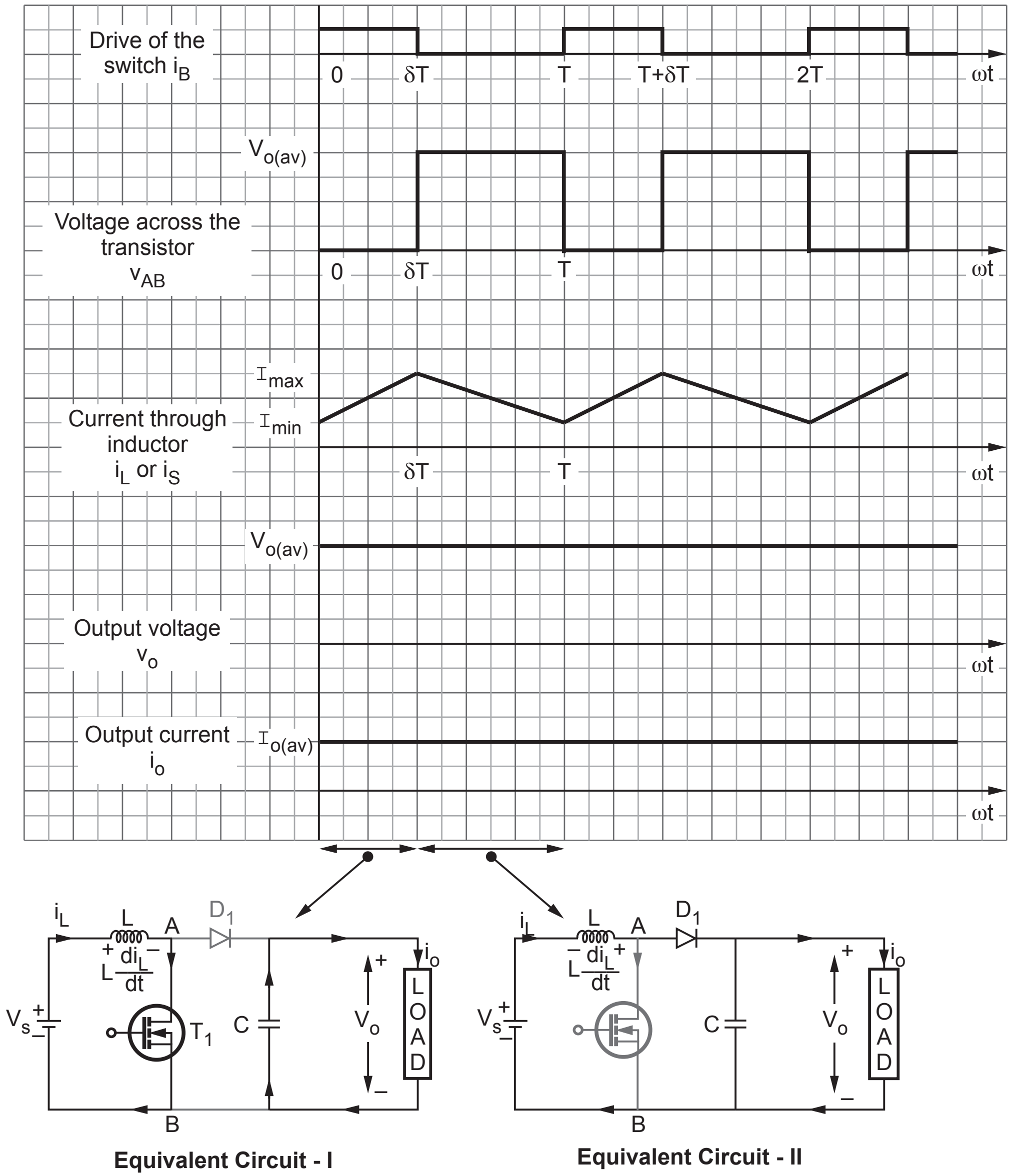


Fig. 4.3.2 Waveforms of the step-up chopper for ripple-free output voltage and currents

Thus the output voltage of the chopper is greater than supply voltage V_s. This shows the step-up operation. The voltage induced in the inductance adds to the supply voltage and this total voltage appears as output voltage. The capacitor also charges to this boosted voltage. The inductance as well as supply provides the energy to the load from δT to T (i.e. when the switch is off). The current through the inductance decreases because its stored energy goes on reducing. At T, the transistor is again turned on and the cycle repeats.

Examples for Understanding

Example 4.3.1 *Derive an expression for average output voltage of the step-up chopper.*

SPPU : Dec.-11, Marks 4; Dec.-09,13, May-15,18, Marks 8

Solution : Let the average voltage across the inductance be V_L. The value of this voltage over one cycle (0 to T) will be,

$$V_L = \frac{1}{T}\int_0^T v_L(t)\, dt$$

The inductance voltage is $v_L(t) = L\frac{d\,i_L}{dt}$. Hence above equation will be,

$$V_L = \frac{1}{T}\int_0^T L\frac{d\,i_L(t)}{dt}\, dt = \frac{L}{T}\int_0^T d\,i_L(t) \qquad \text{... (4.3.1)}$$

The above integration is with respect to inductance current $d\,i_L(t)$, hence we should change the limits appropriately.

At $t = 0$ (lower limit), $i_L(t) = I_{\min}$

and at $t = T$ (upper limit), $i_L(t) = I_{\min}$

Hence equation (4.3.1) will be,

$$V_L = \frac{L}{T}\int_{I_{\min}}^{I_{\min}} d\,i_L(t) = \frac{L}{T}\left[i_L(t)\right]_{I_{\min}}^{I_{\min}}$$

$$= \frac{L}{T}\left[I_{\min} - I_{\min}\right] = 0 \qquad \text{... (4.3.2)}$$

Thus the average voltage across the inductance is zero. The inductance stores the energy when the switch is 'ON' and supplies the energy to the load when the switch is 'OFF'.

Now let us consider the loop formed by supply voltage V_s, inductance and switch. This loop is shown in Fig. 4.3.3. The voltage across the switch is v_{AB}. The waveform of v_{AB} is shown in Fig. 4.3.2. The average value of v_{AB} can be obtained as follows :

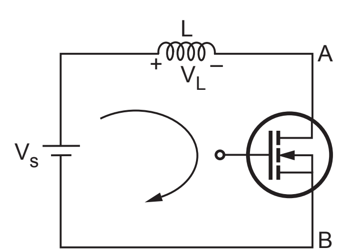


Fig. 4.3.3 Loop formed by supply, inductance and switch in step-up chopper

$$V_{AB} = \frac{1}{T}\int_0^T v_{AB}(t)\, dt$$

In Fig. 4.3.2 observe that $v_{AB} = V_{o(av)}$ from δT to T and rest of the period it is zero. Hence above equation becomes,

$$V_{AB} = \frac{1}{T}\int_{\delta T}^{T} V_{o(av)}\, dt = \frac{V_{o(av)}}{T}(T-\delta T)$$

$$= V_{o(av)}(1-\delta) \qquad \text{... (4.3.3)}$$

By KVL to the loop shown in Fig. 4.3.3,

$$V_s = V_L + V_{AB}$$

The above equation holds for steady state. Putting values from equations (4.3.2) and (4.3.3) in above equation,

$$V_s = 0 + V_{o(av)}(1-\delta)$$

$$\therefore \quad V_{o(av)} = \frac{V_s}{1-\delta} \qquad \text{... (4.3.4)}$$

This equation gives the value of average output voltage. When $\delta = 0$, $V_{o(av)} = V_s$ and $V_{o(av)} \to \infty$ as δ approaches to unity. The value of duty cycle 'δ' lies between 0 and 1.

Example 4.3.2 *Explain the principle of operation of a step up chopper. A step up DC chopper has an input of 200 volts and an output of 250 volts. The blocking period in each cycle of operation is* 0.6×10^{-3} *seconds. Find the period of conduction in each cycle.*

Solution : Given : $V_{o(av)}$ = 250 volts

$$V_s = 200 \text{ volts}$$

$$T_{off} = 0.6\times10^{-3} \text{ sec}$$

For the step up chopper, the average value of output voltage is given as,

$$V_{o(av)} = \frac{V_s}{1-\delta} \text{ from equation (4.3.4)}$$

Here $\delta = \dfrac{T_{on}}{T_{on}+T_{off}}$ is the duty cycle.

Let us calculate δ first. Putting $V_{o(av)}$ *and* V_s,

$$250 = \frac{200}{1-\delta}$$

$$\therefore \quad \delta = 0.2$$

And $\delta = \dfrac{T_{on}}{T_{on}+T_{off}}$

Putting for δ and T_{off},

$$0.2 = \frac{T_{on}}{T_{on} + 0.6 \times 10^{-3}}$$

$$\therefore \quad T_{on} = 0.15 \times 10^{-3}$$

Thus the period of conduction in each cycle is 0.15×10^{-3} seconds.

Example 4.3.3 *Input to the step up chopper is 200 V. The output required is 600 V. If the conducting time of thyristor is 200 μ s, compute -*

i) Chopping frequency ii) If pulse width is halved for constant frequency of operation, find the new output voltage.

Solution : The given data is,

$$V_s = 200 \text{ V}$$

$$V_{o(av)} = 600 \text{ V}$$

$$T_{on} = 200 \ \mu s$$

i) To obtain chopping frequency

For the step up chopper, the average value of output voltage is given as,

$$V_{o(av)} = \frac{V_s}{1-\delta}$$

$$\therefore \quad 600 = \frac{200}{1-\delta}$$

$$\therefore \quad \delta = 0.6667$$

The duty cycle δ is given as,

$$\delta = \frac{T_{on}}{T_{on} + T_{off}} = \frac{T_{on}}{T}$$

$$= f\, T_{on} \qquad \text{since } f = \frac{1}{T}$$

$$\therefore \quad f = \frac{\delta}{T_{on}} = \frac{0.6667}{200 \times 10^{-6}}$$

$$= 3333.33 \text{ Hz} \approx 3.3 \text{ kHz}$$

This is the chopping frequency of the chopper.

ii) To obtain new output voltage

The chopping frequency is constant. Hence

$$T = \frac{1}{f} = \frac{1}{3333.33} = 3 \times 10^{-4} = 300 \ \mu s$$

The T_{on} pulse width is halved. Hence new T_{on} will be $\frac{200 \mu s}{2} = 1000\ \mu s$.

Hence duty cycle will be,

$$\delta = \frac{T_{on}}{T} = \frac{100 \times 10^{-6}}{300 \times 10^{-6}} = 0.3333$$

The new output voltage of chopper will be,

$$V_{o(av)} = \frac{V_s}{1-\delta} = \frac{200}{1-0.3333} = 300 \text{ V}$$

Thus the output is also reduced by half.

Example 4.3.4 *A step up chopper has input voltage of 220 V and output voltage of 660 volts. If the nonconducting time of thyristor chopper is 100 μsec, compute the pulse width of output voltage. In case pulsewidth is halved for constant frequency operation, find new output voltage.*

Solution : Given data

Supply voltage, $V_s = 220$ V

output voltage, $V_{o(av)} = 660$ V

$T_{off} = 100\ \mu$ sec

i) To calculate T_{on}

We know that,

$$V_{o(av)} = \frac{V_s}{1-\delta}$$

$$\therefore \quad 660 = \frac{220}{1-\delta}$$

$$\therefore \quad \delta = 0.6666 \text{ or } \frac{2}{3}$$

Duty cycle is given as,

$$\delta = \frac{T_{on}}{T_{on}+T_{off}}$$

$$\frac{2}{3} = \frac{T_{on}}{T_{on}+100 \times 10^{-6}}$$

$$\therefore \quad T_{on} = 200\ \mu\text{ sec}$$

ii) To obtain output voltage if T_{on} is halved

Chopper frequency is,

$$f = \frac{1}{T} = \frac{1}{T_{on} + T_{off}} = \frac{1}{200\,\mu s + 100\,\mu s} = \frac{1}{300 \times 10^{-6}}$$

Hence chopper period is,

$$T = \frac{1}{f} = 300 \times 10^{-6} \text{ sec}$$

Since T_{on} is halved, it will be,

$$T_{on} = \frac{200\,\mu s}{2} = 100\ \mu \text{ sec}$$

$$\therefore \text{ Duty cycle, } \delta = \frac{T_{on}}{T} = \frac{100\,\mu\text{ sec}}{300\,\mu\text{ sec}} = \frac{1}{3}$$

Therefore new output voltage will be,

$$V_{o(av)} = \frac{V_s}{1-\delta} = \frac{220}{1-\frac{1}{3}} = 330 \text{ V}$$

Thus the output voltage is also reduced by half.

4.3.1 Use of Step-up Operation for Energy Transfer

Normally step-up operation is used in chopper based dc motor drives for energy transfer. The energy is transferred from fixed or variable source (normally dc motors) to fixed dc source (i.e. supply). Fig. 4.3.4 shows the circuit diagram for such operation. The waveforms and functioning of this circuit is same as shown in Fig. 4.3.2.

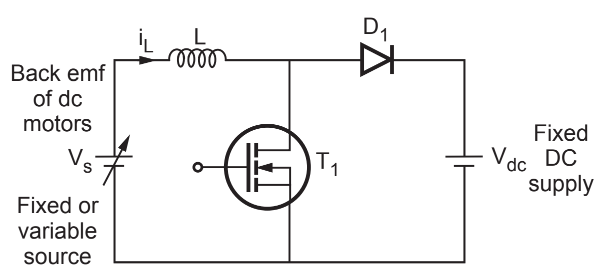


Fig. 4.3.4 Use of step-up operation

The step-up operation is normally used in chopper based dc drives. Let the voltage V_s be due to back emf of the motor. It will depend upon the speed of the motor. Normally during the braking the speed is decreased from the large values. The energy associated with the back emf (speed) of the motor is fedback to the dc supply (V_{dc}).

This operation is called *regenerative braking*. In regenerative braking, the braking energy is not wasted, rather it is fedback to the supply. This increases efficiency of the chopper drives.

When the switch is 'on', the current flows through the inductance. The loop formed is given in Fig. 4.3.5. The inductance stores the energy from the source V_s, when switch is 'on'. The KVL to the above loop gives,

$$V_s = \frac{d\,i_1(t)}{dt} \qquad \text{... (4.3.5)}$$

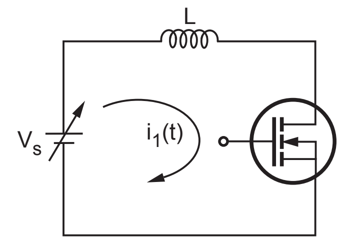


Fig. 4.3.5 Inductance stores the energy from V_s, when the switch is 'on'

If the inductance stores the energy, then it goes on saturating. Hence $i_1(t)$ goes on increasing. Hence $\frac{d\,i_1(t)}{dt}$ must be positive. i.e. from equation 4.4.5 we can write,

$$V_s = \frac{d\,i_1(t)}{dt} > 0$$

$$\therefore \qquad V_s > 0 \qquad \text{... (4.3.6)}$$

Now consider the situation when chopper switch is turned off. From Fig. 4.3.4 the equivalent circuit will be as shown in Fig. 4.3.6 below.

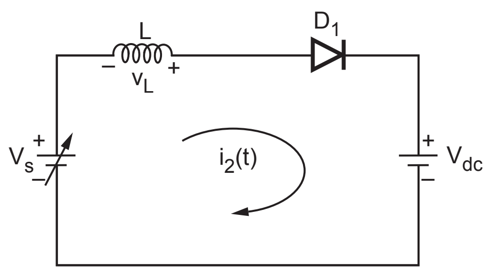


Fig. 4.3.6 Inductance supplies the energy to the supply when switch is off

As shown in the above figure, the current flows through inductance and diode D_1 to the supply V_{dc}. The inductance generates the voltage v_L with the polarity as shown in Fig. 4.3.6. The energy stored in the inductance is supplied to V_{dc}.

We can write KVL in Fig. 4.3.6 as,

$$V_s = L\,\frac{d\,i_2(t)}{dt} + V_{dc} \qquad \text{... (4.3.7)}$$

$$\therefore \qquad V_s - V_{dc} = L\,\frac{d\,i_2(t)}{dt} \qquad \text{... (4.3.8)}$$

Since the energy in the inductance is transferred to V_{dc}, current $i_2(t)$ goes on reducing. Hence $\frac{d\,i_2(t)}{dt}$ must be negative. i.e. above equation becomes,

$$V_s - V_{dc} = L\,\frac{d\,i_2(t)}{dt} < 0$$

$\therefore \qquad V_s - V_{dc} \;<\; 0$

or $\qquad V_s \;<\; V_{dc}$ ... (4.3.9)

Thus energy is transferred to V_{dc} when above condition is satisfied. We can combine above equation and equation (4.3.6), i.e.,

$$0 \;<\; V_s < V_{dc} \qquad \text{... (4.3.10)}$$

This is the condition for power transfer from fixed or variable source (V_s) to the fixed dc supply (V_{dc}).

Here note that step up operation is used for regenerative braking or to transfer power from motors to the dc supply. Condition of equation 4.4.10 must be satisfied to implement such operation.

Review Questions

1. *Explain the operation of step-up chopper with the help of waveforms.*
   SPPU : Dec.-09, 13, Marks 8, Dec.-11, May-15,18, Marks 4
2. *Explain the use of step-up operation for energy transfer.* **SPPU : Dec.-10, Marks 4**
3. *Explain the principle of step up chopper feeding R-L load, with neat diagrams and waveforms of load voltage, load current, voltage across switch and current through switch. Derive the expression of output voltage.* **SPPU : Dec.-18, Marks 8**

4.4 Chopper Classification (Types) **SPPU : May-15, Dec.-16,18, Marks 8**

In the previous sections we discussed the basic principles of chopper operation. The choppers are classified depending upon the directions of current and voltage flows. These choppers operate in different quadrants of $v_o - i_o$ plane.

There are broadly following types of choppers :

i) Class A chopper ii) Class B chopper

iii) Class C chopper iv) Class D chopper v) Class E chopper

4.4.1 Class A Chopper

The class A chopper operates in the first quadrant of $v_o - i_o$ plane as shown in Fig. 4.4.1. The output current and output voltage both are positive. These values never go negative. This type of chopper operates as the rectifier. The energy always flows from source to the load. Hence it is also called as forward motoring. The step-down chopper discussed earlier is basically class A chopper.

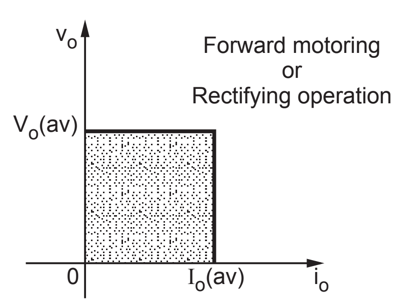


Fig. 4.4.1 Class A chopper operates in the first quadrant

4.4.2 Class B Chopper

The class B chopper operates in the second quadrant of the $v_o - i_o$ plane as shown in Fig. 4.4.2. The load voltage is positive and load current is negative. The load current flows out of the load. Since the current flows from load to the source, the energy is transferred from load to the source. This is also called as inverting operation. Such situation occurs during the braking of dc motor. The energy associated with back emf of the motor is fed back to the source. Hence current becomes negative. Since motor rotates in the same direction, it is called forward regenerative braking. The word *regeneration* means energy is fed from load to the source during braking. Fig. 4.4.3 shows the circuit diagram of class B chopper.

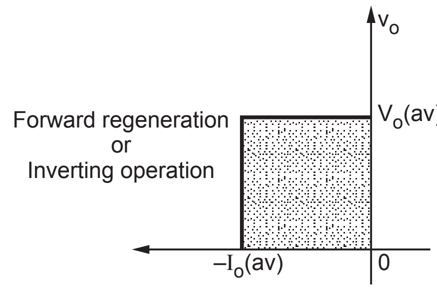


Fig. 4.4.2 Class B chopper operates in the second quadrant

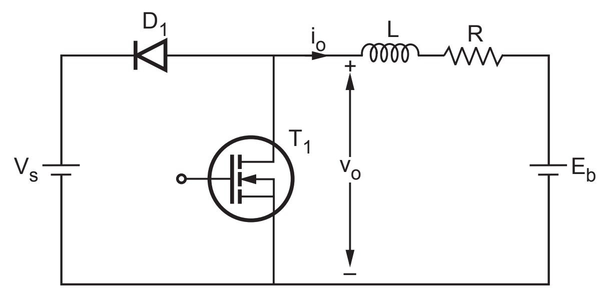


Fig. 4.4.3 Circuit diagram of class B chopper

In the above circuit, the supply voltage is V_s. The diode D_1 allows the current flow only from load to the source. Here motor load is assumed. L and R are the inductance and resistance of the motor. E_b is the back emf of the motor. Here note that E_b is responsible for negative current flow.

When the transistor (i.e. switch) is turned on, the negative current flows from E_b, R, L and T_1. This current keeps on increasing. The waveforms are shown in Fig. 4.4.4. The switch is 'on' from 0 to δT.

The current i_o flows through E_b, R, L and switch in negative direction. Refer to equivalent circuit-I in Fig. 4.4.4. The current rises and reaches to $I_{\max}$ at δT. The inductance stores energy during this period. The energy is supplied by back emf E_b. At δT, the switch is turned off. The diode D_1 is forward biased and the negative output current flows through supply V_s. Equivalent circuit-II in Fig. 4.4.4 shows this situation. The output voltage is equal to $V_{o(av)}$. The current is forced through supply voltage V_s. Thus supply consumes power. This power is transferred from load inductance and E_b. At T, the switch is turned on again and the cycle repeats.

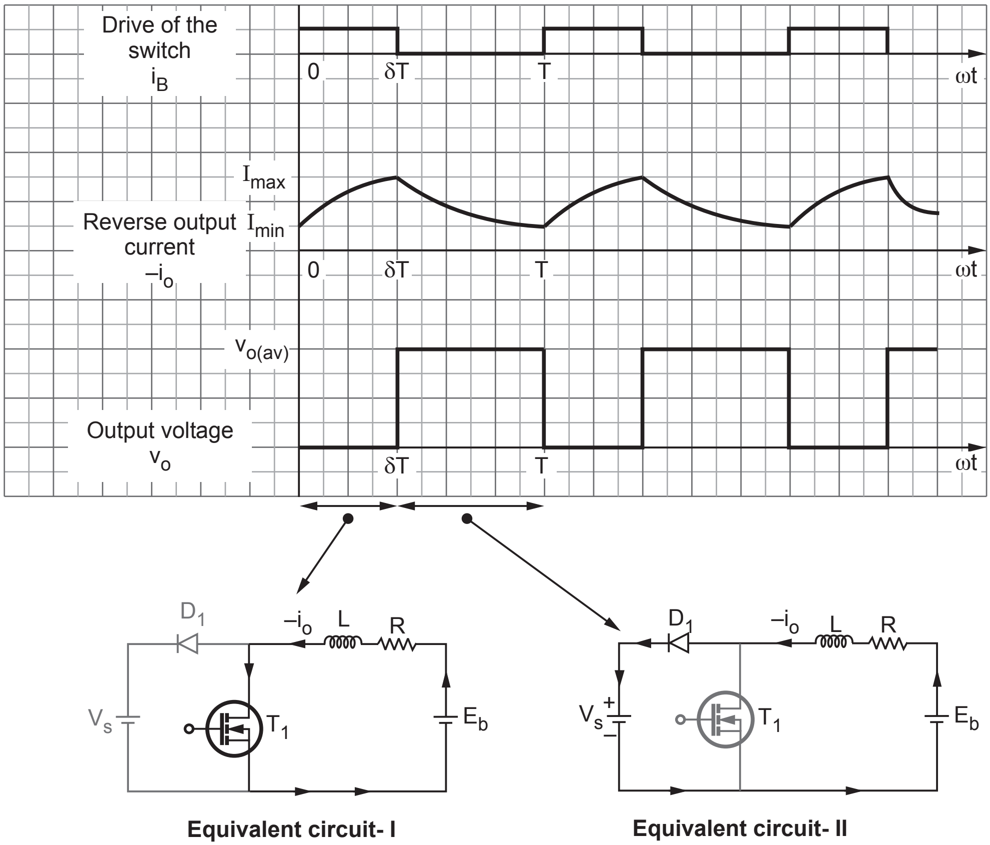


Fig. 4.4.4 Waveforms and operation of class B chopper

The equation for the output current can be obtained on the similar lines as done in example 4.2.1. The expressions for output current are given as follows :

$$i_o(t) = I_{\min} e^{-t\frac{R}{L}} - \frac{E_b}{R}\left(1 - e^{-t\frac{R}{L}}\right) \qquad \text{for } 0 \le t \le \delta T \quad \text{... (4.4.1)}$$

$$i_o(t) = I_{\max} e^{-t\frac{R}{L}} + \frac{V_s - E_b}{R}\left(1 - e^{-t\frac{R}{L}}\right) \qquad \text{for } \delta T \le t \le T \quad \text{... (4.4.2)}$$

Here note that the class B operation is never implemented independently. It takes place in two and four quadrant chopper having motor loads.

4.4.3 Class C Chopper

The class C chopper operates in two quadrants. It is the combination of class A and B choppers. Fig. 4.4.5 shows the quadrants of operation of this chopper. It operates as a rectifier as well as inverter. In the first quadrant forward motoring takes place and in the second quadrant forward regenerative braking takes place.

Fig. 4.4.6 shows the circuit diagram of class C chopper having transistor switches. It is basically obtained by combining class A and B choppers. T_1 and D_2 conducts for the operation in the first quadrant (i.e. class A). In the above circuit diagram, note that whenever T_1 or D_2 conduct, the output current and voltage will be always positive.

Whenever T_2 or D_1 conduct, the chopper operates in the second quadrant (i.e. class B). It is inverting operation. In Fig. 4.4.6 observe that output current is negative whenever T_2 or D_1 conduct. The energy is fed back to the supply when D_1 conducts. Note that v_o always remains positive.

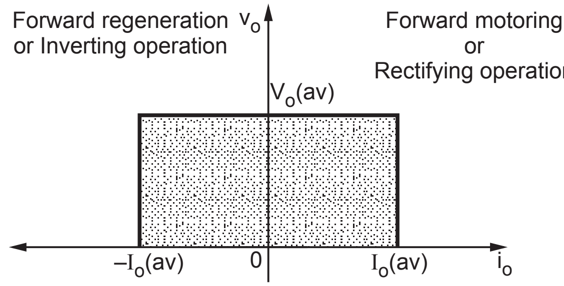


Fig. 4.4.5 Class C chopper operates in two quadrants

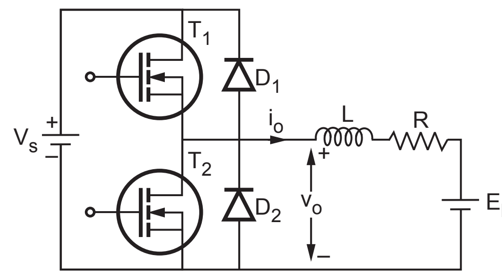
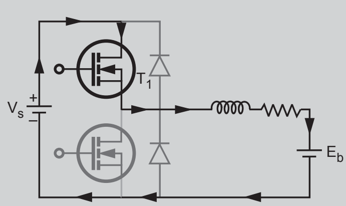
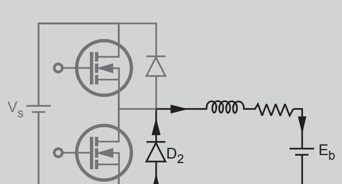


Fig. 4.4.6 Class C chopper

Table 4.4.1 shows the various equivalent circuits showing operation of this chopper.

Equivalent circuit	Quadrant	Description
	I Forward motoring or rectifying	T_1 conducts and energy flows from source to load. v_o and i_o are positive.
 (b)	I Forward motoring or rectifying	D_2 conducts i_o is positive and v_o is zero. Freewheeling takes place. Inductance supplies energy to the load.

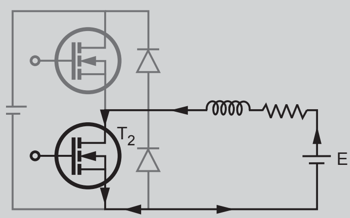
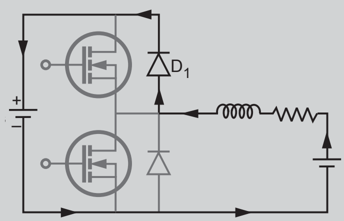
 (c)	II Forward regenerative braking	T_2 conducts i_o is negative. E_b supplies energy to the inductance v_o is zero.
 (d)	II Forward regenerative braking or inverting	D_1 conducts inductance supplies energy to the source v_o is positive and i_o is negative.

Table 4.4.1 Operation of class C chopper

4.4.4 Class D Chopper

The class D chopper also operates in two quadrants. Fig. 4.4.7 shows the quadrants of operation. The output current is always positive. The output voltage can be positive or negative. When v_o and i_o both are positive, the rectifying operation takes place. It is also called forward motoring. When the voltage is reversed, inverting operation takes place. The energy is fed from load to the source. The IV^{th} quadrant operation is also called reverse regeneration.

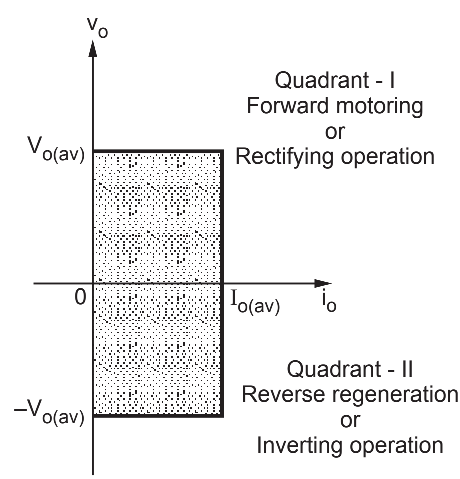


Fig. 4.4.7 Class D chopper operates in I and IV quadrants

Fig. 4.4.8 shows the circuit diagram of class D chopper having transistor switches. When T_1 and T_2 are conducting, output current and output voltage both are positive. Power is taken from the source and given to the load. This is operation in the first quadrant, i.e. rectifying. When T_1 and

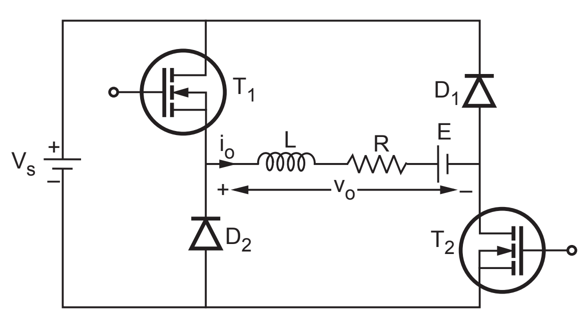


Fig. 4.4.8 Class D chopper

T_2 are switched off, the load inductance generates the large voltage to maintain the current in the same direction. The inductance voltage forward biases diodes D_1 and D_2. This situation is shown in Table 4.4.2. The diodes conduct and supply energy from load to the source. The output voltage is negative. Hence chopper operates in IV^{th} quadrant.

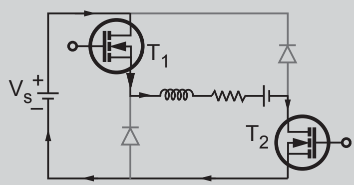
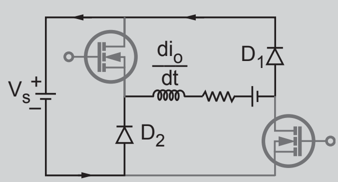
Equivalent circuit	Quadrant	Description
	**I** Rectifying or forward motoring	T_1, T_2 conduct power flows from source to the load
	**IV** Inverting or reverse regenerative braking	i_o is maintained in the same direction by inductance voltage $L\frac{d\,i_o}{dt}$. Diodes D_1 and D_2 are forward biased and conduct.

Table 4.4.2 Operation of class D chopper

4.4.5 Class E Chopper (Four Quadrant Chopper)

Class E is a four quadrant chopper. It operates in the four quadrants of $v_o - i_o$ as shown in Fig. 4.4.9. The output current as well as voltage both can take positive or negative values.

The first quadrant is forward motoring. The output voltage and current both are positive. The III^{rd} quadrant is reverse

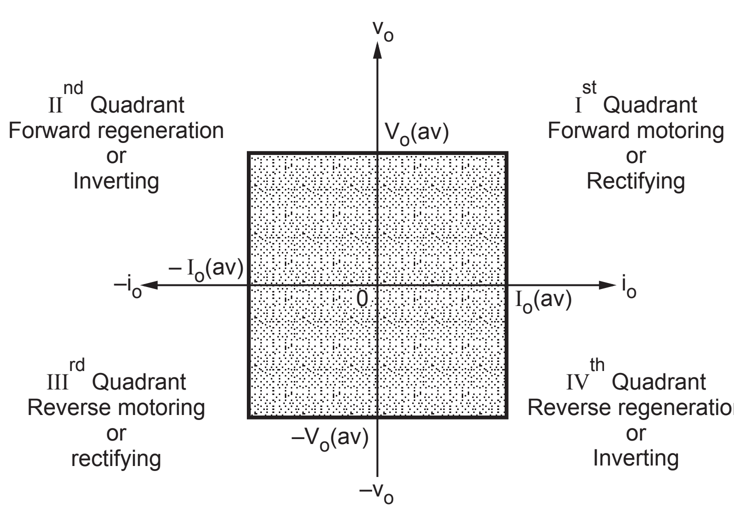


Fig. 4.4.9 Four quadrant operation

motoring. This means the motor rotates in the opposite direction compared to first quadrant. Since the power flows from source to the load in III^{rd} quadrant, it is called rectifying operation. In II^{nd} and IV^{th} quadrant, the power flows from load to the source hence it is called inverting operation.

Fig. 4.4.10 shows the circuit diagram of the four quadrant chopper having transistor switches. Whenever T_1 and T_2 conducts the chopper operates in the I^{st} quadrant. v_o and i_o both are positive. When T_3 and T_4 conduct v_o and i_o both are negative. The chopper operates in the third quadrant. Table 4.4.3 shows the operation of this chopper with equivalent circuits.

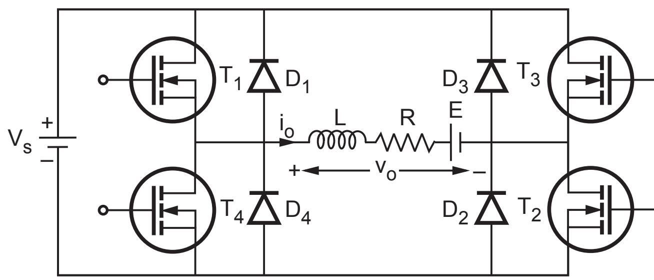
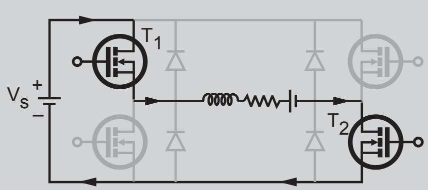
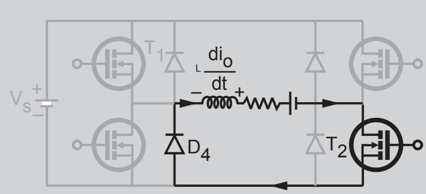
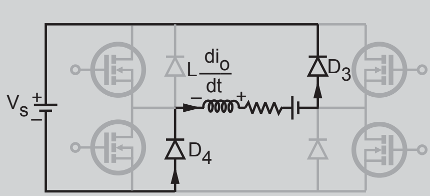


Fig. 4.4.10 Circuit diagram of four quadrant chopper

Equivalent circuit	Quadrant	Description
	I Forward motoring or rectifying	T_1 and T_2 conducts load consumes the power from the source
	**I** Forward motoring	T_1 turned off but T_2 conducts Hence current i_o flows through T_2 and D_4. Load inductor induces voltage as shown freewheeling action takes place.
	**IV** Inverting operation i_o positive v_o negative.	T_2 is turned off. Hence inductance forces current through D_3 and D_4. This current flows through supply. load energy is fed to the supply.

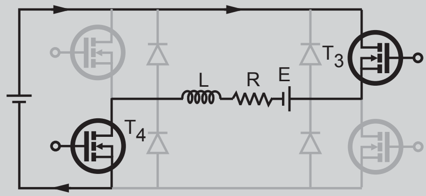
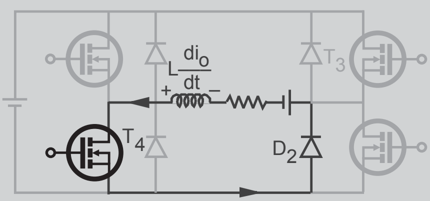
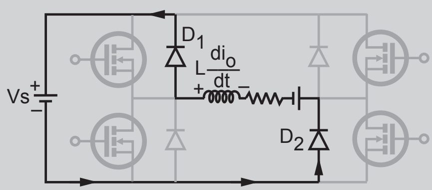
	III Rectifying operation motor rotates in opposite direction	To reverse the direction of rotation of the motor, T_3 and T_4 are turned on. v_o and i_o both are negative. E is shown negative since motor rotates in opposite direction.
	III Freewheeling operation motor rotates in the same direction	T_3 is turned off, but T_4 remains on. To maintain the current in the same direction inductance generates voltage and i_o flows in same direction through D_2 and T_4 This is freewheeling action.
	II Inverting operation i_o negative v_o positive	T_4 is turned off. Hence inductance forces current through D_1 and D_2. This current flows through supply. load energy is fed to the supply.

Table 4.4.3 Operation of four quadrant chopper

Four quadrant chopper has the capability to operate in all the four quadrants. Hence it is used in reversible dc drives. The braking is regenerative. Hence four quadrant chopper drives are highly efficient. Their dynamic response is also fast.

Review Questions

1. *How choppers are classified ?*
2. *Explain two quadrant and four quadrant choppers.*
3. *Explain operation of four quadrant chopper with circuit diagram.* **SPPU : May-15, Marks 6**
4. *What is DC to DC converter? Explain 4 quadrant chopper with circuit diagram and waveforms.* **SPPU : Dec.-16, Marks 9**
5. *Explain 4 quadrant operation of chopper for DC motor as a load.* **SPPU : Dec.-18, Marks 8**

4.5 Applications of Choppers

Choppers are used in following applications :

i. DC motor drives when the DC supply is available.

ii. Battery operated vehicles.

iii. Switched mode power supplies.

iv. Battery charges where uncontrolled rectifiers give DC to choppers.

v. Traction drives use four quadrant choppers for energy saving.

vi. Lighting and lamp controls also prefer choppers.

Table 4.5.1 lists the comparison between chopper and controlled rectifiers :

Sr. No.	Controlled rectifiers	Choppers
1.	Operate on AC input	Operate on DC input
2.	Output ripple depends on input supply and type of rectifier	Output ripple depends on switching frequency.
3.	Large filters are required to reduce ripple	At high ripple frequencies, small filters are required.
4.	Power factor can be poor for inductive loads.	Power factor is better.
5.	Efficiency is poor	Efficiency is better.
6.	Regenerative braking is slow	Regenerative braking can be made effective.
7.	Costly and bulky	Small and compact, but circuits are complex.

Table 4.5.1 Comparison between choppers and controlled rectifiers

4.6 Switching Mode Power Supply (SMPS) SPPU : Dec.-11,16, May-15,17,19

- The dc output of the rectifier or battery is not regulated. It varies according to the load variations. Switching mode regulators are used to convert unregulated dc to regulated DC output.
- The switching mode regulators use dc choppers. Fig. 4.6.1 shows the block diagram of switching mode regulator. The dc chopper takes the input V_s from some unregulated supply. The chopper may use Transistor, MOSFET, IGBT, SCR or GTO for switching.

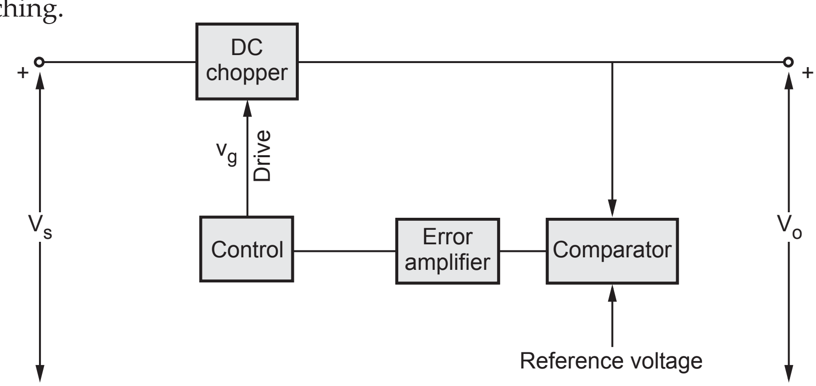


Fig. 4.6.1 Block diagram of switching mode regulator

- The comparator compares the reference voltage with output voltage. The reference voltage is set for the particular output voltage. The comparator generates the error signal. This error signal acts as the control voltage.
- The control block uses the control voltage v_c to generate the drives of the chopper.
- Fig. 4.6.2 shows the control waveforms. The control voltage v_c is compared with the sawtooth waveform. The result of comparison is the drive of the chopper as shown in Fig. 4.6.2 (b). This drive is given to the switch in the chopper. The sawtooth waveform is generated by an oscillator in the control circuit. The frequency of the sawtooth waveform decides the switching frequency of the chopper. Normally the switching period is 100 times longer than the switching time of the switch. Excessive switching frequencies may increase losses in the chopper.

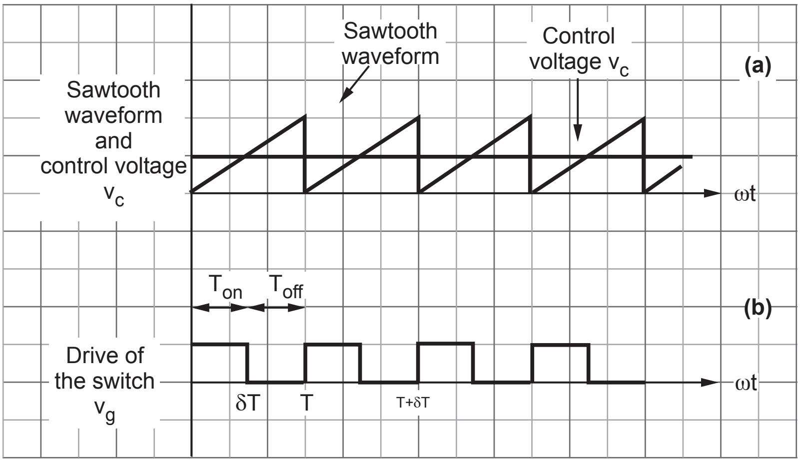


Fig. 4.6.2 Control waveforms of the switched mode regulators

- The filters are normally used in the output to make the output voltage ripple free and smooth. The regulation is also improved. The width of the drive is continuously adjusted to regulate output voltage. Hence it is also called as pulse width modulation (PWM) control.

4.6.1 Classification of SMPS

SMPS can be classified as shown in Fig. 4.6.3. (See Fig. 4.6.3 on next page)

Now we will study these converters in detail.

Nonidealities in SMPS

SMPS have the nonidealities because of following :

i) The magnetizing inductance of the transformers used in isolated type of SMPS need to be taken care-of.

ii) The leakage inductance of transformer used in isolated SMPS needs to be considered for snubber design.

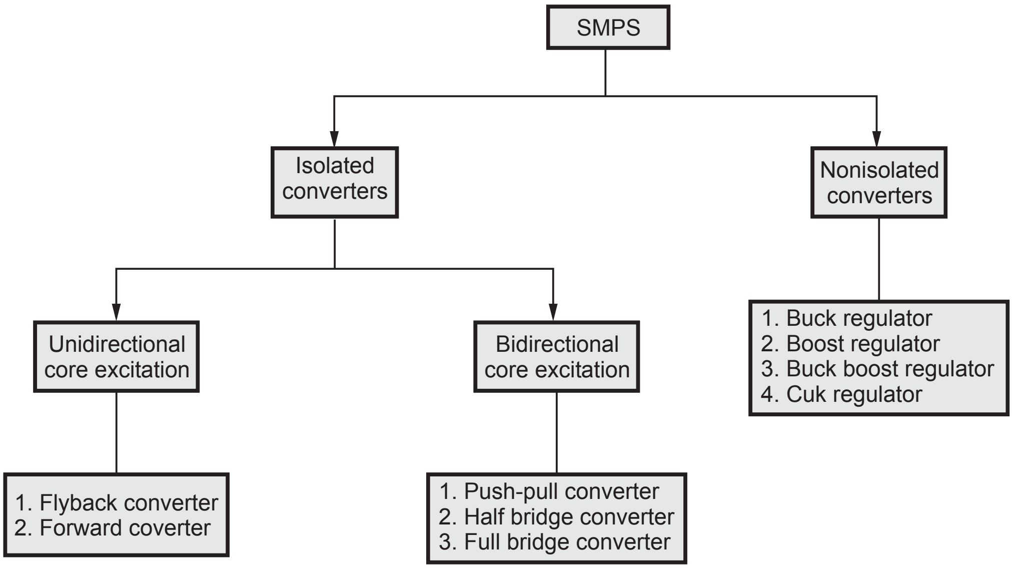


Fig. 4.6.3 Classification of SMPS

Review Questions

1. *Explain with block schematic working of SMPS. What are its advantages over linear power supply ?* **SPPU : Dec.-11,16, May-15,17, Marks 5**
2. *Classify SMPS, draw a generalized block diagram of SMPS. State its advantages and limitations.* **SPPU : May-19, Marks 8**

4.7 Nonisolated Converters

4.7.1 Buck Regulators

In the buck regulator, the average output voltage $v_{o(av)}$ is less than the supply voltage. Fig. 4.7.1 shows the circuit diagram of the buck regulator having transistor switch. Observe that the buck regulator is similar to the step-down chopper. The inductance L and capacitance C are the filtering components. Due to freewheeling diode D_{FW},

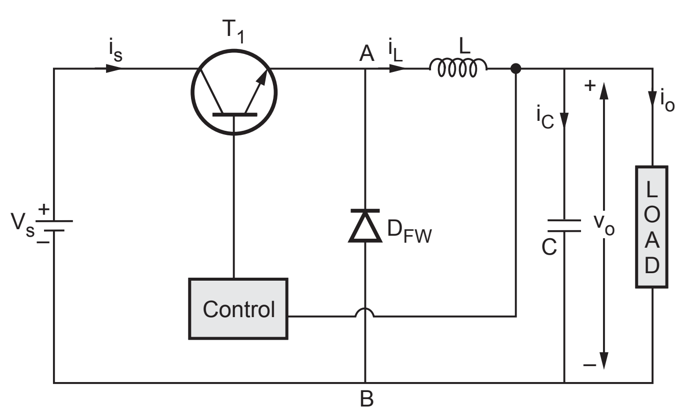


Fig. 4.7.1 Circuit diagram of the buck regulator

L and C, the output voltage and current are maintained continuous and ripple free. Fig. 4.7.2 shows the waveforms of buck regulator. The switch (transistor) is turned 'on' from 0 to δT. Hence current through the inductance increases. The equivalent circuit-I in Fig. 4.7.2 shows this situation. The current reaches to I_{max} at δT. The transistor switch is turned off at δT. The inductance tries to maintain the current i_L in the same direction.

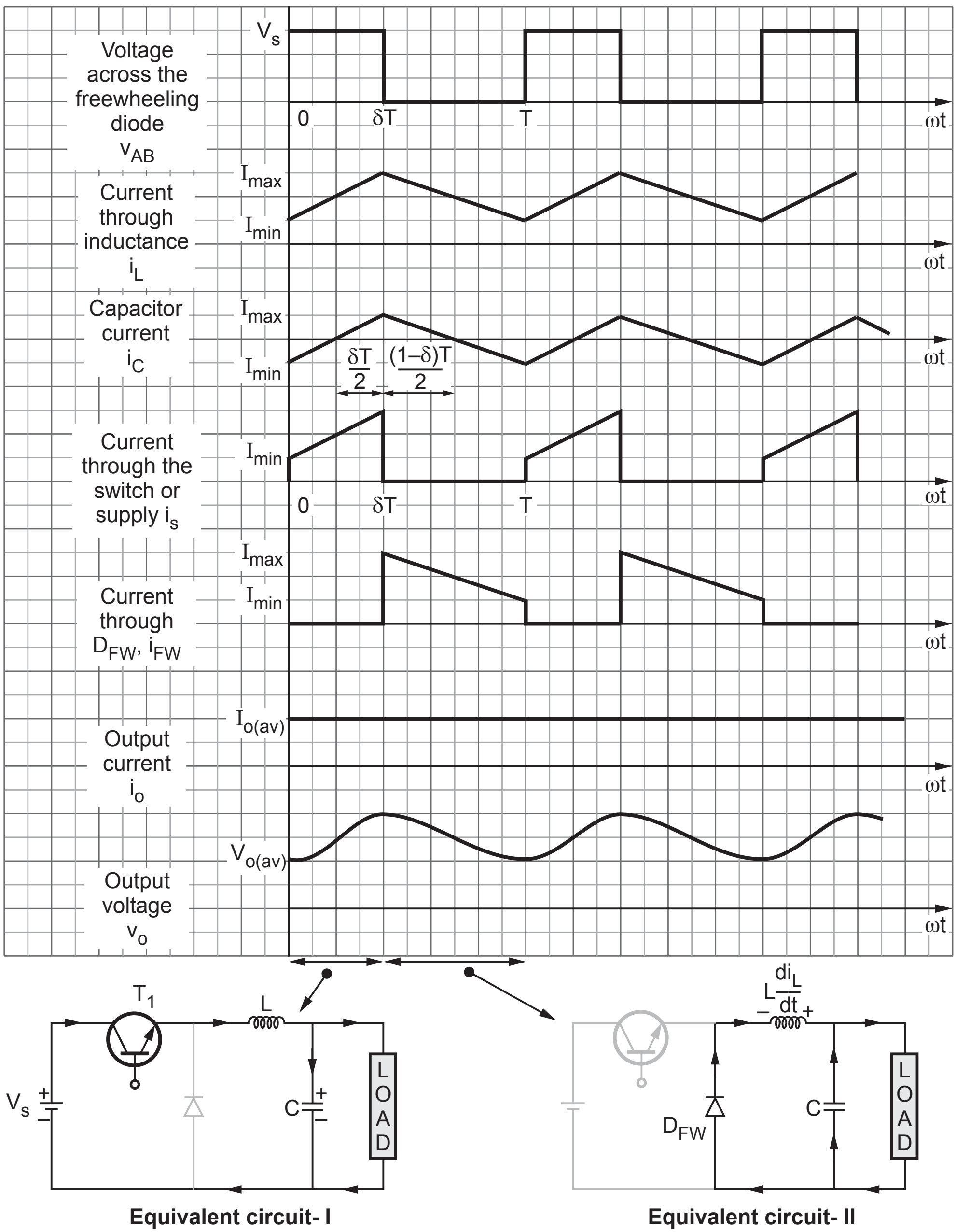


Fig. 4.7.2 Operation of the buck regulator

The voltage of the inductance $L \frac{d\,i_L}{dt}$ is induced with the polarity as shown in equivalent circuit-II in Fig. 4.7.2. This voltage forward biases the freewheeling diode D_{FW}. The inductance current goes on reducing and reaches to minimum at T. The inductance tries to remove ripple in the output current. The output current is maintained at $I_{o(av)}$ with negligible ripple. The capacitance tries to remove the ripple in the output voltage. The output voltage has very small ripple around $V_{o(av)}$. The capacitance value is increased to remove the ripple in v_o. Thus LC filter makes v_o and i_o ripple free and continuous.

The average value of the output voltage is given as,

$$V_{o\,(av)} = \delta\, V_s \qquad \text{... (4.7.1)}$$

Here $\delta = \frac{T_{on}}{T}$ is duty cycle of the chopper. The ripple in the output voltage is given as,

$$V_{o\,(ripple)} = \frac{V_s\,(1-\delta)\,\delta}{8\,L\,C\,f^2} \qquad \text{... (4.7.2)}$$

Here $f = \frac{1}{T}$ is frequency of the chopper. And the ripple in the output current is given as,

$$i_{o(ripple)} = \frac{V_s\,(1-\delta)\,\delta}{L\,f} \qquad \text{... (4.7.3)}$$

Applications

1. Battery operated portable equipments.
2. For unidirectional supplies.

Advantages

1. Buck regulator is very simple and it requires only one transistor (switch).
2. Efficiency is about 90%.
3. Low cost and size.
4. Large tolerance of line voltage variation.

Disadvantages

1. Only unidirectional output is available.
2. High output ripple.
3. Slow transient response.
4. Input filter is normally required.

Example 4.7.1 *Derive an expression for peak to peak ripple voltage of the capacitor for buck regulator.*

Solution : Fig. 4.7.1 shows the circuit diagram of buck regulator. Let the capacitor voltage be v_C. When the switch T_1 is conducting, the voltage across inductances is,

$$e_L = V_s - V_{o(av)}$$

The current through inductance is i_L.

Hence,

$$e_L = L\frac{di_L}{dt}$$

Hence from above two equations we can write,

$$V_s - V_{o(av)} = L\frac{di_L}{dt} \quad \text{... (4.7.4)}$$

Assuming linear change in i_L, we can write R.H.S. of above equation as,

$$\frac{di_L}{dt} = L\frac{(I_{\max} - I_{\min})}{(\delta T - 0)}, \quad \text{when } T_1 \text{ is on.}$$

Hence equation (4.7.4) can be written as,

$$V_s - V_{o(av)} = L\frac{(I_{\max} - I_{\min})}{\delta T} = \frac{L\, i_{L(ripple)}}{\delta T}$$

Here $I_{L(ripple)} = I_{\max} - I_{\min}$ is the ripple in inductance current. We can write the above equation as,

$$\delta T = \frac{L\, i_{L(ripple)}}{V_s - V_{o(av)}} \quad \text{... (4.7.5)}$$

When the chopper switch T_1 is off, we can write,

$$e_L = V_{o(av)}$$

and

$$e_L = L\frac{di_L}{dt}$$

Assuming linear change in current we can write above equation as (when T_2 is off)

$$e_L = L\frac{I_{\max} - I_{\min}}{T - \delta T} = L\,\frac{i_{L(ripple)}}{(1-\delta)T}$$

Since $e_L = V_{o(av)}$, above equation becomes,

$$V_{o(av)} = L\,\frac{i_{L(ripple)}}{(1-\delta)T}$$

$$\therefore \quad (1-\delta)T = \frac{L\, i_{L(ripple)}}{V_{o(av)}} \quad \text{... (4.7.6)}$$

We know that,

$$T = (1-\delta)T + \delta T$$

Putting expression for $(1-\delta)$ T from equation (4.7.6) and δT from equation (4.7.5) in above equation,

$$T = \frac{L\, i_{L(ripple)}}{V_{o(av)}} + \frac{L\, i_{L(ripple)}}{V_s - V_{o(av)}}$$

$$= L\, i_{L(ripple)} \left\{ \frac{1}{V_{o(av)}} + \frac{1}{V_s - V_{o(av)}} \right\}$$

$$= L\, i_{L(ripple)} \left\{ \frac{V_s - V_{o(av)} + V_{o(av)}}{V_{o(av)}(V_s - V_{o(av)})} \right\}$$

$$= \frac{L\, i_{L(ripple)} V_s}{V_{o(av)}(V_s - V_{o(av)})}$$

The peak to peak ripple current ΔI from above equation will be,

$$i_{L(ripple)} = \frac{V_{o(av)}\,(V_s - V_{o(av)})T}{L V_s} = \frac{V_{o(av)}\left(1 - \frac{V_{o(av)}}{V_s}\right)T}{L}$$

We know that $V_{o(av)} = \delta V_s$ or $\frac{V_{o(av)}}{V_s} = \delta$ and $T = \frac{1}{f}$ where f is the frequency of buck regulator. Hence above equation can be written as,

$$i_{L(ripple)} = \frac{\delta V_s (1-\delta)}{Lf} \qquad \text{... (4.7.7)}$$

Observe that this equation is same as that of equation (4.7.1).

Using Kirchhoff's law at the +ve point of load,

$$i_L = i_C + i_o$$

The ripple in i_o is very very small and hence it can be neglected. Hence from above equation,

$$\text{ripple in } i_L = \text{ripple in } (i_C + i_o)$$

$$i_{L(ripple)} = i_{C(ripple)}$$

The average value of capacitor current during period $\frac{\delta T}{2} + \frac{(1-\delta)T}{2}$, i.e. $\frac{T}{2}$ is (See capacitor current of Fig. 4.7.4),

$$I_{C(av)} = \frac{i_{C(ripple)}}{2\times 2} = \frac{i_{C(ripple)}}{4}$$

Since $i_{C(ripple)} = i_{L(ripple)}$, above equation becomes,

$$I_{C(av)} = \frac{i_{L(ripple)}}{4} \qquad \text{... (4.7.8)}$$

The capacitor voltage is given as

$$v_C(t) = \frac{1}{C}\int i_C\, dt + v_C(t=0)$$

$$\therefore \qquad v_C(t) - v_C(t=0) = \frac{1}{C}\int i_C\, dt$$

Over the half cycle period, $v_C(t) - v_C(t=0)$ will give ripple voltage of capacitor.

Hence, $$v_{C(ripple)} = \frac{1}{C}\int_0^{T/2} i_C\, dt$$

Equation (4.7.8) gives average value of i_C. Hence above equation becomes,

$$v_{C(ripple)} = \frac{1}{C}\int_0^{T/2} \frac{i_{L(ripple)}}{4}\, dt$$

$$= \frac{1}{C}\frac{i_{L(ripple)}}{4}\int_0^{T/2} dt = \frac{1}{C}\cdot\frac{i_{L(ripple)}}{4}\cdot\frac{T}{2}$$

Putting the value of $i_{L(ripple)}$ from equation (4.7.7),

$$v_{C(ripple)} = \frac{1}{C}\cdot\frac{\delta V_s(1-\delta)}{4\times Lf}\cdot\frac{T}{2}$$

Since $T = \frac{1}{f}$, above equation becomes,

$$v_{C(ripple)} = \frac{\delta V_s(1-\delta)}{8LC f^2} \qquad \text{.... (4.7.9)}$$

This is the required expression for ripple voltage of capacitor. In Fig. 4.7.3, observe that capacitor voltage is same as output voltage. Hence above equation gives ripple voltage in the output.

4.7.2 Boost Regulators

The boost regulator provides higher output voltage than the input voltage. The boost regulator is like the step-up chopper. Fig. 4.7.3 shows the circuit diagram of the boost regulator having MOSFET as a switch. The switch is first turned on. It conducts from

0 to δT. Hence current flows in the inductance. Inductance stores the energy during this period. The output voltage and current is maintained by the filter capacitor.

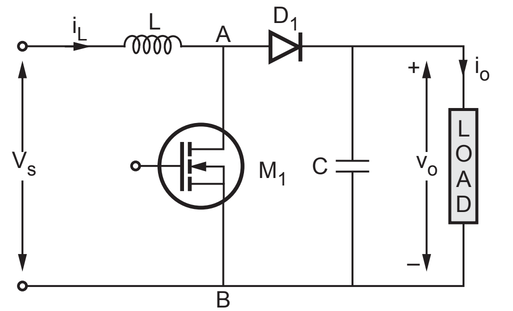


Fig. 4.7.3 Circuit diagram of boost regulator

Fig. 4.7.4 shows the waveforms and equivalent circuits. The output voltage drops slightly due to discharge of capacitor from 0 to δT. The switch is turned off

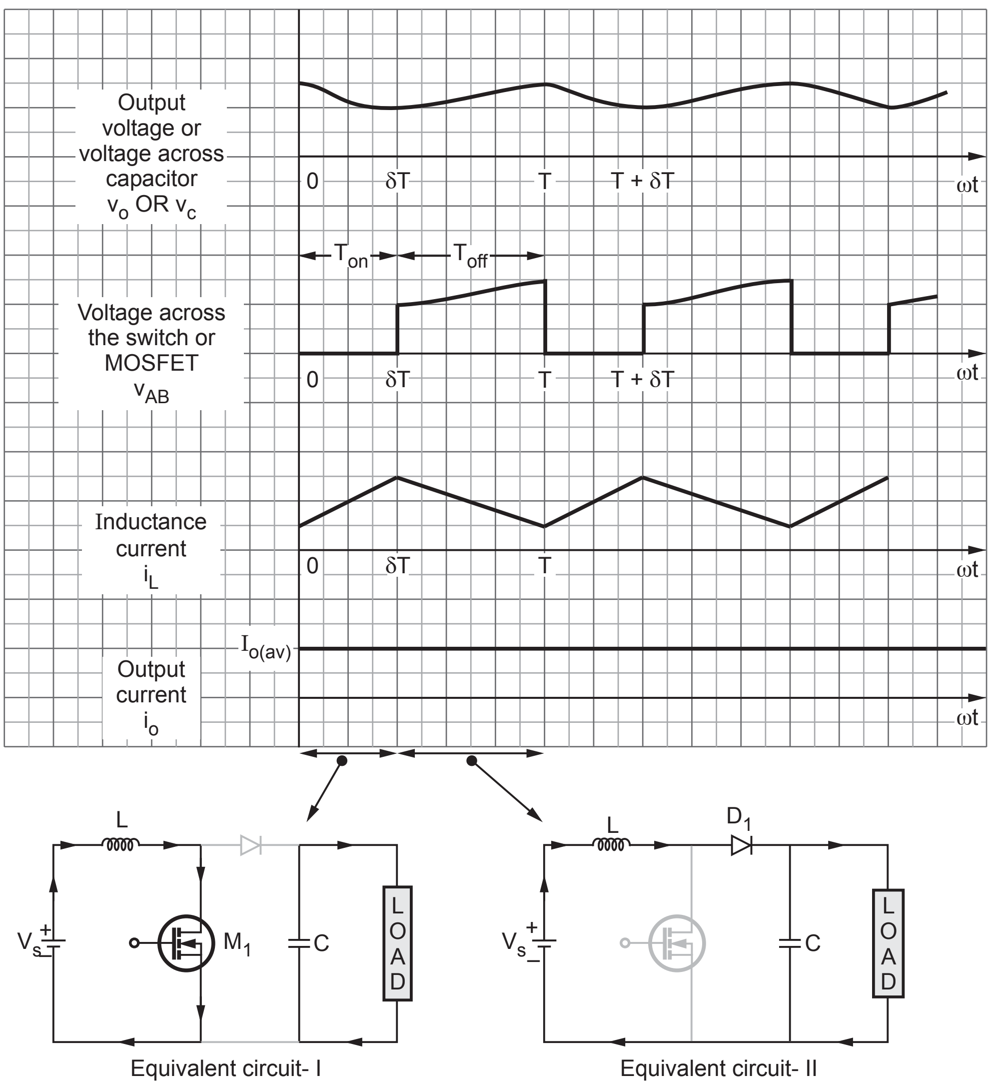


Fig. 4.7.4 Waveforms and operation of boost regulator

at δT. Hence inductance generates a large voltage $L\,\frac{d\,i_L}{dt}$ with the polarity shown in equivalent circuit-II in Fig. 4.7.4. This voltage forward biases D_1 to maintain current. The current flows through load. The output current is ripple free and continuous due to capacitor. From δT to T the inductance energy is transferred to the capacitance and load. (See Fig. 4.7.4 on previous page)

The ripple in the output voltage is given as,

$$v_{o\,(ripple)} = \frac{I_{o\,(av)}\,\delta}{f\,C} \qquad \text{... (4.7.10)}$$

Here $f = \frac{1}{T}$ is the frequency of the chopper.

And the ripple in the output current is given as,

$$i_{o\,(ripple)} = \frac{V_s\,\delta}{f\,L} \qquad \text{... (4.7.11)}$$

The output average voltage is given as,

$$V_{o\,(av)} = \frac{V_s}{1-\delta} \qquad \text{... (4.7.12)}$$

Applications

Used in the applications where required output voltage is greater than the supply voltage.

Advantages

1. It can step up the output voltage without a transformer.
2. High efficiency due to single switch.

Disadvantages

1. High peak current flows through to switch (MOSFET).
2. Output voltage is highly sensitive to changes in duty cycle.
3. Large inductance and capacitance are required.

4.7.3 Buck Boost Regulators

The output voltage polarity of buck boost regulator is opposite to that of the input voltage. Hence this is also called as inverting regulator. The output voltage of this regulator can be greater or less than the input voltage. Hence, the name is given as 'buck boost' regulator. Fig. 4.7.5 shows the circuit diagram of buck-boost regulator. The L, C and D_1 are the filtering components. T_1 is the transistor switch. Note the inverted output voltage polarity. The output current is also shown negative.

T_1 is turned on at $t = 0$. It conducts from 0 to δT. Hence current flows through inductance. Diode D_1 is reverse biased. Fig. 4.7.6 shows the waveforms and equivalent circuits of buck-boost regulator. Inductance stores the energy from 0 to δT.

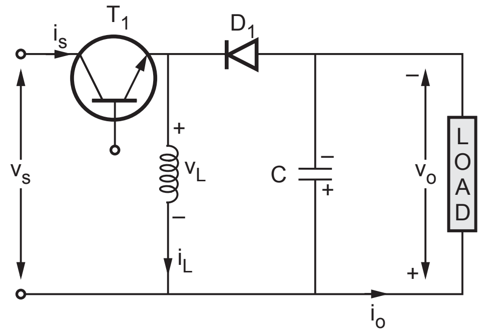


Fig. 4.7.5 Buck boost regulator

The current through inductance keeps on rising. The capacitor discharges and supplies current to load. Load current is assumed continuous and ripplefree. The output voltage varies according to capacitor voltage.

At δT, transistor switch is turned off. The equivalent circuit-II in Fig. 4.7.6 shows the position from δT to T. Inductance generates the voltage $L \frac{d\,i_L}{dt}$ with the polarity shown in equivalent circuit-II. This forward biases the diode D_1. Thus inductance supplies energy to the load from δT to T. Hence inductance current decreases. The capacitor is also charged. Hence its voltage also rises. (See Fig. 4.7.6 on next page.)

The average output voltage is given as,

$$V_{o(av)} = -\frac{\delta}{1-\delta} V_s \qquad \text{... (4.7.13)}$$

The ripple in the output current is given as,

$$i_{o(ripple)} = \frac{\delta V_s}{f L} \qquad \text{... (4.7.14)}$$

Here $f = \frac{1}{T}$ is switching frequency of the chopper. Similarly ripple in the output voltage is given as,

$$v_{o(ripple)} = \frac{\delta I_{o(av)}}{f C} \qquad \text{... (4.7.15)}$$

Applications

It is used in the applications where inverted output is required. The output is also greater or less than input voltage.

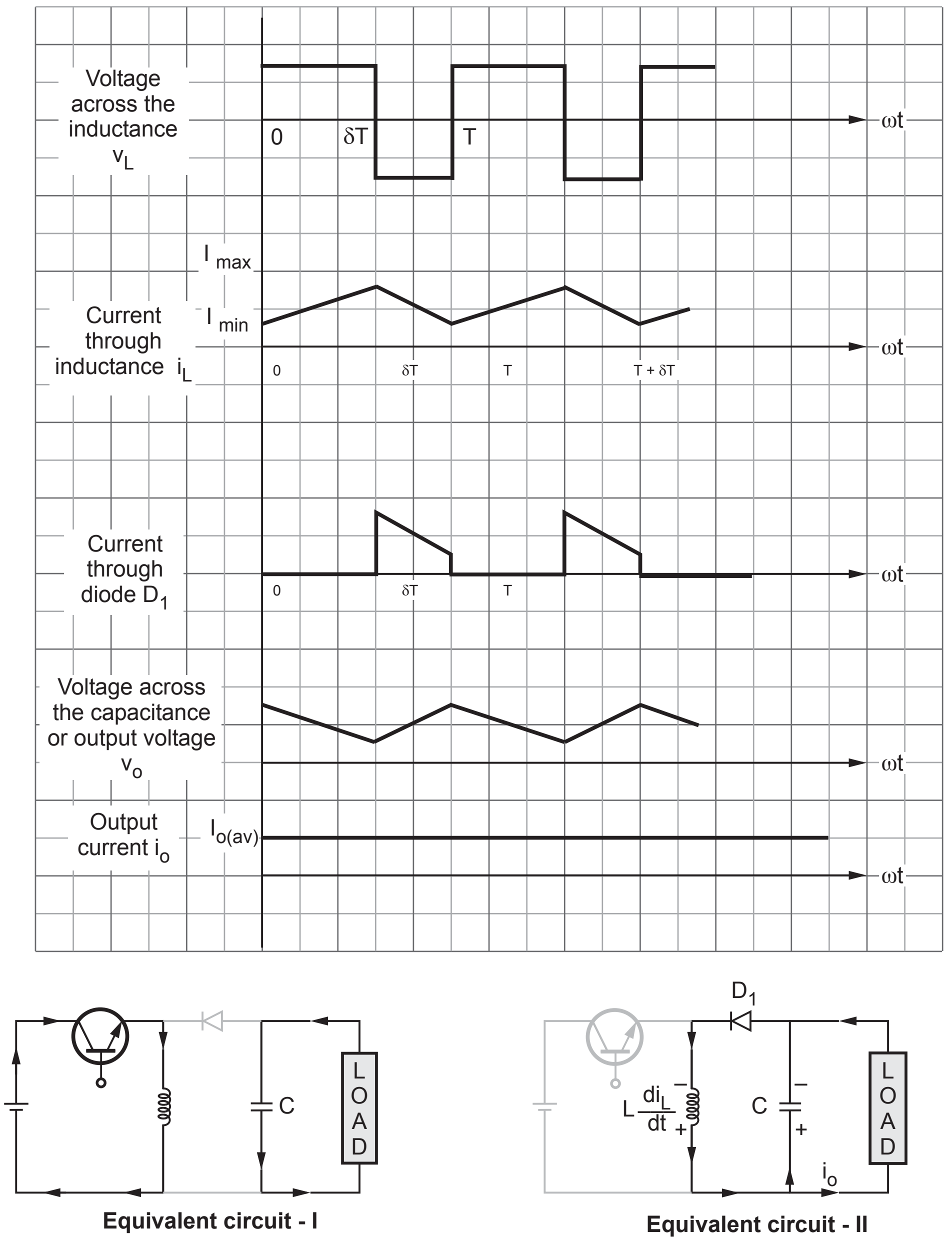


Fig. 4.7.6 Waveforms and operation of buck-boost regulator

Advantages

1. Provides inverted output.
2. Both buck/boost operations simultaneously.
3. High efficiency.
4. Short circuit protection can be easily implemented.

4.7.4 Cuk Regulators

The Cuk regulator provides the negative output voltage. Hence it is also inverting regulator. The output voltage can be less than or greater than the input voltage. Thus it is similar to buck-boost regulator. Fig. 4.7.7 shows the circuit diagram of Cuk regulator.

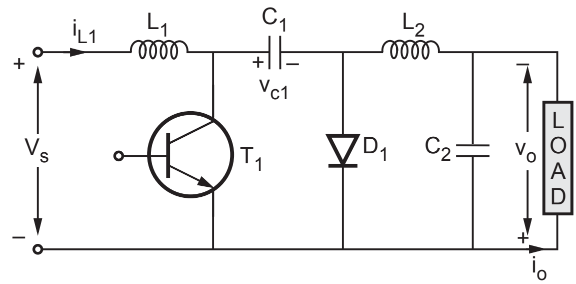


Fig. 4.7.7 Circuit diagram of Cuk regulator

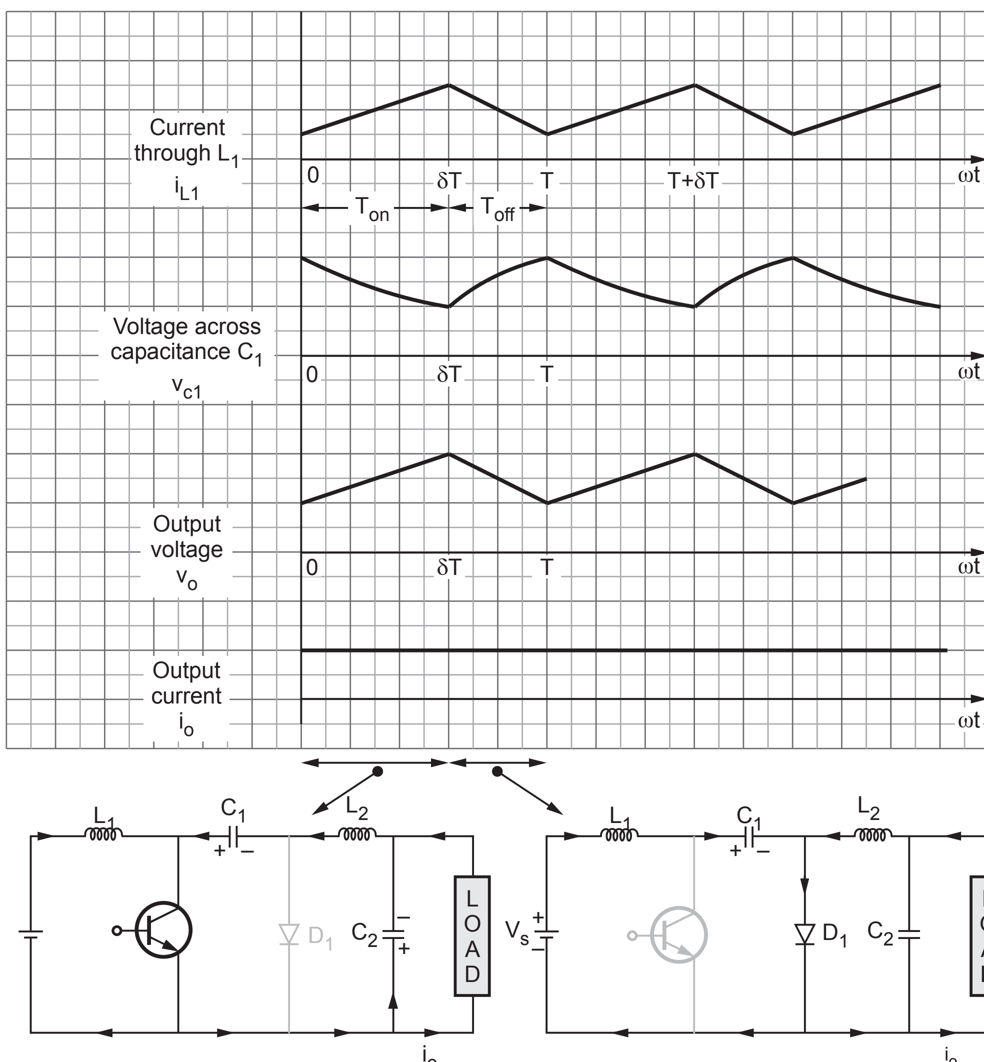


Fig. 4.7.8 Waveforms and operation of Cuk regulator

The operation of the above circuit can be presented as follows : T_1 is turned on at $t = 0$. It conducts from 0 to δT as shown in waveforms of Fig. 4.7.8. The equivalent circuit-I in Fig. 4.7.8 shows the situation. L_1 stores the energy from the supply. Current through L_1 increases. Capacitor C_1 discharges through T_1, load and L_2. Capacitance C_2 also stores the energy. The output voltage also increases.

At δT, transistor T_1 is turned off. Hence inductance L_1 current flows through $L_1 - C_1 - D_1$ and V_s. Capacitance C_1 charges and energy stored in L_1 is transferred to capacitance C_1. The load current flows through L_2 and D_1. The capacitor C_2 also provides load current and tries to maintain the load voltage. Equivalent circuit-II in Fig. 4.7.8 shows this situation. The transistor remains off from δT to T.

Here note that when T_1 is on, L_1 stores energy from supply. L_2 and C_2 get energy from C_1. When T_1 is off, C_1 gets energy from L_1 and supply. C_2 and L_2 supply energy to the load. This is clear from current flow directions in equivalent circuits in Fig. 4.7.8. (See Fig. 4.7.8 on previous page.)

Average value of output voltage is given as,

$$V_{o(av)} = -\frac{\delta}{1-\delta} V_s \qquad \text{... (4.7.16)}$$

The ripple in the output voltage is given as,

$$v_{o(ripple)} = \frac{\delta V_s}{\delta C_2 L_2 f^2} \qquad \text{... (4.7.17)}$$

Here $f = \frac{1}{T}$ is switching frequency of the chopper.

Advantages

1. Low switching losses.
2. Continuous output current since intermediate energy transfer takes place through capacitor.
3. High efficiency.

Disadvantages

Additional inductance and capacitor is required.

4.8 Isolated Converters

SPPU : Dec.-18

4.8.1 Flyback Converter

Principle

The Flyback converter is derived from buck-boost converter discussed earlier.

Circuit diagram and waveforms of flyback converter

Fig. 4.8.1 shows the circuit diagram of Flyback converter.

In the above diagram the transformer is of high frequency having turns ratio $\frac{N_p}{N_s}$. The dc supply V_s is applied to the switching transistor through the transformer primary. Note the 'dot' conventions on the transformer primary and secondary.

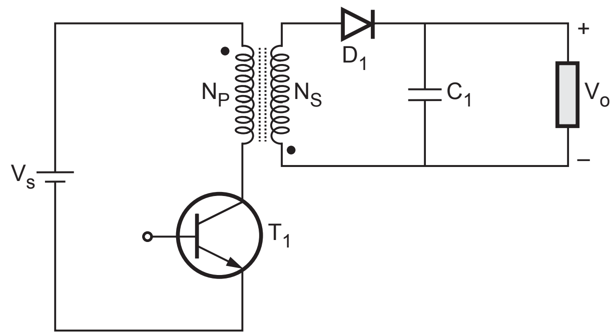


Fig. 4.8.1 Circuit diagram of flyback converter

Operation and Waveforms

The operation of the flyback converter can be explained with the help of following modes.

Mode - I, T_1 - on

In this mode transistor T_1 is turned ON. Current starts flowing in the primary.

In the equivalent circuit - I of Fig. 4.8.2, observe that secondary voltage reverse biases diode D_1 when T_1 is conducting. Therefore load current is supplied by capacitor C_1. In the waveform of Fig. 4.8.2 (b), observe that current through transistor T_1 rises from 0 to t_1. At t_1, the transistor T_1 is turned off.

Mode - II, T_1 - OFF D_2 - conducts

This mode starts when transistor is turned-off at t_1. As shown in equivalent circuit-II of Fig. 4.8.2, the voltage polarity of the transformer secondary is inverted. This forward biases diode D_1 and it starts conducting. Thus the transformer secondary supplies energy to the capacitor C_1 as well as load. Note that this energy was stored in the transformer when T_1 was conducting in mode-I.

In the waveform of of Fig. 4.8.2 (d) observe that the transformer secondary voltage fluctuates between $\pm V_o$. Fig. 4.8.2 (e) shows the waveform of transformer primary. When T_1 is ON the primary voltage is equal to supply voltage, V_s. When T_1 is off the primary voltage is equal to supply voltage, V_s. When T_1 is off, the primary voltage is $-\frac{N_p}{N_s} v_o$.

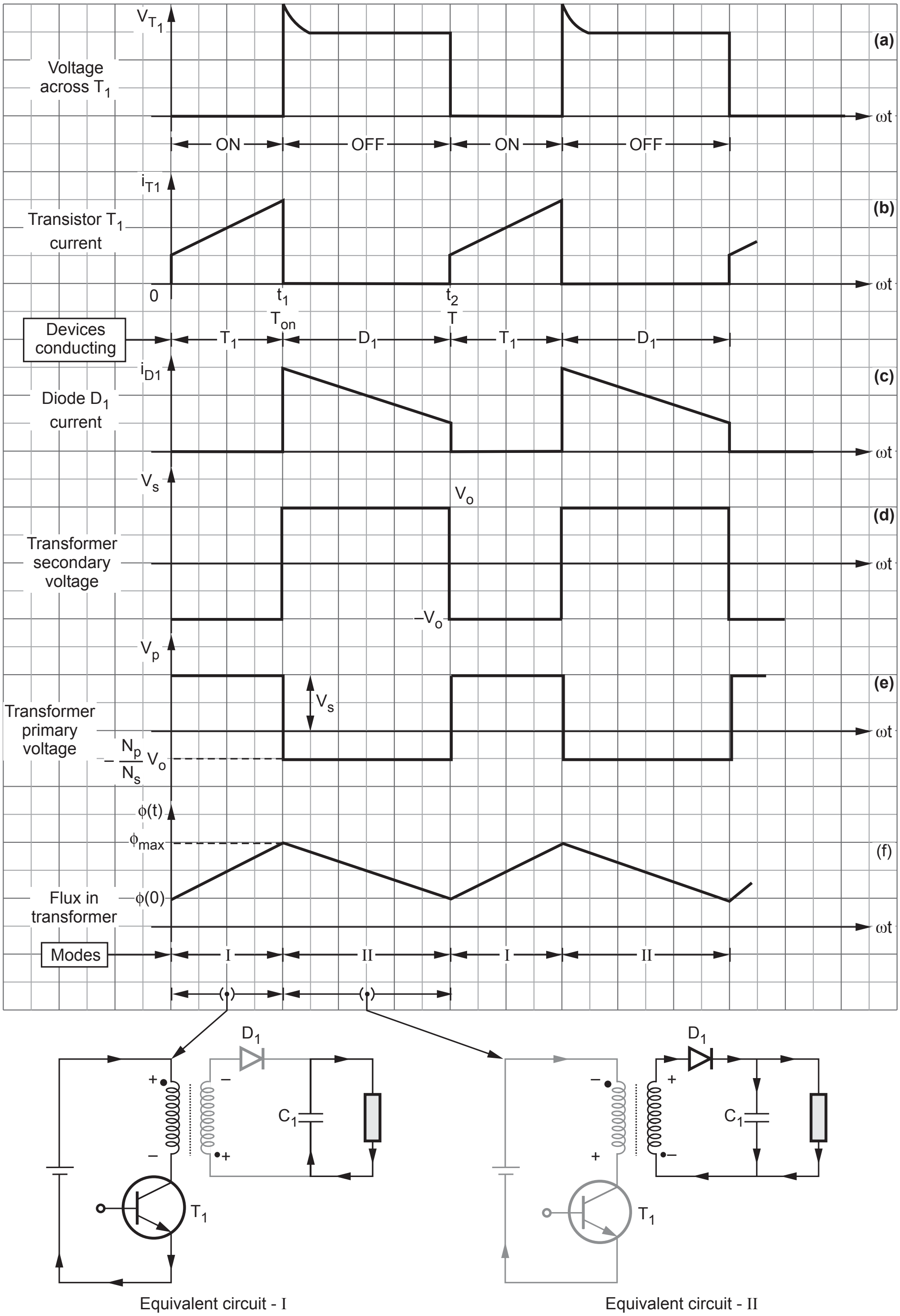


Fig. 4.8.2 Waveforms and opration of flyback converter (continuous mode)

4.8.2 Half Bridge

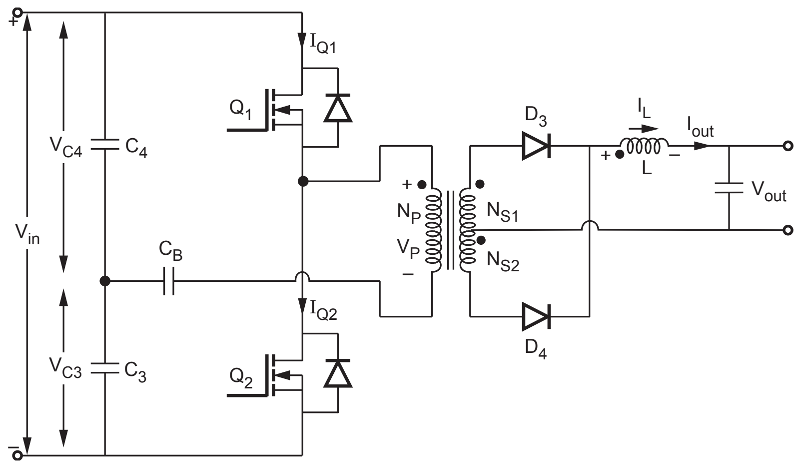
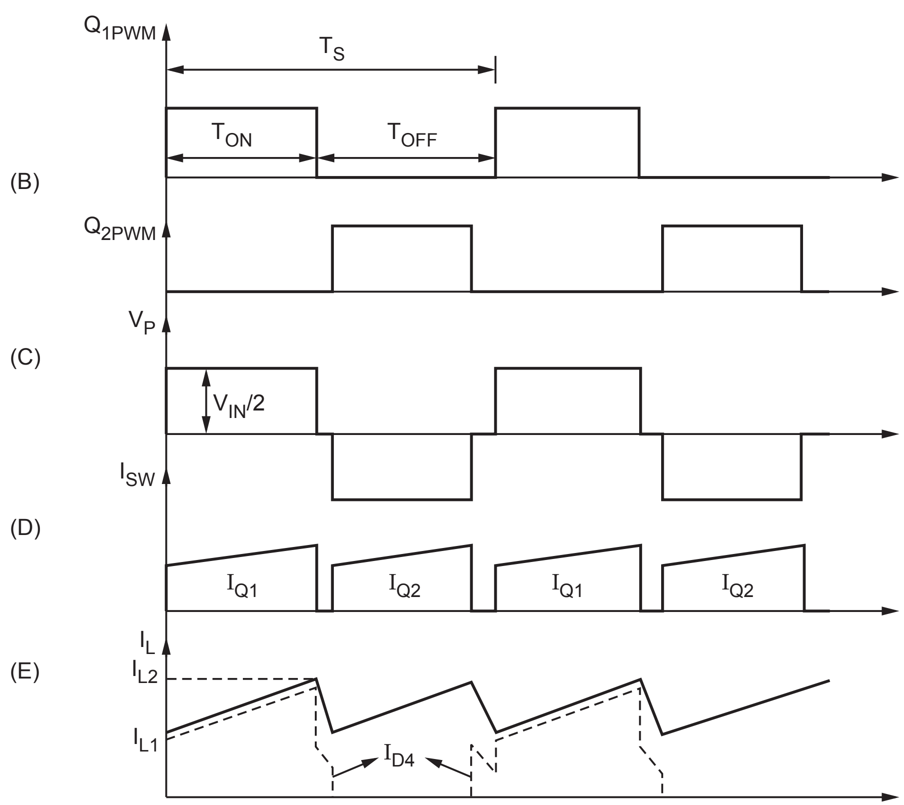


Fig. 4.8.3



(B) = Gate pulse waveform of Q_1

(C) = Voltage across transformer primary

(D) = Current through the switch Q_1 and Q_2

(E) = Output inductor and diode D_4 current

Fig. 4.8.4 Half-bridge converter

Example 4.8.1 *Derive an expression for voltage transfer ratio $\frac{V_o}{V_s}$ in terms of transformer turns ratio and duty cycle for flyback converter operating with continuous load current.*

Solution : Fig. 4.8.2 (f) shows the waveform of flux in the transformer. The flux increases linearly from 0 to t_1, with initial value of $\phi(0)$. i.e.,

$$\phi(t) = \phi(0)+\frac{V_s}{N_p}t \qquad \text{for } 0 \le t \le t_1$$

$$\phi(t) = \phi_{max} \quad \text{when} \quad t = t_1. \text{ i.e.,}$$

$$\phi_{max} = \phi\ (0)+\frac{V_s}{N_p}t_1 \qquad \ldots(4.8.1)$$

When transistor is turned-off, secondary voltage becomes V_o and the flux decreases linearly from t_1 to t_2. This flux will be $\frac{V_o}{N_s}(t-t_1)$. It reduces from ϕ_{max}. Hence $\phi(t)$ will be,

$$\phi(t) = \phi_{max}-\frac{V_o}{N_s}(t-t_1)$$

Putting for ϕ_{max} from equation 4.8.1,

$$\phi(t) = \phi(0)+\frac{V_s}{N_p}t_1-\frac{V_o}{N_s}(t-t_1)$$

Note that $t = t_2$, $\phi(t) = \phi(0)$ (See Fig. 4.8.2 (f)) and above equation becomes,

$$\phi(0) = \phi(0)+\frac{V_s}{N_p}t_1-\frac{V_o}{N_s}(t_2-t_1)$$

$$\therefore \qquad \frac{V_s}{N_p}t_1 = \frac{V_o}{N_s}(t_2-t_1)$$

$$\therefore \qquad \frac{V_o}{V_s} = \frac{N_s}{N_p}\cdot\frac{t_1}{t_2-t_1}$$

One cycle completes at t_2. Therefore $t_2 = T$. and $t_1 = T_{on}$.

$$\therefore \qquad \frac{V_o}{V_s} = \frac{N_s}{N_p}\cdot\frac{T_{on}}{T-T_{on}} = \frac{N_s}{N_p}\cdot\frac{T_{on}/T}{T-T_{on}/T}$$

$$= \frac{N_s}{N_p}\cdot\frac{\delta}{1-\delta} \qquad \text{since } \delta = \frac{T_{on}}{T} \text{ i.e. duty cycle.}$$

Thus $$\boxed{\frac{V_o}{V_s} = \frac{N_s}{N_p}\cdot\frac{\delta}{1-\delta}} \qquad \ldots(4.8.2)$$

or $$V_o = \frac{N_s}{N_p} \cdot \frac{\delta V_s}{1-\delta} \qquad \text{...(4.8.3)}$$

This equation gives an output voltage of flyback converter.

Example 4.8.2 *An isolated flyback converter operating in the continuous conduction mode at a frequency of 50 kHz, is fed from the 230 V, 50 Hz mains via a full wave rectifier and LC filter so as the maintain continuous supply current. The output voltage is 24 V and maximum duty cycle is limited to 60%. If the supply mains varies from 180 V to 270 V calculate -*

i) The minimum voltage rating of the power switch if it is required to keep a safety margin of 100 V for voltage spikes due to leakage inductance effects.

ii) The flyback converter transformer turns ratio required to obtain rated output voltage at 50 % duty cycle under normal mains conditions.

iii) Range of operating duty cycles with above transformer turns ratio.

Solution : Given :

V_{ac} = 230 V and 180 – 270 V.

After full wave rectification and LC filtering peak dc voltage obtained is,

$$V_s = 230\sqrt{2} = 325.27 \text{ V}$$

$$V_o = 24 \text{ V}, \quad \delta_{max} = 60\% \text{ or } 0.6$$

$$V_{spike} = 100 \text{ V}$$

i) To obtain voltage rating of T_1

In the equivalent circuit II of Fig. 4.8.2 observe that when T_1 turns off the voltage across it is,

$$V_{T_1} = V_s + V_p + V_{spike} = V_s + \frac{N_p}{N_s} V_o + V_{spike}$$

from equation (4.8.3) $V_o = \frac{N_s}{N_p} \cdot \frac{\delta V_s}{1-\delta}$. Hence above equation becomes,

$$V_{T_1} = V_s + \frac{N_p}{N_s} \cdot \frac{N_s}{N_p} \cdot \frac{\delta V_s}{1-\delta} + V_{spike}$$

$$= V_s + \frac{\delta V_s}{1-\delta} + V_{spike} = V_s\left(1 + \frac{\delta}{1-\delta}\right) + V_{spike}$$

$$= \frac{V_s}{1-\delta} + V_{spike} \qquad \text{...(4.8.4)}$$

Putting values in above equation,

$$V_{T_1} = \frac{325.27}{1-0.6} + 100 = 913.175 \text{ V}$$

Thus the minimum voltage rating of T_1 is 1 kV.

ii) To obtain transformer turns ratio

From equation (4.8.3) we know that the output voltage is given as,

$$V_o = \frac{N_s}{N_p} \cdot \frac{\delta V_s}{1-\delta}$$

Here V_o = 24 (rated), δ = 50 % or 0.5 and V_s = 325.27 V.

$$\therefore \quad 24 = \frac{N_s}{N_p} \cdot \frac{0.5 \times 325.27}{1-0.5}$$

$$\therefore \quad \frac{N_s}{N_p} = 0.07378$$

$$\text{or} \quad \frac{N_s}{N_p} = 13.55 : 1$$

iii) To obtain the range of duty cycles

The ac input voltage varies from 180 to 270 V. Therefore

for V_{ac} = 180 V, $V_{s(\min)} = 180\sqrt{2} = 254.55$ V

for V_{ac} = 270 V, $V_{s(\max)} = 270\sqrt{2} = 381.83$ V

For minimum supply voltage, duty cycle will be maximum i.e.,

$$\therefore \quad V_o = \frac{N_s}{N_p} \cdot \frac{\delta_{\max} V_{s(\min)}}{1-\delta_{\max}}$$

$$24 = 0.07378 \cdot \frac{\delta_{\max} \times 254.55}{1-\delta_{\max}}$$

$$\therefore \quad \delta_{\max} = 0.561 \text{ or } 56.1 \text{ \%}$$

For maximum supply voltage, duty cycle will be minimum. i.e.,

$$V_o = \frac{N_s}{N_p} \cdot \frac{\delta_{\min} V_{s(\max)}}{1-\delta_{\min}}$$

$$24 = 0.07378 \cdot \frac{\delta_{\min} \times 381.83}{1-\delta_{\min}}$$

$$\delta_{\min} = 0.46 \text{ or } 46\%$$

Thus the range of duty cycles is 0.46 to 0.561.

Example 4.8.3 *An isolated flyback converter, operating in the continuous conduction mode at a frequency of 40 kHz uses a 800 V power MOSFET and is fed from the supply mains via a full wave bridge rectifier cum capacitor filter. Assuming a ripple free capacitor filter output and neglecting rectifier drops, calculate :*

i) The maximum permissible duty cycle of the MOSFET switch if the mains supply varies between 180 V and 260 V and margin of 100 V is required to allow for voltage spikes on the drain of the MOSFET.

ii) The flyback transformer turns ratio required to limit the DC supply current from the bridge rectifier cum capacitor filter to 500 mA at maximum duty cycle for a load current of 2 A.

Solution : Given : f = 40 kHz, V_{T_1} = 800 V

$$V_{s(\min)} = 180\sqrt{2} = 254.55 \text{ V}$$

$$V_{s(\max)} = 260\sqrt{2} = 367.69 \text{ V}$$

$$V_{spike} = 100 \text{ V}, \quad I_o = 2 \text{ A}, \quad I_s = 500 \text{ mA}$$

i) To obtain maximum duty cycle

From equation (4.8.4), $V_{T_1} = \frac{V_s}{1-\delta} + V_{spike}$

Maximum duty cycle is obtained with minimum supply voltage i.e.,

$$V_{T_1} = \frac{V_{s\,(\min)}}{1-\delta_{\max}} + V_{spike}$$

$$800 = \frac{254.55}{1-\delta_{\max}} + 100$$

$$\therefore \quad \delta_{\max} = 0.636 \text{ or } 63.6 \text{ \%}$$

ii) To obtain transformer turns ratio

Maximum supply current is given as,

$$I_{s(\max)} = I_s(0) + \frac{V_{s(\max)}}{L_{(pri)}} t_{on}$$

Here $t_{on} = \delta T = \frac{\delta}{f}$ and $I_s(0)$ is initial supply current.

$$\therefore \quad I_{s(\max)} = I_s(0) + \frac{V_{s(\max)}}{L_{(pri)}} \frac{\delta}{f}$$

$$500\times 10^{-3} = 0 + \frac{367.69}{L_{(pri)}} \times \frac{0.636}{40\times 10^3} \qquad \text{assuming } I_s(0) = 0$$

$$\therefore \quad L_{(pri)} = 11.69 \text{ mH}$$

$$\text{Now} \quad L_{(pri)} = \frac{V_{s\,(\min)}\delta_{\max}}{I_{c\,(\max)}f}$$

$$\therefore \quad 11.69\times10^{-3} = \frac{254.55\times0.636}{I_{c\,(\max)}\times50\times10^{3}}$$

$$\therefore \quad I_{c\,(\max)} = 0.277 \text{ A}$$

$$\text{Now} \quad I_{c\,(\max)} = \frac{1.2\,P_o}{V_{s\,(\max)}\delta_{\max}} \qquad \text{assuming 100 \% efficiency}$$

$$0.277 = \frac{1.2\,P_o}{367.69\times0.636}$$

$$\therefore \quad P_o = 53.98 \text{ W}$$

$$P_o = V_o\times I_o$$

$$53.98 = V_o\times2$$

$$\therefore \quad V_o = 26.99 \text{ V.}$$

$$V_o = \frac{N_s}{N_p}\cdot\frac{\delta V_s}{1-\delta} \qquad \text{By equation (4.8.3)}$$

$$26.99 = \frac{N_s}{N_p}\cdot\frac{0.636\times254.55}{1-0.636}$$

$$\therefore \quad \frac{N_s}{N_p} = 0.06068$$

$$\text{or} \quad \frac{N_p}{N_s} = 16.47 : 1$$

4.8.3 Forward Converter

Principle

The forward converter is derived from step-down (buck) converter.

Circuit diagram and operation of forward converter

Fig. 4.8.5 shows the circuit diagram of forward converter.

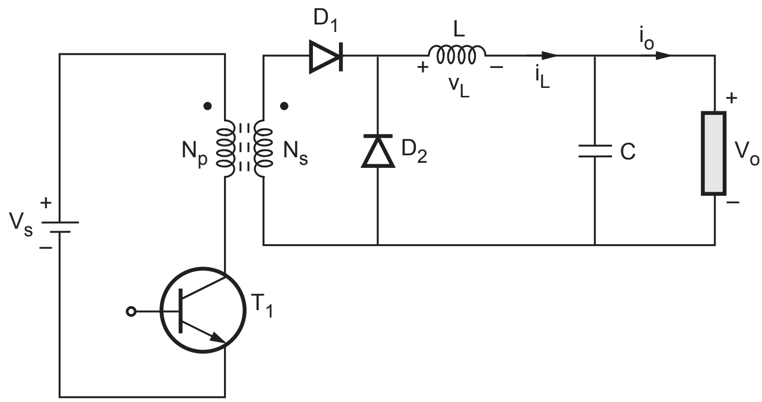


Fig. 4.8.5 Forward converter

Operation

- **Mode-I, T_1 on**

  When T_1 is on, the diodes D_1 is forward biased and D_2 is reverse biased. As shown in the waveforms, current through inductance (i_L) increases.

- **Mode-II, T_1 off**

  When T_1 is turned off, diode D_2 is reverse biased and D_1 is forward biased because of induced voltage in the inductance. The inductance now supply energy to the load. As the energy in inductance goes on reducing, the current through inductance (i_L) also goes on reducing.

Example 4.8.4 *Derive an expression for output voltage of forward converter.*

Solution :

Step 1 : When T_1 is ON, diode D_1 conducts and D_2 is reverse biased. Hence voltage across inductor is,

$$v_L = \frac{N_s}{N_p} V_s - V_o$$

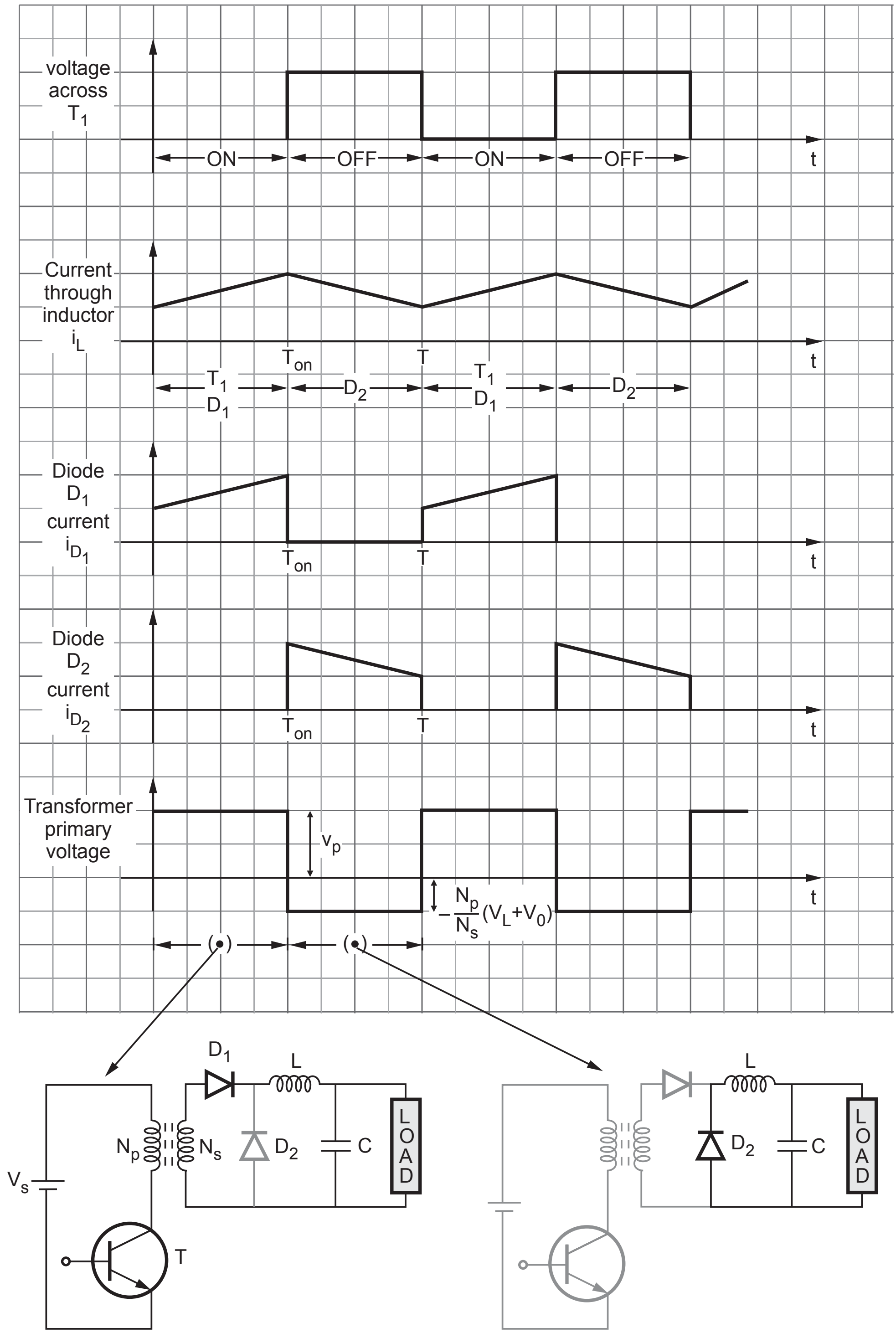
Step 2 : When T_1 is turned off, D_1 is reverse biased and diode D_2 starts conducting. The voltage across inductor will be,

$$v_L = -V_o$$

Step 3 : Integration of voltage across inductor over one time period will be zero. i.e.,

$$\int_0^{T_{on}} v_L \, dt + \int_{T_{on}}^{T} v_L \, dt = 0$$

$$\therefore \quad \int_0^{T_{on}} \left(\frac{N_s}{N_p} V_s - V_o \right) dt + \int_{T_{on}}^{T} (-V_o) \, dt = 0$$



Equivalent circuit - I

Equivalent circuit - II

Fig. 4.8.6 Waveforms of forward converter

$$\therefore \quad \left(\frac{N_s}{N_p} V_s - V_o\right) T_{on} - V_o (T - T_{on}) = 0$$

$$\therefore \quad V_o = \frac{N_s}{N_p} V_s \times \frac{T_{on}}{T} = \delta \frac{N_s}{N_p} \cdot V_s$$

This is the expression for output voltage.

Example for Practice

Example 4.8.5 : *A flyback converter, operating in the continuous conduction mode at a frequency of 40 kHz, uses a 800 V power MOSFET as the switching element and is fed from the rectified mains with V_{DC} = 325 V.*
i) Calculate the maximum duty cycle, allowing a margin of 150 V for voltage spikes on the drain of the MOSFET due to leakage inductance effects.
ii) Calculate the flyback converter transformer turns ratio required to obtain a maximum output voltage of 12 V.
iii) Obtain the peak current rating of the MOSFET if the maximum load current is 5 A and the inductance of the transformer, referred to primary, is 10 mH.

[Hint and Ans. : $V_{T1} = \frac{V_s}{1-\delta} + V_{spike}$, δ **= 0.5 or 50 %,** $\frac{V_o}{V_s} = \frac{N_s}{N_p} \cdot \frac{\delta}{1-\delta}$, $\frac{N_p}{N_s}$ **= 27:1,**
$I_{s\,(max)} = I_s(0) + \frac{V_{s\,(max)}}{L_{(pri)}} \cdot \frac{\delta}{f}$, $I_{s(max)} = \frac{N_s}{N_p} I_{o(max)}$ **= 0.1846 A]**

Review Question

1. *Explain the operation of Flyback type SMPS and discuss advantages and limitations.*

SPPU : Dec.-18, Marks 8

4.9 Concept of Integrated Converter and Design of LM 3524

SPPU : May-18

A complete step-down switching regulator schematic, using the LM 3524D, is illustrated in Fig. 4.9.1. Transistors Q1 and Q2 have been added to boost the output to 1 A. The 5 V regulator of the LM 3524D has been divided in half to bias the error amplifier's non- inverting input to within its common-mode range. Since each output transistor is on for half the period, actually 45 %, they have been paralleled to allow longer possible duty cycle, up to 90 %. This makes a lower possible input voltage. The output voltage is set by :

$$V_o = V_{NI}\left(1 + \frac{R_1}{R_2}\right)$$

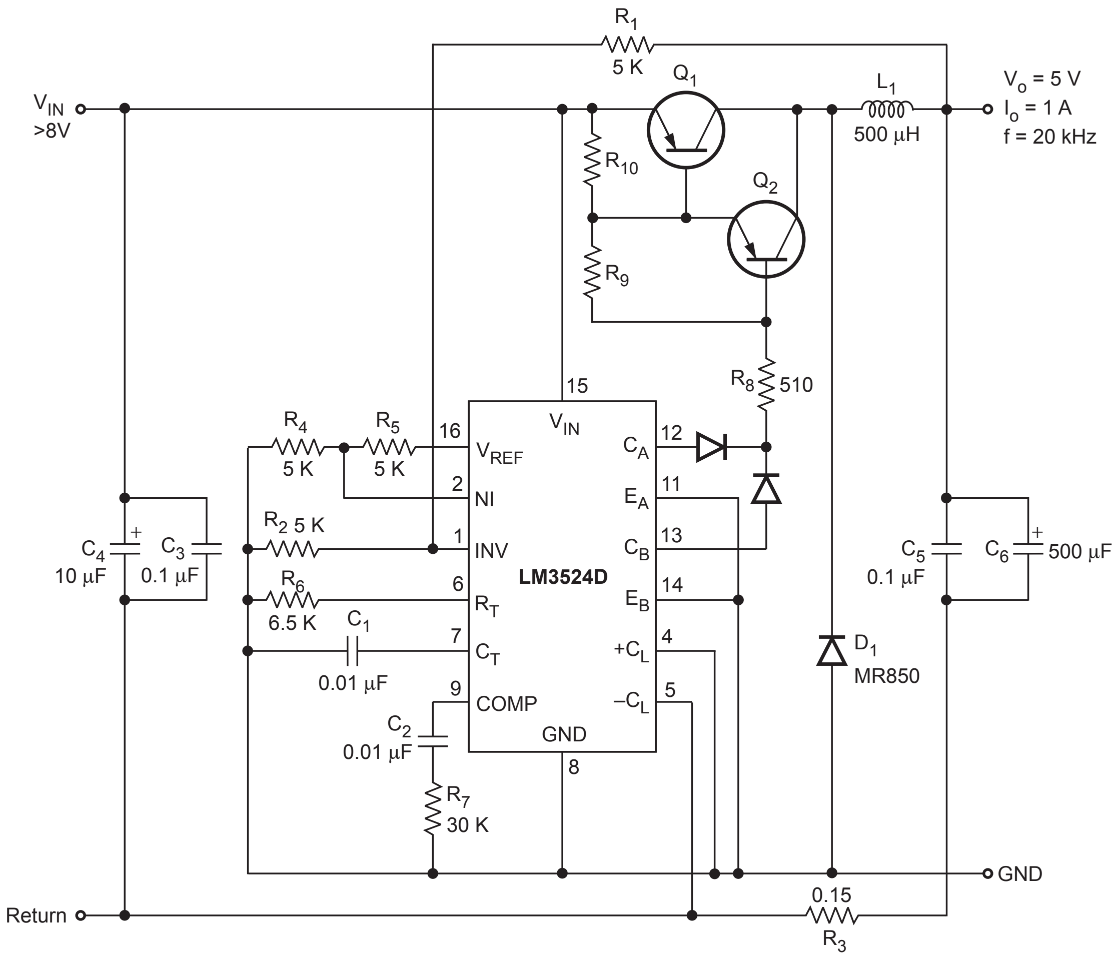


Fig. 4.9.1

where VNI is the voltage at the error amplifier's non-inverting input. Resistor R_3 sets the current limit to:

$$\frac{200\,mV}{R_3} = \frac{200\,mV}{0.15} = 1.3 \text{ A}$$

Review Question

1. *Draw the diagram and explain the operation of step down SMPS ? Draw the diagram showing implementation of this SMPS using PWM IC LM 3524 ?*

SPPU : May-18, Marks 8

4.10 Concept of Maximum Power Point Tracking (MPPT)

Principle of MPPT or PPT : It maximizes the power extraction from the variable power source to the load such as batteries, inverter systems, external grids and other electrical loads.

- MPPT is user with variable power sources such as Photo Voltaic (PV) solar systems, wind turbines, optical power transmission and thermo photo voltaics.
- In case of solar panel, the efficiency of power transfer depends upon amount of available sunlight, temperature of solar panel and electrical conditions of the load.
- MPPT observes there conditions and adjusts the load characteristic in such a way so that highest power transfer takes place. Thus MPPT ensures highest efficiency of the system.
- The optimal load characteristic is called *Maximum Power Point (MPP).* The chopper or inverter circuits present optimal loads to photovoltaic cells so that maximum power transfer takes place.
- The voltage, current or frequency of these converters is adjusted by MPPT system to achieve MPP.
- MPPT devices are integrated with DC choppers or solar inverters.

Block diagram and operation :

- Fig. 4.10.1 shows the block diagram of MPPT with chopper. The available power from the solar panel such as PV array is sensed continuously by the MPPT control unit.

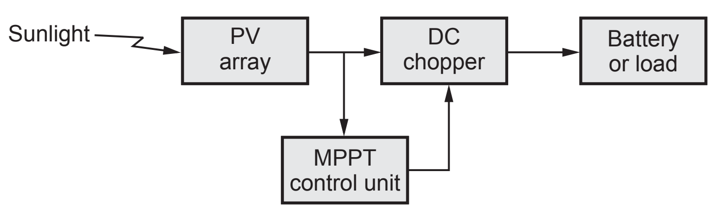


Fig. 4.10.1 : MPPT system with DC chopper

- The triggering of chopper is adjusted in such a way that optimal load is presented to the solar panel. This ensures highest efficiency of the solar panel.

4.11 Advantages, Disadvantages and Applications

4.11.1 Advantages

i) In linear power supply the series pass transistor operates inactive region. Hence there is high power loss. But in SMPS, all devices operate in saturation and cut-off regions. Therefore losses are reduced in SMPS.

ii) Due to reduced power loss, SMPS have efficiencies upto 95% but linear power supplies have very small efficiencies.

iii) SMPS operate at very high frequencies. Therefore filtering components and transformers have very small size. Where as linear power supplies have bulky components.

iv) SMPS have transistors in switching mode. Hence their power handing capacity is more as compared to linear mode.

v) SMPS are more cost effective due to reduced size of transformer and filters.

4.11.2 Disadvantages

i) Since SMPS operate at high switching frequencies, they generate radio frequency interference (RFI) to neighbouring circuits.

ii) Since the devices operate in switched mode, there are switching losses at high frequencies.

iii) The transient response of SMPS is very slow compared to linear power supplies.

iv) SMPS have pooor load regulation as compared to linear power supply.

4.11.3 Applications of SMPS

i) Television sets, DVD players

ii) Computers, printers, monitors.

iii) Battery charges, electronic ballasts

iv) Video games, toys.

Large number of applications use SMPS due to their high power efficiencies.

Review Questions

1. *With the help of neat circuit diagram and waveforms explain the operation of flyback converter.*
2. *Derive an expression for output voltage of flyback converter in terms of duty cycle, battery voltage and transformer turns ratio.*
3. *State important advantages, disadvantages and applications of SMPS.*

4.12 Multiple Choice Questions

Q.1 Choppers converts :

a AC to DC

b DC to AC

c DC to DC

d AC to AC

Q.2 What is the duty cycle of a chopper ?

a Ton / Toff
b Ton / T
c T / Ton
d Toff x Ton

Q.3 The load voltage of a chopper can be controlled by varying the _________.

a duty cycle
b firing angle
c reactor position
d extinction angle

Q.4 Find the output voltage expression for a step down chopper with Vs as the input voltage and k as the duty cycle.

a $v_o = V_s/k$
b $v_o = V_s \times k$
c $v_o = V_{s2}/k$
d $v_o = 2V_s/k\pi$

Q.5 In a step down chopper, if V_s = 100 V and the chopper is operated at a duty cycle of 75 %. Find the output voltage.

a 100 V
b 75 V
c 25 V
d none of the mentioned

Q.6 Find the expression for output voltage for a step-up chopper, assume linear variation of load current and k as the duty cycle.

a V_s
b V_s/k
c $V_s/(1 - k)$
d $V_s/\sqrt{2}$

Q.7 SMPS is used for ________.

a obtaining controlled ac power supply
b obtaining controlled dc power supply
c storage of dc power
d switch from one source to another

Q.8 SMPS are based on the ________ principle.

a phase control
b integral control
c chopper
d MOSFET

Q.9 In the external control of dc input voltage __________.

- a a chopper is placed just after the inverter block
- b a chopper is placed just after the filter block
- c a chopper is placed before the filter and the inverter block
- d none of the mentioned

Q.10 Usually __________ batteries are used in the UPS systems.

- a NC
- b Li-On
- c lead acid
- d all of the mentioned

Explanations

Q.1 Explanation : Choppers are used to step up or step down DC voltage / current levels. Hence, they are DC to DC converters.

Q.2 Explanation : It is the time during which the chopper is on (Ton) relative to the whole period (T= Ton + Toff).

Q.3 Explanation : The output voltage can be changed by changing the duty cycle (Ton / T).

Q.4 Explanation : The chopper output voltage is Duty cycle x The input voltage (ideal condition).

Q.5 Explanation : V_o = Duty cycle x V_s = 0.75 x 100 = 75 V.

Q.7 Explanation : SMPS (Switching Mode Power Supply) is used for obtaining controlled dc power supply.

Q.9 Explanation : Constant AC - Rectifier - Chopper - Filter - Inverter.

Q.10 Explanation : Lead acid batteries are cheaper and have certain advantages over the other types. NC batteries would however be the best, but are three to four times more expensive than lead acid.

Answer Keys for Multiple Choice Questions :

Q.1	c	**Q.2**	b	**Q.3**	a	**Q.4**	b	**Q.5**	b
Q.6	c	**Q.7**	b	**Q.8**	c	**Q.9**	c	**Q.10**	c

❑❑❑

Notes

UNIT V

5 Power Devices Protection and Circuits

Syllabus

Over voltage, over current, di/dt and dv/dt protection circuits and their design, Various cooling techniques and heat sink design, Resonant converters such as Zero current switching (ZCS) and Zero voltage switching (ZVS), Electromagnetic interference such as radiated and conducted EMI, Difference between EMI and EMC, EMI sources and soft switching and minimizing / shielding techniques for EMI, Various EMI and EMC standards, Importance of isolation transformer.

Contents

5.1 Over Voltage Protection

SPPU : May-15,17, Dec.-16

5.1.1 Over Voltage Conditions

Over voltage can arrive in power electronic circuits because of following conditions :

i) Incorrect selection of power devices.

ii) Voltage surges or spikes from load or supply side.

iii) Imbalance in the load.

iv) Failure of one or more power devices in the same circuit.

v) Insufficient snubber components.

vi) Insufficient cooling of power devices.

vii) Inappropriate mounting of power devices.

All the above situations lead to average or repetitive over voltage in the circuit. It damages the power device.

5.1.2 Over Voltage Protection Circuit

Overvoltage protection can be achieved in different ways. Fig. 5.1.1 shows the overvoltage protection circuit using SCRs. T_1 and T_2 are antiparallel SCRs used to bypass the voltage transients in case of overloads. Thus the load is protected. R_1 is used to limit the current through T_1 and T_2 in case of overvoltage zener diode D_5 and R_2 form the voltage sensing circuit. These components also work as a trigger circuit for the SCRs along with diodes D_1 to D_4.

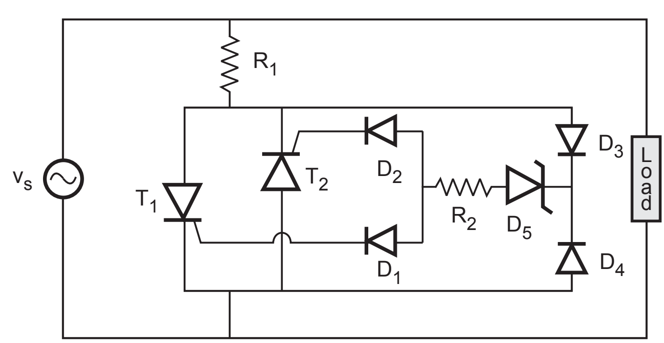


Fig. 5.1.1 Overvoltage protection circuit

Circuit Operation

- When there is overvoltage, the values of R_2 is set such that zener diode D_5 breaks. This applies gate drive to T_1 and T_2. For positive half cycle T_1 conducts and the overvoltage is reduced by drawing heavy current through R_1 and T_1. Then T_1 turns off by natural commutation at the end of positive half cycle.
- If over voltage persists, zener diode again breaks in negative half cycle and applies gate drive to T_2. Heavy current flows through T_2 and R_1 and the load is protected.

- As soon as the voltage returns to its safe value, the zener diode D_5 doesnot break and no current flows through it. Hence T_1 and T_2 are turned off and supply voltage appears across the load.
- The value of R_1 is selected such that enough current is drawn through the supply or load and overvoltage is returned to its safe limit.
- This circuit provides overvoltage protection arised due to either supply or load.

Review Question

1. *Explain overvoltage and over current protection circuits.*

SPPU : May-17 (End Sem.), Dec.-16 (End Sem), Marks 6

5.2 Over Current Protection

SPPU : Dec.-16, May-17

5.2.1 Over Current Fault Conditions

Over current can occur in power electronic circuits because of following conditions :

i) Short circuit of the load.

ii) Over load situation for long period.

iii) Shoot through fault in inverters/choppers.

iv) Malfunctioning of control circuit.

v) Failure of triggering circuit.

vi) Short circuitting of power devices in same circuit.

vii) Current spikes or surges from load, snubber circuit, communication circuit or supply side.

5.2.2 Overcurrent Protection

5.2.2.1 Fuse

The overcurrents flow in the thyristor circuits due to short circuits. The short circuits can take place because of short circuitted load, misalignment of firing pulses, failure of the thyristors due to overvoltages etc. The short circuit currents can be protected automatically because of load or supply transformers appear in the circuit. However the thyristors must be protected against overcurrents in the circuit. Normally fast acting fuse are used for the protection of thyristor against overcurrents.

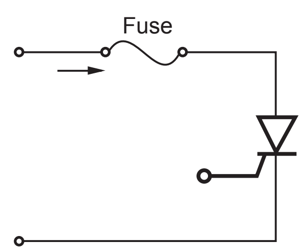


Fig. 5.2.1 Fast acting fuse is used to protect thyristor against overcurrent

These fuse melt at comparatively lower currents than current rating of the thyristor. Thus fuse melts and disconnects the circuit and the thyristor is protected. This is shown in Fig. 5.2.1. The fuse should be selected such that it should not melt or disconnect the circuit at normal load currents.

5.2.2.2 Semiconductor Fuses

Fig. 5.2.2 shows the internal structure of the semiconductor fuse. The fusing element is made of silver with one or more notches as shown in the Fig. 5.2.2. The cross section of the fuse at the notch is less. When heavy current flows through the fuse, there is high current density at the notch. Because of high current density, temperature rises at the notch and arc is developed. This arc reduces the current flow. Therefore high voltage is formed across the notch. This further increases the temperature. Therefore the fuse element is vapourized and arc length is increased. Due to increased arc length, the current further reduces. At some stage the current is zero and the fuse becomes open. There is no arc and the complete voltage appears across the fuse. Note that the fuse has to withstand the voltage in open condition. The fusing element is embedded in quartz sand. This helps to conduct heat and serves as a quenching medium for the arc at the time of fusing.

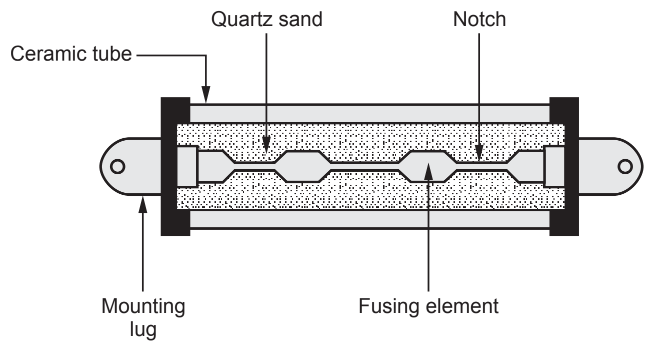


Fig. 5.2.2 Cross section of semiconductor fuse

Fig. 5.2.3 shows the current versus time characteristic for fuse. At the peak let through value of the current, arcing starts at the notches in the fuse. This time is called melting time t_m. After t_m, the arcing starts at notches and current begins to reduce. The time 't_a' is the total arcing time. At the end of t_a, fuse current is zero and it is completely open. The sum of t_m and t_a is called clearing time (t_c) of the fuse. At the peak let through current, the I^2t value of the fuse must be less than I^2t value of the device being protected. Therefore fuse protects the device before reaching to prospective fault current value.

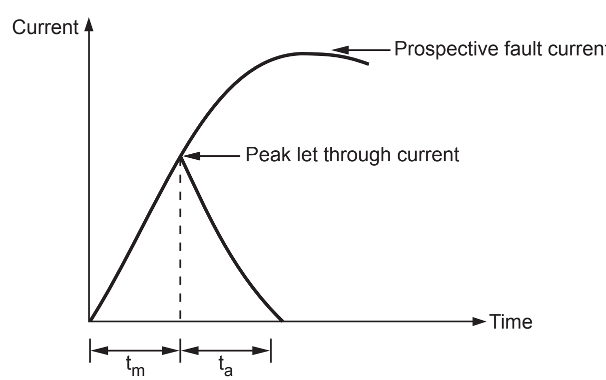


Fig. 5.2.3 Fuse current with respect to time

Normally semiconductor fuses are used in series with each device being protected. Fig. 5.2.4 shows the placement of semiconductor fuses for single phase converter.

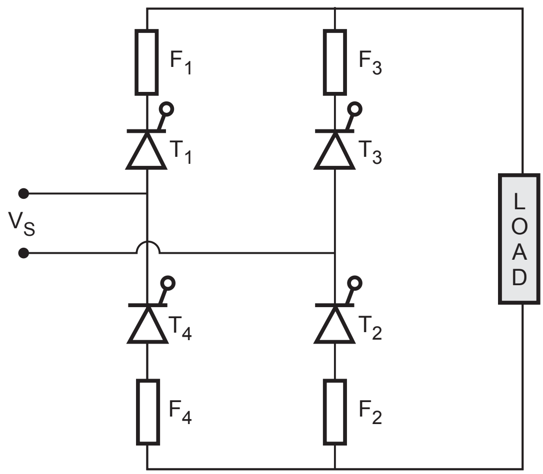


Fig. 5.2.4 Placement of semiconductor fuses for 1ϕ converter

Review Questions

1. *Explain the working of semiconductor fuse. How it protects the device ?*
2. *Explain overvoltage and over current protection circuits.*

SPPU : Dec.-16 (End Sem), May-17 (End Sem), Marks 6

5.3 Protection against dv/dt and Overvoltages

SPPU : May-2000,04,05,16,17, Dec.-03,04,18

5.3.1 Snubber Circuits (Turn-off Snubber)

The transient overvoltages can switch on the thyristor. In some cases the thyristor can be damaged due to these transient voltages. These transient voltages are very common when the converter is having inductive loads. The thyristors can be protected against transient voltages by a RC network as shown in Fig. 5.3.1. This RC network is connected in parallel

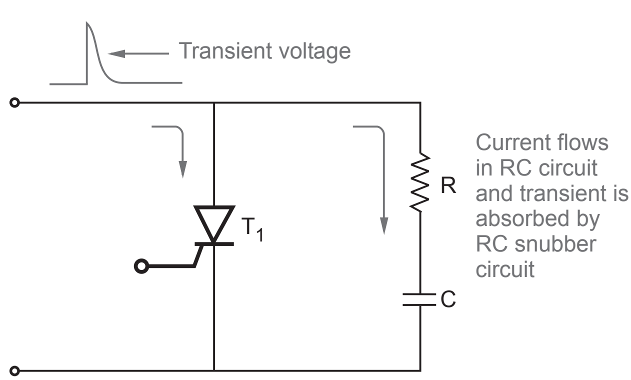


Fig. 5.3.1 A snubber (RC) network is used for transient voltage protection

across the thyristor. It is called *snubber circuit.* The resistance has the value of few hundred ohms. Whenever there is a large spike or voltage transient across the thyristor, it is absorbed by the RC circuit. The RC circuit (snubber) acts as a lowpass filter for this voltage transient. The resistance has normally low value so that the transient is absorbed by the capacitor quickly. Thus the thyristor is protected against voltage transients. The RC snubber circuit is very commonly used for protection of thyristors against transient voltages (high frequency voltage spikes).

$\frac{dv}{dt}$ also generates large voltage transients. These rapid voltage variations can also be suppressed by snubber circuit. The capacitor acts as a short for these $\frac{dv}{dt}$ variations. The snubber can be made more effective by connecting a diode across the resistance as shown in Fig. 5.3.2.

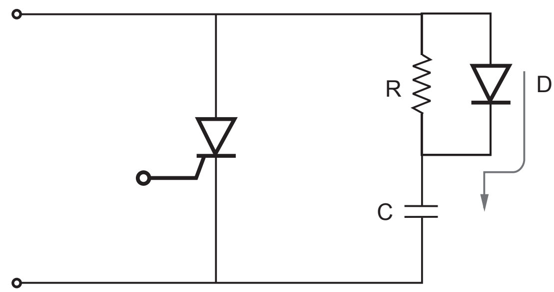


Fig. 5.3.2 Snubber is used for $\frac{dv}{dt}$ protection

In case of voltage transient, the current flows through diode and capacitor. The capacitor acts as a short for the voltage transient. Thus it is suppressed. When thyristor turns-on, the capacitor discharges through resistance R. The R, C and diode snubber is more commonly used because it is very effective for $\frac{dv}{dt}$ and other voltage transients.

Design of snubber

The value of capacitor is given as,

$$C = \frac{1}{2L}\left(\frac{0.564\ V_m}{\frac{dv}{dt}}\right)^2 \qquad \text{... (5.3.1)}$$

Here V_m is the peak value of supply voltage

$\frac{dv}{dt}$ is the permissible $\frac{dv}{dt}$.

L is the source inductance.

And resistance is given as,

$$R = 2\sigma\sqrt{\frac{L}{C}} \qquad \text{... (5.3.2)}$$

Here σ is the damping factor. It's value is normally taken as 0.65.

Example 5.3.1 *Calculate the values of snubber components R and C in Fig. 5.3.3 to protect SCR from reapplied dv/dt, if dv/dt rating of SCR is 100 V/μsec.*

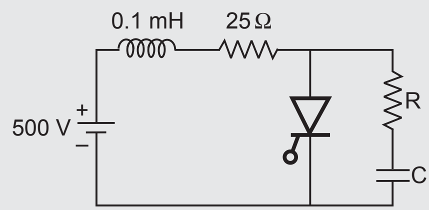


Fig. 5.3.3

Solution : Given :

$$L = 0.1 \text{ mH}$$

$$V_m = 500 \text{ V}$$

$$\frac{dv}{dt} = 100\ V/\mu \text{ sec} = \frac{100}{10^{-6}}\ V/\mu \text{ sec}$$

$$C = \frac{1}{2L}\left[\frac{0.564\,V_m}{dv/dt}\right]^2$$

$$= \frac{1}{2\times 0.1\times 10^{-3}}\left[\frac{0.564\times 500}{100}\times 10^{-6}\right]^2$$

$$= 0.04\ \mu\text{F}$$

$$R = 2\sigma\sqrt{\frac{L}{C}} = 2\times 0.65\sqrt{\frac{0.1\times 10^{-3}}{0.04\times 10^{-6}}}$$ assuming σ = 0.65. = 65 Ω

Out of this, 25 Ω is already present in the circuit. Hence R = 64 – 25 = 40 Ω.

Example 5.3.2 *For the circuit shown in Fig. 5.3.4, the thyristor is operated at 2 kHz. The required $\frac{dv}{dt}$ is 100 V/μs. The discharge current is to be limited to 100 A. Determine*

i) Values of R_s and C_s ii) Snubber loss

iii) Power rating of R_s

Load and stray inductances are negligible.

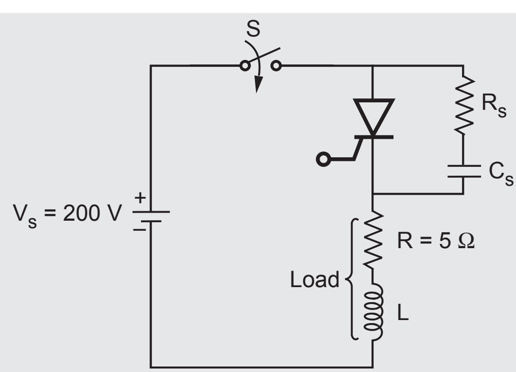


Fig. 5.3.4

Solution : Given :

Load resistance, R = 5 Ω

Frequency, $f = 2$ kHz

$$V_s = 200 \text{ V}$$

$$\frac{dv}{dt} = 100 \text{ V/}\mu\text{s}$$

$$I_{TD} = 100 \text{ A}$$

$$L = 0$$

i) To obtain values of R_s and C_s

R_s limits the discharge current through T_1. From Fig. 5.3.4, T_1 - R_s - C_s forms a loop when T_1 turns-on. Prior to turn-on of T_1, C_s charges to 200 V. Fig. 5.3.5 shows this situation.

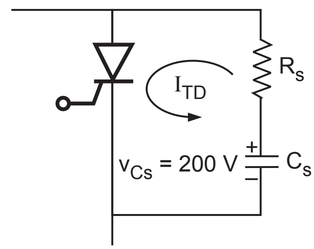


Fig. 5.3.5 Path of I_{TD}

From this figure we can write,

$$v_{Cs} = R_s I_{TD}$$

$$\therefore \quad R_s = \frac{v_{Cs}}{I_{TD}} = \frac{V_s}{I_{TD}} = \frac{200}{100} = 2\ \Omega$$

The charging current of C_s can be expressed by KVL to V_s - R_s - C_s - R - L loop as,

$$V_s = R_s i_C(t) + \frac{1}{C_s}\int i_C(t)dt + v_C(t=0) + R\, i_C(t)$$

On solving above equation,

$$i_C(t) = \frac{V_s}{R_s + R} e^{-\frac{t}{\tau}},$$

Here $\tau = (R_s + R)C_s$ and $v_C(t=0) = 0$.

Hence the voltage across the SCR can be expressed as,

$$v_{T_1}(t) = V_s - R\, i_C(t) = V_s - \frac{RV_s}{R_s + R} e^{-\frac{t}{\tau}}$$

At t = 0, $$v_{T_1}(0) = V_s - \frac{RV_s}{R_s + R} \frac{R_s V_s}{R_s + R}$$

and at t = τ, $$v_{T_1}(\tau) = V_s - \frac{RV_s}{R_s + R} e^{-1} = V_s - \frac{0.3678\, RV_s}{R_s + R}$$

$$= \frac{R_s V_s + 0.6321\, RV_s}{R_s + R}$$

Now $\frac{dv}{dt}$ can be expressed as,

$$\frac{dv}{dt} = \frac{v_{T_1}(\tau) - v_{T_1}(0)}{\tau}$$

$$= \frac{\frac{R_s V_s + 0.6321\, R V_s}{R_s + R} - \frac{R_s V_s}{R_s + R}}{(R_s + R)\, C_s}$$

$$= \frac{0.632\, R V_s}{(R_s + R)^2 C_s}$$

$$\therefore \quad C_s = \frac{0.632\, R V_s}{\frac{dv}{dt}(R_s + R)^2} = \frac{0.632 \times 5 \times 200}{\frac{100}{1 \times 10^{-6}}(2+5)^2}$$

$$= 0.1289\ \mu\text{F}$$

ii) To obtain snubber loss

The power stored in C_s is dissipated in R_s. Hence it is snubber loss

$$P_s = \frac{1}{2} C_s V_s^2 f_s$$

$$= \frac{1}{2} \times 0.1289 \times 10^{-6} \times 200^2 \times 2 \times 10^3$$

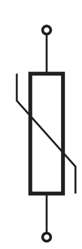
$$= 5.2\ \text{W}$$

iii) To obtain power rating of R_s

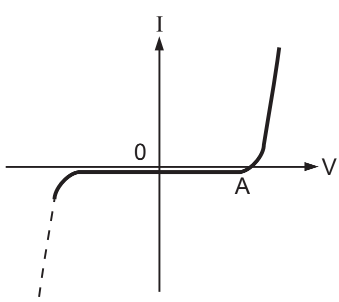
The power stored in C_s is disspated in R_s. It is 5.2 W. Hence power rating of R_s will be 5.2 W.

5.3.2 Metal Oxide Varistors (MOVs)

High dv/dt and transient over voltages can also be suppressed with the help of Metal Oxide Varistors (MOV). MOVs are also called varistors or nonlinear voltage dependent resistor. MOVs consists of metal oxide particles, which are separated by an oxide film or insulation. When the applied voltage is less than specific value, then MOV offers high impedence. When the applied voltage



(a) Symbol of MOV



(b) V-I characteristics of MOV

Fig. 5.3.6

is more than specific value, the oxide film becomes conductive and current starts flowing. Thus the voltage spike is suppressed by the MOV. Fig. 5.3.6 shows the characteristics and symbol of MOV.

In the Fig. 5.3.6 observe that voltage increases above point 'A', the MOV starts conducting heavily.

The current and voltage of MOV are related as,

$$I = KV^{\alpha}$$

Here K is the device constant and 'α' lies in the range of 30 to 40.

Normally MOVs are connected across the supply lines over which the voltage transients are to be suppressed.

5.3.3 Improving *dv/dt* Rating with the Help of Cathode Short

The Fig. 5.3.7 shows the modification in the structure of SCR to improve dv/dt capability.

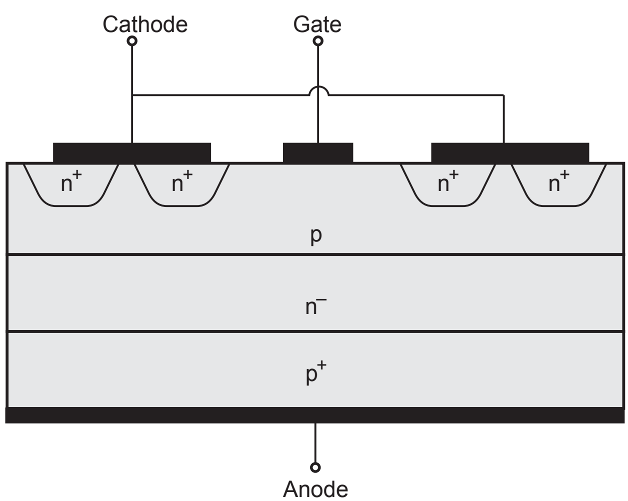


Fig. 5.3.7 Shorted emitter structure

- The cathode metallization is overlapped over the gate region, i.e. p2 region. It is called cathode short.
- The SCR turns on by dv/dt mainly due to lateral flow of current in the p-type region. This lateral current is intercepted in large amount mainly by the cathode shorts. It does not flow across the gate -cathode junction but flows directly to cathode.
- This intercept of lateral current improves dv/dt capability of the SCR.

Examples for Practice

Example 5.3.3 : *Calculate the required parameters for a snubber circuit to provide reliable* $\frac{dv}{dt}$ *protection to a SCR used in the single phase fully controlled bridge. The SCR has a maximum* $\frac{dv}{dt}$ *capability of 40 V/µs. The input line to line voltage has a peak value of 325 V and the source inductance is 0.1 mH.*

[Ans. : R = 41 Ω and C = 0.1 µF]

Example 5.3.4 : *Calculate the required parameters for snubber circuit to provide* $\frac{dv}{dt}$ *protection to a SCR used in single phase bridge converter. The SCR has a maximum* $\frac{dv}{dt}$ *capability of 60 V / µ sec. The input line to line voltage has a peak value of 425 volts and the source inductance is 0.2 mH.*

[Hints and Ans. : For σ = 0.65, *C* = 0.04 µ*F*, and R = 92 Ω]

Review Questions

1. *Explain the protection of power devices by snubber circuit.* **SPPU : May-2000, Marks 4**
2. *Explain the use of Metal Oxide Varistors (MOV) for protection against overvoltages and voltage transients?*
3. *Explain the shorted emitter structure to improve the dv/dt ratings of SCRs.* **SPPU : May-04,05,17, Marks 4**
4. *Write a short note on snubber circuits.* **SPPU : Dec.-03,04, Marks 6; May-2000,16,17 (End Sem.), Marks 4**
5. *Explain dv/dt and snubber circuit protection.* **SPPU : Dec.-18, (End Sem), Marks 8**
6. *Explain dv/dt, di/dt and snubber circuit protection.* **SPPU : Dec.-18 (End Sem), Marks 8**

5.4 $^{di}/_{dt}$ Protection with the Help of Inductor (Turn-on Snubber)

SPPU : May-02,04,05,10,16,17, Dec.-09,18

We know that at the time of turn-on, anode current increases rapidly. This rapid variation of anode current doesnot spread across the junction area of the thyristor. This creates the local hot-spots in the junction and increases the junction temperature. If the junction temperature exceeds permissible value, then the thyristor is damaged. The rapid variations of the thyristor current are also called $\frac{di}{dt}$. Every thyristor has maximum permissible value of $\frac{di}{dt}$.

The thyristor can be protected from excessive $\frac{di}{dt}$ by using an inductor in series as shown in Fig. 5.4.1. The inductance opposes for rapid current variations $\left(\frac{di}{dt}\right)$. Whenever there is rapid current variation, the inductor smooths it and protects the thyristor from damage.

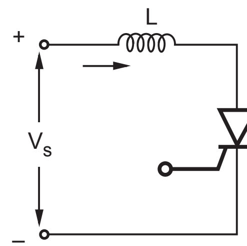


Fig. 5.4.1 An inductance in series with the thyristor provides protection against $\frac{di}{dt}$

The value of inductance can be calculated as,

$$L \geq \frac{V_s}{\frac{di}{dt}} \quad \text{... (5.4.1)}$$

Here $\frac{di}{dt}$ is the maximum value and L is the series inductance including stray inductance.

Example 5.4.1 *Design the snubber circuit elements R_s and C_s connected across the SCR given that $\frac{dv}{dt}$(max) = 180 V/μs and $\frac{di}{dt}$(max) = 45 A/μs. An inductance L = 0.1 H and a resistance $R << R_s$ are in series with the SCR with a 300 V DC applied to the circuit.*

Solution : The value of $\frac{di}{dt}$ is given. Hence let us determine the required value of series inductance. From equation (5.4.1), it is given as,

$$L \geq \frac{V_s}{\frac{di}{dt}}$$

Here V_s = 300 V and $\frac{di}{dt}$ = 45 A/μs. putting these values in above equation,

$$L \geq \frac{300}{45/10^{-6}}$$

$$\geq \frac{300}{45} \times 10^{-6}$$

$$\geq 6.667 \times 10^{-6} H$$

This inductance includes stray inductance also. There is an inductance of 0.1 H (given) in series with the SCR. Since this is more than 6.667×10^{-6} H, there is no need to connect extra inductance. Thus $\frac{di}{dt}$ protection is obtained through existing 0.1H inductance. The capacitance of the snubber is given by equation (5.3.1) as,

$$C = \frac{1}{2L}\left[\frac{0.564\,V_m}{\frac{dv}{dt}}\right]^2$$

Here V_m = 300 V, $\frac{dv}{dt} = 180$ V/μs and L = 0.1 H. Hence above equation becomes,

$$C = \frac{1}{2\times 0.1}\left[\frac{0.564\times 300}{180/10^{-6}}\right]^2$$

$$= \frac{1}{2\times 0.1}\left[\frac{0.564\times 300}{180}\times 10^{-6}\right]^2$$

$$= 4.418\times 10^{-12} \text{ F or } 4.418 \text{ pF}$$

The resistance of the snubber is given by equation (5.3.2) as,

$$R = 2\sigma\sqrt{\frac{L}{C}}$$

Here $\sigma = 0.65$ (damping factor) and putting values of L and C calculated earlier,

$$R = 2\times 0.65\sqrt{\frac{0.1}{4.418\times 10^{-12}}} = 195.58 \; k\Omega$$

It is mentioned in the example that series resistance is very very small than snubber resistance. Hence it can be neglected. Fig. 5.4.2 shows the snubber circuit.

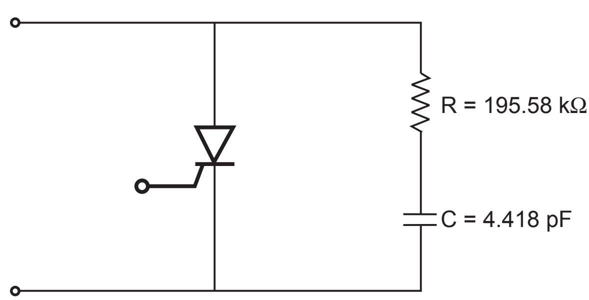


Fig. 5.4.2 Snubber circuit of example 5.4.1

Example 5.4.2 *The capacitance of the reverse biased junction J_2 in a thyristor is 25 pF and can be assumed to be independent of the off-state voltage. The limiting value of the charging to turn-on the thyristor is 16 mA. Determine the critical value of $\frac{dv}{dt}$.*

Solution : The current through the junction J_2 capacitance is given as,

$$i = \frac{dQ}{dt} = \frac{d}{dt}(C_{j2}V_{j2})$$

Here C_{j2} is capacitance of J_2 and

V_{j2} is voltage across J_2

$$\therefore \quad i = V_{j2}\frac{dC_{j2}}{dt} + C_{j2}\frac{dV_{j2}}{dt} \qquad \text{... (5.4.2)}$$

The capacitance is independent of the off-state voltage. Hence $\frac{dC_{j2}}{dt} = 0$. Hence above equation will be,

$$i = C_{j2}\frac{dV_{j2}}{dt}$$

Here V_{j2} is the voltage across J_2. This voltage is nearly equal to applied voltage V. Hence,

$$i = C_{j2}\frac{dv}{dt} \qquad \text{... (5.4.3)}$$

$$\therefore \quad \frac{dv}{dt} = \frac{i}{C_{j2}}$$

Here i = 16 mA is the limiting value of charging current and

C_{j2} = 25 pF. Therefore above equation becomes,

$$\frac{dv}{dt} = \frac{16\times 10^{-3}}{25\times 10^{-12}}$$

$$= 6.4\times 10^{8} \text{ V/sec} = 640 \text{ V/}\mu s$$

This is the critical value of $\frac{dv}{dt}$.

Example 5.4.3 *Calculate the required parameters for snubber circuit to provide $\frac{dv}{dt}$ protection to a SCR used in a single phase bridge converter. The SCR has a maximum $\frac{dv}{dt}$ capability of 60 V/μs. The input line to line voltage has a peak value of 425 volts and the source inductance is 0.2 mH.*

Solution : Given :

$$\frac{dv}{dt} = 60 \text{ V/}\mu s$$

$$V_m = 425 \text{ V}$$

$$L = 0.2 \text{ mH}$$

We have to calculate the values of R and C for the snubber. From equation (5.3.1), capacitor is given as,

$$C = \frac{1}{2L}\left[\frac{0.564V_m}{\frac{dv}{dt}}\right]^2$$

Putting the values in above equation,

$$C = \frac{1}{2\times 0.2\times 10^{-3}}\left[\frac{0.564\times 4.25}{60\times 10^6}\right]^2 = 0.04\ \mu F$$

And the value of resistance is given by equation (5.3.2) as,

$$R = 2\sigma\sqrt{\frac{L}{C}}$$

Value of σ is normally taken as 0.65. Putting for L and C,

$$R = 2\times 0.65\sqrt{\frac{0.2\times 10^{-3}}{0.04\times 10^{-6}}} = 92\ \Omega$$

Thus we obtained the values of snubber components as,

$$R = 92\ \Omega \quad \text{and} \quad C = 0.04\ \mu F$$

Example 5.4.4 *The junction capacitance of the thyristor shown in Fig. 5.4.3 is 15 pF and is assumed to be independent of the off-state voltage. The value of charging current to turn-on the device is 5mA and the critical value of* $\frac{dv}{dt} = 200$ *V/µs. Determine the value of* C_s *so that the thyristor will not be turned on due to* $\frac{dv}{dt}$.

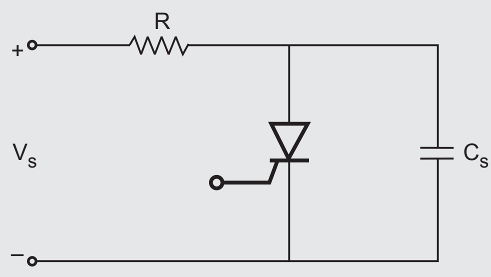


Fig. 5.4.3 Circuit of example 5.4.4

Solution : Here the junction capacitance of the thyristor and external capacitance (C_s) both will absorb the effect of $\frac{dv}{dt}$. These two capacitors will be in parallel. Hence charging current can be given as (using equation 5.4.3),

$$i = (C_s + C_j)\frac{dv}{dt}$$

The charging current should not exceed 5 mA. Hence above equation becomes,

$$5 \text{ mA} \leq (C_s + C_j)\frac{dv}{dt}$$

$$\text{or } C_s + C_j \geq \frac{5\,mA}{\frac{dv}{dt}}$$

$$\geq \frac{5\times 10^{-3}}{200\times 10^{6}}$$

$$\geq 25\ pF$$

Thus the total capacitance should be more than 25 pF. Out of this, C_j = 15 pF. i.e.,

$$C_s + 15\,pF \geq 25\ pF$$

$$\therefore \quad C_s \geq 10\,\text{pF}$$

Thus external capacitance of at least 10 pF is required to avoid false triggering due to $\frac{dv}{dt}$.

Example 5.4.5 *Design the values of $\frac{di}{dt}$ inductor and RC snubber components for an SCR working in a 230 V system. Given $\frac{di}{dt}$ rating is 90 A/μs and $\frac{dv}{dt}$ rating is 200 V/μs. Effective series resistance is 1.5 Ω. Take damping factor is as 0.6.*

Solution : The given data is,

Maximum voltage,

$$V_s = 230 \text{ V}$$

$$\frac{di}{dt} = 90\ A/\mu s$$

$$\frac{dv}{dt} = 200\ A/\mu s$$

Series resistance R_s = 1.5 Ω

Damping factor σ = 0.6

The circuit diagram will look like the one shown in Fig. 5.4.4.

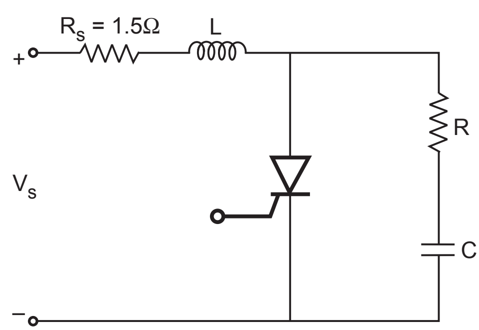


Fig. 5.4.4 Circuit of example 5.4.5

Let us calculate value of inductance for $\frac{di}{dt}$ protection. From equation (5.4.1) it is given as,

$$L \geq \frac{V_s}{\frac{di}{dt}} \geq \frac{230}{90 \times 10^6}$$

$$= 2.556 \times 10^{-6} \text{ H}$$

$$\therefore \quad L = 2.556 \times 10^{-6} \text{ H} = 2.556 \ \mu\text{H}$$

Since there is no stray inductance given, this value of inductance must be connected for $\frac{di}{dt}$ protection.

Now the value of capacitance C can be calculated from equation (5.3.1) as,

$$C = \frac{1}{2L}\left[\frac{0.564\, V_m}{\frac{dv}{dt}}\right]^2$$

Putting value in above equation,

$$C = \frac{1}{2 \times 2.556 \times 10^{-6}}\left[\frac{0.564 \times 230}{200 \times 10^6}\right]^2$$

$$= 0.08229 \ \mu F$$

In Fig. 5.4.4 observe that the resistance R_s and snubber resistance R are in series. These two resistors affect the charging rate of snubber capacitor. Hence, equation (5.3.2). must be written as,

$$(R_s + R) = 2\sigma\sqrt{\frac{L}{C}}$$

Putting values in above equation,

$$(1.5 + R) = 2 \times 0.6\sqrt{\frac{2.556 \times 10^{-6}}{0.08229 \times 10^{-6}}}$$

$$\therefore \quad R = 5.18 \ \Omega$$

Thus the snubber components are,

$$R = 5.18 \ \Omega, \quad C = 0.08229 \ \mu F$$

$$\text{and} \quad L = 2.556 \ \mu H$$

Example 5.4.6 *A SCR circuit operates from 300 V DC supply, has series inductance of 4 μH. A resistance of 4 Ω and capacitance of 0.2 μF is connected across the SCR. Calculate the safe $\frac{dv}{dt}$ and $\frac{di}{dt}$ ratings of SCR.*

Solution : Here the given data is,

$$V_m = 300 \text{ V}$$
$$L = 4\ \mu H$$
$$R = 4\ \Omega$$
$$C = 0.2\ \mu F$$

The value of series inductance for $\frac{di}{dt}$ protection is given by equation (5.4.1) as,

$$L \geq \frac{V_s}{\frac{di}{dt}}$$

Here $V_s = V_m = 300$ and L = 4 μH. Hence above equation becomes,

$$4\ \mu H \geq \frac{300}{\frac{di}{dt}}$$

$$\therefore \quad \frac{di}{dt} = \frac{300}{4 \times 10^{-6}} = 75 \text{ A/}\mu s$$

The value of snubber capacitor is given by equation (5.3.1) as,

$$C = \frac{1}{2L}\left[\frac{0.564\, V_m}{\frac{\text{dv}}{\text{dt}}}\right]^2$$

Putting values in above equation,

$$0.2 \times 10^{-6} = \frac{1}{2 \times 4 \times 10^{-6}}\left[\frac{0.564 \times 300}{\frac{dv}{dt}}\right]^2$$

$$\therefore \quad \frac{dv}{dt} = 133.76 \text{ V/}\mu s$$

Example 5.4.7 *A SCR has a* $\frac{di}{dt}$ *= 120 A/μs and a* $\frac{dv}{dt}$ *of 300 V/μ s. It operates on a 250 V DC source with a load resistance of 10 Ω. Find the suitable values for the components of the snubber circuit.*

Solution : The given data is,

$$\frac{di}{dt} = 120 \text{ A/}\mu s$$

$$\frac{dv}{dt} = 300 \text{ V/}\mu s$$

$$V_m = 250 \text{ V}$$

$$R_L = 10\ \Omega$$

The value of inductance for $\frac{di}{dt}$ protection is given by equation (5.4.1) as,

$$L \geq \frac{V_m}{\frac{di}{dt}}$$

$$\therefore \quad L \geq \frac{250}{120 \times 10^6}$$

$$\therefore \quad L \geq 2.08 \mu H$$

The snubber circuit capacitor is given by equation (5.3.1) as,

$$C = \frac{1}{2L}\left[\frac{0.564\, V_m}{\frac{dv}{dt}}\right]^2$$

Putting values in above equation,

$$C = \frac{1}{2 \times 2.08 \times 10^{-6}}\left[\frac{0.564 \times 250}{300 \times 10^6}\right]^2$$

$$= 0.053\ \mu F$$

Here note that the load resistance is $R_L = 10\ \Omega$. This resistance appears in series with the snubber resistance. Hence the snubber resistance given by equation (5.3.2) can be given as,

$$R + R_L = 2\sigma\sqrt{\frac{L}{C}}$$

Let the damping factor σ = 0.65. Putting other values in above equation,

$$R + 10 = 2 \times 0.65\sqrt{\frac{2.08 \times 10^{-6}}{0.053 \times 10^{-6}}}$$

$$\therefore \quad R = -1.856\ \Omega$$

The negative snubber resistance indicates that the load resistance is more than sufficient for snubber action. There is no need to connect additional snubber resistance.

Review Questions

1. *How the devices are protected against $di/_{dt}$?* **SPPU : May-16,17 (End Sem.), Marks 4**
2. *Explain turn-on and turn-off snubbers.*
   SPPU : May-02, Marks 8; May-04,05, Dec.-09, Marks 6, May-10 Marks 4
3. *Explain di/dt protection.* **SPPU : Dec.-18 (End Sem), Marks 4**
4. *Explain dv/dt, di/dt and snubber circuit protection.* **SPPU : Dec.-18 (End Sem), Marks 8**

5.5 Cooling and Heat Sinks

SPPU : May-19

Power is dissipated across the device due to switching and on-state conduction. This power heats the device. Hence its junction temperature increases. It is necessary to keep the junction temperature of the device within the specified limit, otherwise the device is damaged. The heat dissipated across the junction can be taken away with the help of heat sinks. The heat sink provides greater area for heat conduction. The cooling of the heat sink can take place by natural convection, forced air, liquid or vapour phase cooling.

5.5.1 Concept of Thermal Resistance

The heat transfer from the device can be expressed by following equation,

$$P = \frac{\Delta T}{R_{\theta}} \qquad \text{... (5.5.1)}$$

Here P is the power disssipated in device

ΔT is the temperature difference between junction and ambient

R_{θ} is the thermal resistance to heat flow.

Here note that power/heat is dissipated at the junction of the device. This heat is carried to the case through the encapsulation. The resistance offered to the flow of heat is called thermal resistance.

5.5.2 Thermal Model of a Power Device

Now let us construct thermal model of the power device which is mounted on the heat sink. Fig. 5.5.1 shows such model.

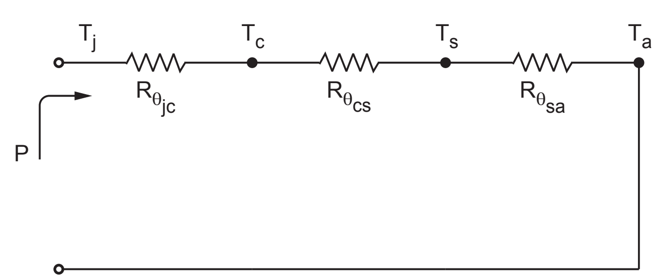


Fig. 5.5.1 Thermal model of a power device

In the above model, 'P' is the dissipated power at the junction. This power is conveyed in the form of heat to the ambient.

T_j is the junction temperature

T_c is the case temperature

T_s is the sink temperature

T_a is the ambient temperature

$R_{\theta_{jc}}$ is the junction to case thermal resistance.

$R_{\theta_{cs}}$ is the case to sink thermal resistance.

$R_{\theta_{sa}}$ is the sink to ambient thermal resistance.

Here total R_θ will be,

$$R_\theta = R_{\theta_{jc}} + R_{\theta_{cs}} + R_{\theta_{sa}}$$

and $$\Delta T = T_j - T_a$$

Hence equation (5.5.1) can be written as,

$$P = \frac{T_j - T_a}{R_{\theta_{jc}} + R_{\theta_{cs}} + R_{\theta_{sa}}} \quad \text{... (5.5.2)}$$

The thermal resistance normally depends upon the area of the device or sink. It is related to area by following equation,

$$R_\theta = \frac{1}{kA} \quad \text{... (5.5.3)}$$

Here 'A' is the area of the heat sink and 'k' is the heat transfer coefficient.

For high frequency switching, reverse recovery losses are also added to the conduction loss. The reverse recovery loss in watts/pulse is given as,

$$J = VQ$$

Here 'V' is the reverse voltage applied to the device after turn-off 'Q' is the reverse recovery charge.

Then the reverse recovery average power loss will be given as,

$$P_{rr} = Jf = VQF \quad \text{... (5.5.4)}$$

Here 'f' is the pulse frequency of the device.

Example 5.5.1 *Determine the junction temperature for the thyristor which is dissipating the average power of 120 watts and* $R_{\theta_{jc}}$ *= 0.15 °C/W,* $R_{\theta_{cs}}$ *= 0.075 °C/W and* $R_{\theta_{sa}}$ *= 0.45 °C/W.*

Solution :

$$\text{Here P} = 120 \text{ W}$$

$$R_{\theta_{jc}} = 0.15\ °\text{C/W}$$

$$R_{\theta_{cs}} = 0.075\ °\text{C/W}$$

$$R_{\theta_{sa}} = 0.45\ °\text{C/W}.$$

Assume ambient temperature as $T_a = 35°\,C$ consider equation (5.5.2),

$$P = \frac{T_j - T_a}{R_{\theta_{jc}} + R_{\theta_{cs}} + R_{\theta_{sa}}}$$

$$\therefore \quad T_j = P(R_{\theta_{jc}} + R_{\theta_{cs}} + R_{\theta_{sa}}) + T_a$$

Putting values in above equation,

$$T_j = 120(0.15 + 0.075 + 0.45) + 35 = 116°\,C$$

Thus the junction temperature of the device will be $116°\,C$.

Example 5.5.2 *A power transistor develops a power loss of 3.42 watts and is mounted on a square heat sink. Transistor is linearly derated from 20° C to 200° C at 40° C/watt. Calculate the sink temperature.*

Solution : Power dissipation, P = 3.42 W

$$T_1 = 200\ °\,C$$

$$T_2 = 20\ °\,C$$

$$R_\theta = 40\ °\,C/\text{watt}$$

$$\therefore \quad P = \frac{T_1 - T_{sink}}{R_\theta}$$

$$\therefore \quad 3.42 = \frac{200 - T_{sink}}{40}$$

$$T_{sink} = 63.2\ °\,C$$

Example 5.5.3 *The maximum junction temperature of the thyristor is 150 ° C. Thermal resistance for the thyristor-sink combination is 0.015 ° C/W and 0.08 ° C/W. Determine the total average power loss in the thyristor-sink combination if the heat sink temperature is 60 ° C. If the heat sink temperature is reduced to 50° C by forced air cooling, find the percentage increase in the device rating.*

Solution :

Here $\quad R_{\theta\,js} = 0.015 + 0.08 = 0.095\ °\,C/W$

$$P = \frac{T_j - T_s}{R_{\theta js}} = \frac{150-60}{0.095} = 947.36 \text{ W}$$

With forced air cooling $T_s = 50° C$. Hence power dissipation will be,

$$P = \frac{150-50}{0.095} = 1052.63 \text{ W}$$

Thyristor rating is proportional to square root of the average power loss.

Hence,

$$\% \text{ increase in thyristor rating} = \frac{\sqrt{1052.63} - \sqrt{947.36}}{\sqrt{947.36}}$$

$$= 5.4 \%$$

Thus thyristor rating increases approximately by 54 % due to forced air cooling.

Example 5.5.4 *A power device is used in a circuit and has the following data*

Total steady state thermal impedance of 0.3 ° C/W

Transient thermal impedance of 0.05° C/W for 100 ms

$T_{j(\max)}$ *= 125 ° C and* T_a *= 40 ° C*

What power loss the device can withstand following a steady state power loss of 200 W ?

Solution : To calculate junction temperature for steady state operation

$$P = \frac{T_j - T_a}{R_{\theta ja}}$$

Here $R_{\theta ja} = 0.3 \, ° C/W$, $T_a = 40 \, ° C$ and P = 200 W, then above equation will be,

$$200 = \frac{T_j - 40}{0.3}$$

$$\therefore \quad T_j = 100° C$$

Thus in steady state the junction temperature will be $100 \, ° C$.

To calculate power loss for transient operation

In steady state, the junction temperature is $100 \, ° C$. The maximum junction temperature that the device can withstand is $125 \, ° C$. The transient thermal impedance is $0.3 \, ° C/W$. The the power dissipation will be,

$$P = \frac{T_{j(\max)} - T_j}{R_{\theta(transient)}} = \frac{125-100}{0.05} = 500 \text{ W}$$

Thus the transient power dissipation can be increased to 500 W for 100 ms.

Example 5.5.5 *Fig. 5.5.2 shows the switch waveform of the device. The duty cycle is 0.5 and switching frequency is 1 kHz. A power of 1000 W is dissipated when the device is ON. No power is dissipated when the device is off. The thermal impedance from junction to case is 0.035 ° C/W when the device is on, and it is 0.025 ° C/W when the device is off. Plot the difference temperature between junction and case.*

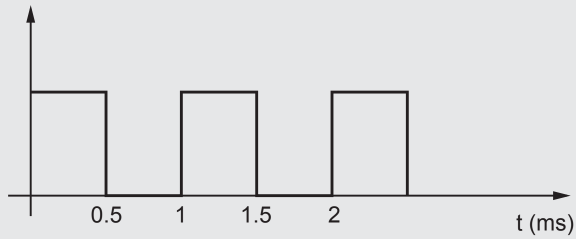


Fig. 5.5.2 Switching waveform of the device

Solution :

Here $$R_{\theta jc} = \begin{cases} 0.035° \, C/W \text{ when device is on} \\ 0.025° \, C/W \text{ when device is off} \end{cases}$$

$$P = \begin{cases} 1000\,W \text{ when device is on} \\ 0 \quad \text{ when the device is off} \end{cases}$$

We know that, $P = \dfrac{\Delta T}{R_\theta}$

At 0.5 msec, $1000 = \dfrac{\Delta T}{0.035}$

$$\Delta T = 35 \, ° C$$

For $0.5 \le t \le 1$ msec there is no power dissipation from the device but available heat due to preceding 1000 W is reduced. Hence we can write,

At 1 msec, $-1000 \times 0.025 + 35 \, ° C = \Delta T$

$\therefore \quad \Delta T = 10 \, °C$

Similarly at 1.5 msec,

$1000 \times 0.035 + 10 \, ° C = \Delta T$

$\therefore \quad \Delta T = 45° \, C$

At 2 msec, $-1000 \times 0.025 + 45 \, ° C = \Delta T$

$\therefore \quad \Delta T = 20 \, ° C$

Thus the difference temperature goes on increasing. Fig. 5.5.3 shows the plot of difference temperature.

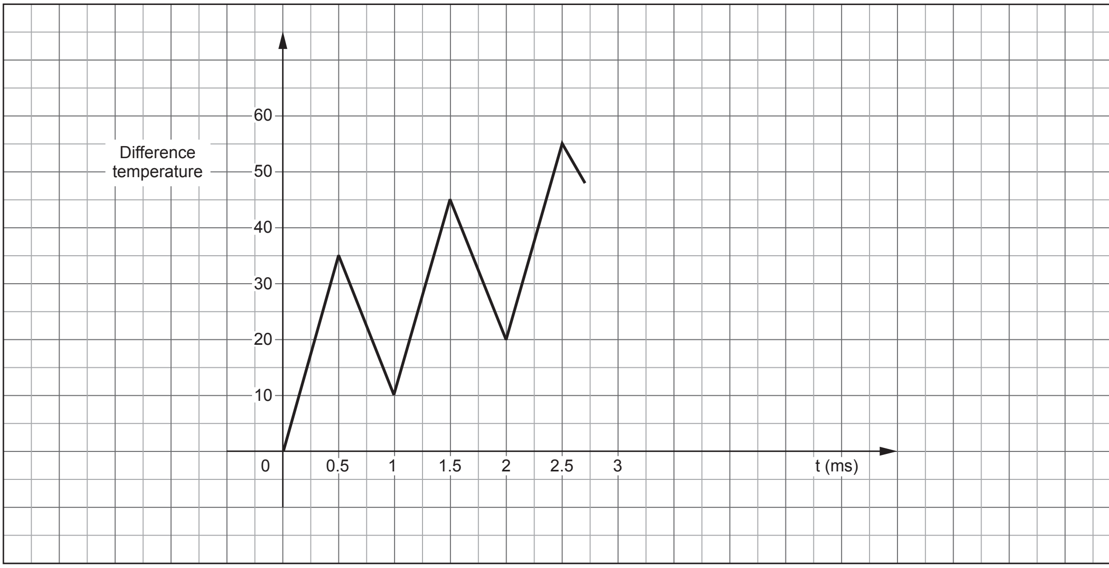


Fig. 5.5.3 Plot of junction to case difference temperature

Example for Practice

Example 5.5.6 : *The power device has the steady state thermal resistance of 0.625 °C/W. The case temperature is 100 °C. The device carries a DC current of 25 A and voltage drop of 2 V. Determine its junction temperature.*

[Ans. : T_j = 131.25° C]

Review Questions

1. *What is the concept of thermal resistance ? Explain its model.*
2. *Explain design considerations of heat sink to reduce switching losses in the power circuits. Name four protection devices.* **SPPU : May-19 (End Sem), Marks 8**

5.6 Cooling Methods

SPPU : Dec.-01

We have seen that the heat is transmitted from device to the heat sink. Heat sink dissipates more heat due to its increased area. Normally heat sinks have fins to increase area. The heat can be dissipated into ambience from the surface of the heat sink by following ways :

i) Natural convection ii) Forced air cooling

iii) Liquid cooling iv) Vapour phase cooling

Let us now study these techniques in detail.

5.6.1 Natural Convection

The heat sink surfaces have some treatment to support heat transfer by radiation and natural convection. Copper fins are plated or painted. Aluminium fins are normally painted or anodized. Presently most of the heat sinks used are black anodized. The surface of heat sink under the device is free of paint or anodization. This gives minimum contact thermal resistance. The heat can move from heat sink to ambience naturally due to temperature difference. The equation of heat transfer is given as,

$$Q = hA(T_1 - T_2)$$

Here Q is the heat rate

h is the convection heat transfer coefficient

A is the area available for convection

$T_1 - T_2$ is the temperature difference.

Natural convection is used when there is not much heat dissipation from the device. Normally the devices are mounted in the open air. The heat exchange takes place due to natural flow of the air. Natural convection is more effective when area of the heat sink is more.

5.6.2 Forced Air Cooling

The circulation of air over the fins of heat sink can be increased with the help of fans or compressors. The hot air is taken away from the heat sink fins with the help of cooling fan. Therefore heat convection is fast and cooling of power device is more effective. The heat rate is similar to that of natural convection. But the heat transfer coefficient now depends upon,

$$h = 11.2\sqrt{\frac{v}{l}} \times 10^{-4} W / in^{2} {}^{\circ}C$$

Here v is free steam linear cooling air velocity across fin surface.

l is length of the fin parallel to air flow.

Above equation shows that heating is more effective if air flow is more. Presently almost all the equipments right from computers to power supplies use forced air cooling. The exhaust fans are mounted on the equipments, then remove hot air. Forced air cooling is always better than natural convection.

5.6.3 Liquid Cooling

The power devices can also be cooled with the help of liquids. Normally oil or water is used as a coolent in liquid cooling. Liquid cooling can be of two types :

i) Oil-immersed natural cooling and ii) Forced liquid cooling.

1. **Oil-immersed natural cooling :** In the oil-immersed natural cooling the heat sink assembly is immersed in oil tank. The heat is transferred from the device to the heat sink fins and then to the oil. The heat is the transferred from the oil to tank surface and then to the atmosphere. The tanks also have fins on their surface. Hence the heat transfer from tank to atmosphere is also increased.

2. **Forced liquid cooling :** The liquid flows at some velocity around the heat sinks assembly. The liquid normally flows in a closed loop system. After passing over the heated device and heat sink, the liquid gets hot. Then it is passed through the narrow fins of the tank. These fins are open to the air. Therefore liquid gets cooled through the fins. Then again it is passed over the device. Forced liquid cooling is more effective. Water is not used as a liquid coolent, since it has corrosion problem. Other liquids like ethylene glycol-water 60 % by weight, ethylene glycol 100 % and mineral oil like mobiltherm 600 are normally used for forced liquid cooling.

Fig. 5.6.1 shows the forced liquid cooling heat exchanger.

Fig. 5.6.1 (a) shows the section of Fig. 5.6.1 (b) when it is cut along B-B.
Fig. 5.6.1 (b) shows the vertical cut view of the device and the shaded area shows the passage for liquid. Observe that the liquid surrounds the complete device. It enters from one side and leaves the other side.

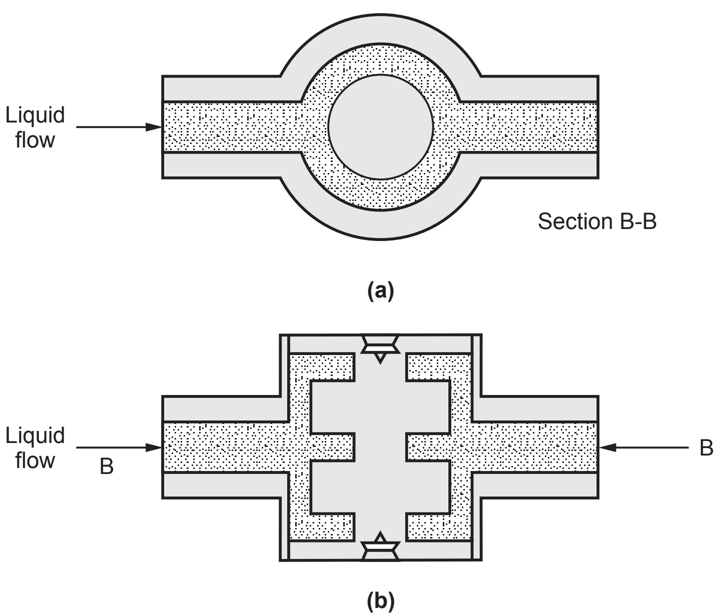


Fig. 5.6.1 Liquid cooling

Relationship between liquid flow rate and thermal resistance

The thermal resistance of heat sink is inversely proportional to rate of liquid flow. Fig. 5.6.2 shows the relationship.

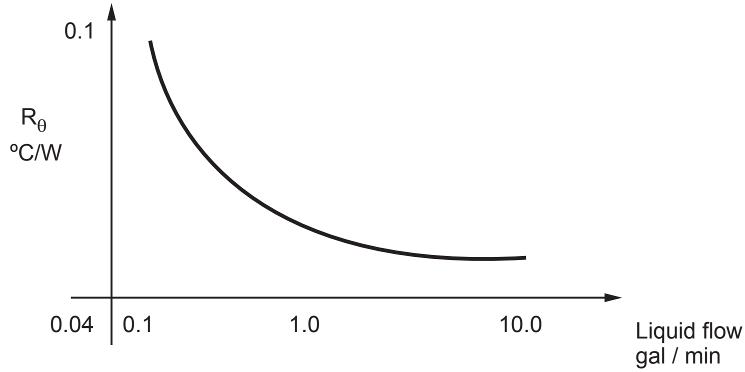


Fig. 5.6.2 Thermal resistance Vs liquid flow

The thermal resistance of the liquid cooled heat sink is much less compared to thermal resistance of copper heat sink.

5.6.4 Vapour Phase Cooling

Vapour phase cooling is normally used for high power devices. The heat produced by the device evaporates the liquid. This vapour then flows to the condenser. The condenser again converts the vapour to liquid and sents it to the device. Fig. 5.6.3 shows an arrangement for vapour-phase cooling.

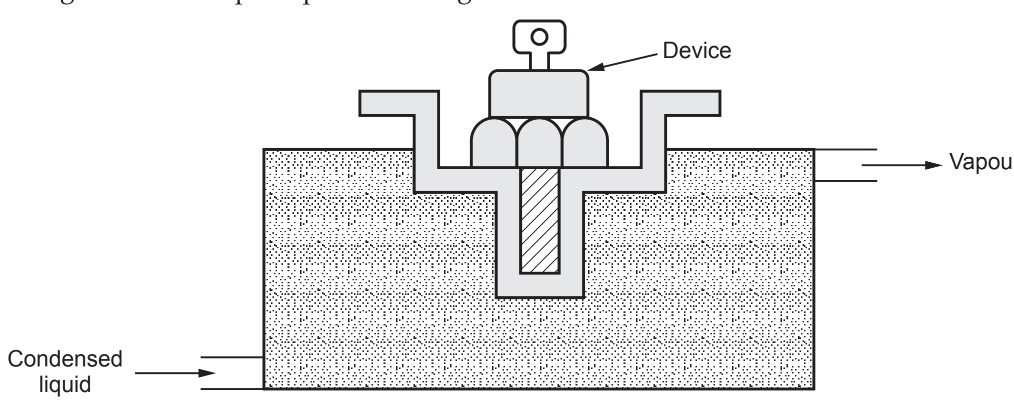


Fig. 5.6.3 Vapour phase cooling

The hermetically sealed copper tubing is used to transport liquid to and vapour from the device. Freon 113 is used as the coolant because it boils at 47° C. It is chemically inert and nontoxic. It has good dielectric constant.

Advantages of vapour phase cooling

i) Heat is exchanged through flow of vapour. Hence overall thermal resistance is reduced.

ii) Heat is uniformly spread or dispersed over large area condensor. Therefore thermal resistance is reduced.

iii) The thermal resistance can be made lower than 0.075° C/W.

iv) The condenser and device can be placed at distance from each other. Hence equipment cabinet can be more compact.

Disadvantages

i) Additional condenser unit is required to condense the vapour to liquid.

ii) Overall cost of the cooling system is more.

Review Question

1. *Explain various cooling methods for power devices. Compare liquid cooling and vapour phase cooling.* **SPPU : Dec.-01, Marks 8**

5.7 Resonant Converters

SPPU : May-15,16,17,18,19, Dec.-15,16,18

- The resonant converters use some form of LC resonance.
- This resonance is used to adjust ringing frequencies of voltage or current. The switches in the resonant converters are turned on or turned off when current through it or voltage across it is zero.
- Due to zero current or voltage switching, there is practically no Loss in the switches of resonant converter.

  Resonant converters are classified as follows :

  1. Load resonant converters
  2. Resonant switch converters
  3. Resonant dc link converters
  4. High frequency link integral half cycle converters.

In this section we will study series load resonant converter which comes under the first category of the above.

5.7.1 Need for Resonant Converters

- In chopper, inverter or SMPS, the switches operate at some voltage and current. Therefore switching losses take place in the switches.
- In PWM control, the switching losses increase with the PWM frequency.
- All switched mode converters generate electromagnetic interference (EMI) to neighbouring circuits due to switching operation.

- In resonant converters, the switch is turned-on or turned-off when current through it or voltage across it is zero. Because of this the switching loss in the device is zero.
- Thus resonant converters provide zero switching loss.

5.7.2 Series Load Resonant (SLR) Half Bridge DC to DC Converter

Fig. 5.7.1 shows the circuit diagram of a Series Load Resonant (SLR) dc-dc converter.

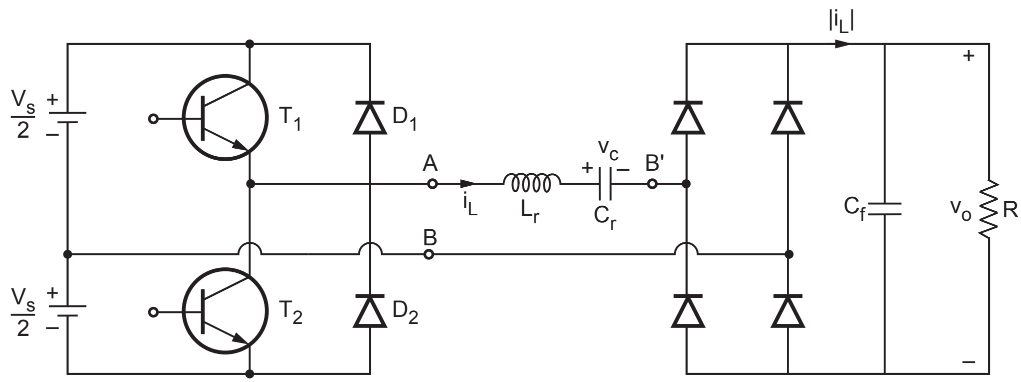


Fig. 5.7.1 SLR dc-dc converter

- In the circuit the half bridge consisting of $T_1 D_1$ and $T_2 D_2$ is used for switching the power.
- L_r and C_r forms a resonant circuit. 'i_L' is the current through the resonant circuit and 'v_C' is the voltage across the resonant capacitor.
- The switches T_1 T_2 and diodes $D_1 D_2$ turn-on or turn-off when either i_L or v_C is zero.
- The load voltage v_o is obtained after rectification and filtering through C_f. Hence output voltage is almost constant.
- The load appears in series with the resonant circuit. Hence it is called series loaded resonant converter.

Operation and waveforms of SLR convertor

Fig. 5.7.2 shows the waveforms of SLR dc-dc converter.

- There are six modes of operation. ω_0 is the resonant frequency of the tank circuit ($L_r C_r$).
- When switching frequency ω_s is less than $\frac{\omega_0}{2}$, then inductor current becomes discontinuous. This is called discontinuous mode of operation of SLR converter.

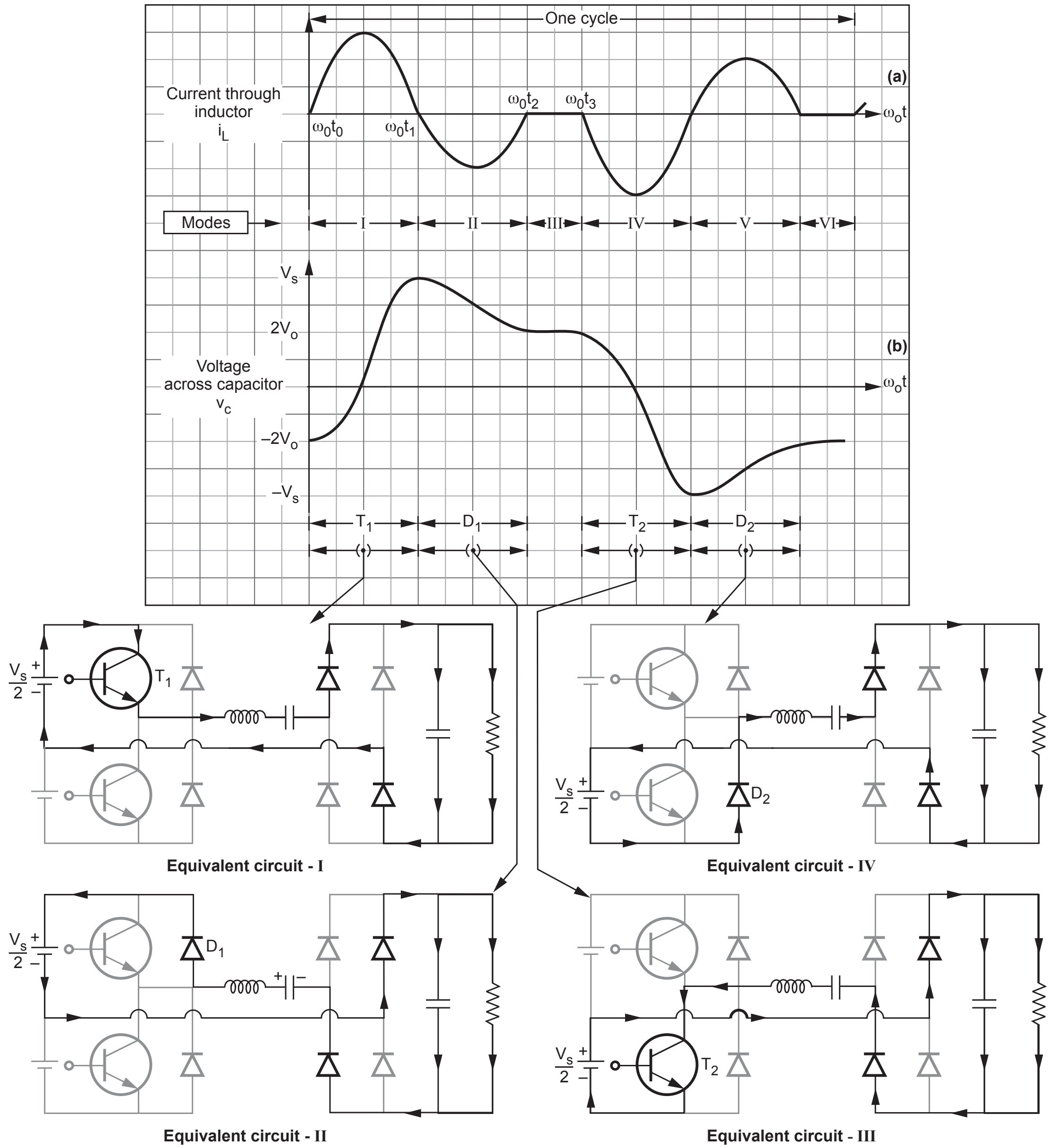


Fig. 5.7.2 Waveforms of SLR DC-DC converter

Mode-I Devices conducting - T_1

At the beginning i.e. at $\omega_o t_o$, the switch T_1 is turned on. Note that the current increases from zero. This current is shown in Fig. 5.7.2 (a). It is assumed that capacitor was charged to $-2V_o$. Hence capacitor voltage starts reducing towards zero. This waveform is shown in Fig. 5.7.2 (b). Equivalent circuit-I shows the current path. When capacitor voltage is zero, inductor current is at its peak. Now capacitor starts charging in positive direction. Therefore inductor current starts reducing. Inductor current becomes zero at $\omega_o t_1$ and capacitor charges to $+V_s$. Note that the capacitor charges higher than supply voltage due to LC circuit. At $\omega_o t_1$ the switch T_1 is turned off at zero current. Hence there are no switching losses.

Mode-II Devices conducting D_1

Due to ringing property of the LC circuit, inductor current reverses at $\omega_o t_1$. At $\omega_o t_1$, the capacitor voltage is $+V_s$. Hence diode D_1 is forward biased and inductance current starts flowing through it. Thus inductance current is now negative. Equivalent circuit-II in Fig. 5.7.2 shows the current path. The energy stored in $L_r C_r$ tank circuit is partially fed back to the supply and to the load. This mode comes to an end when inductor current becomes zero. At $\omega_o t_2$ the inductor current becomes zero and capacitor voltage is $+2V_o$. Thus diode D_1 is turned on and off at zero current. Therefore there are no switching losses in the diode.

Mode-III

In this mode all the devices are off. But load current continues to flow. Capacitor C_f maintains constant voltage V_o across the load.

Mode-IV and V

These modes are similar to mode-I and II but the devices conducting are T_2 and D_2 respectively.

Note

- The period of one cycle of i_L and v_c is greater than ringing time of $L_r C_r$ circuit. In other words, the switching frequency ω_s is less than resonant frequency $\frac{\omega_o}{2}$.

  Therefore the inductor current is discontinuous.
- The continuous mode can be obtained if $\omega_s > \frac{\omega_o}{2}$.

5.7.3 Concept of Zero Current Switching (ZCS) Resonant Converters

- **Principle :** In ZCS topology, the switch turns - on and turns - off at zero current.
- **Circuit diagram and waveforms :** Fig. 5.7.3 shows the circuit diagram and Fig. 5.7.4 shows the waveforms of the ZCS converter.
- L_r and C_r are the resonating components. L_f and C_f are the filter components.
- Before the switch 'T' is turned on at 't_0'. The output current $i_0 = I_o$ freewheels through the diode D. The voltage across C_r is $v_c = V_s$.

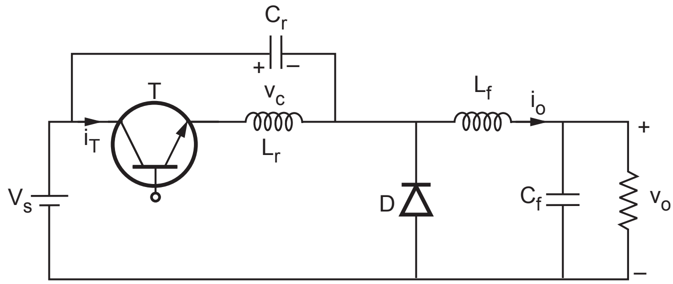


Fig. 5.7.3 ZCS DC-DC converter

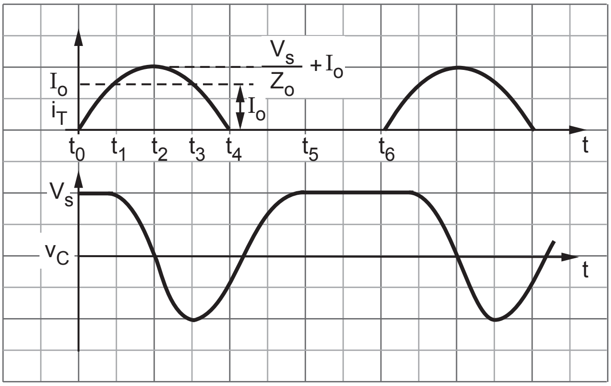


Fig. 5.7.4 Waveforms of ZCS DC-DC converter

- At 't_0' the switch 'T' is turned on at 'zero current'. From t_0 to t_1, i_T is less than I_o, hence D keeps on conducting and carrying I_o. Therefore $v_c = V_s$ till t_1.
- At t_1, $i_T = I_o$, hence D stops conducting. C_r starts discharging through C_r–T–L_r. It becomes a resonant circuit. Hence v_c starts reducing after t_1.
- At 't_2' i_T peaks to $\frac{V_s}{Z_o}+I_o$ and $v_c = 0$. The capacitor C_r then starts charging in opposite direction and v_c becomes negative.
- At 't_3', $i_T = I_o$ and v_c becomes negative peak.
- At 't_4', $i_T = 0$ and switch 'T' naturally turns off. Negative current is not possible through 'T'. The capacitor C_r then starts charging from V_s and its voltage rises towards positive value. The diode 'D' conducts and $i_o = I_o$. The 'C_r' current flows through V_s–C_r–L_f–C_f, load – V_s.
- At 't_5' C_r is charged to V_s, i.e. $v_c = V_s$ and it remains constant.
- Next cycle repeats when 'T' is switched 'on' at 't_6' again.

Advantages

i) Forward switch voltage is limited to V_s.

ii) Reduced losses due to zero current switching.

Limitations

At 't_4', the device have to be forced turn-off, otherwise it may remain in conduction.

5.7.4 Zero Voltage Switching (ZVS) Resonant Converters

- **Principle :** The resonant converter produces a zero voltage across the switch. The switch is turned on or off at this instant results in Zero Voltage Switching (ZVS) operation.
- **Circuit diagram and waveforms :** Fig. 5.7.5 shows the circuit diagram and Fig. 5.7.6 shows the waveforms of the ZVS converter.

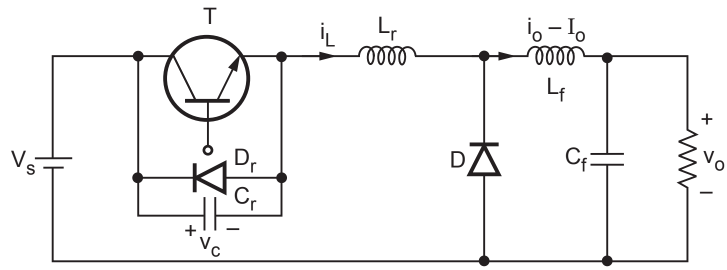


Fig. 5.7.5 ZVS DC-DC converter

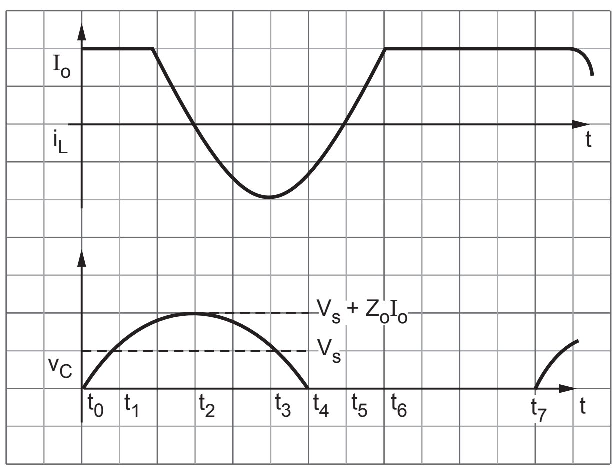


Fig. 5.7.6 Waveforms of ZVS DC-DC converter

- Before 't_0', the switch 'T' is conducting and $i_L = I_o$. Capacitor C_r is not charged and $v_c = 0$.
- At 't_0', switch 'T' is turned off at zero voltage across it. Now v_c increases and it becomes V_s at t_1. $i_L = I_o$ and it flows through $V_s – C_r – L_r – L_f – C_f$, load $– V_s$.
- At t_1, $v_c = V_s$ and after t_1 $v_c > V_s$. Hence $L_r – C_r$ circuit starts resonating. v_c starts increasing beyond V_s and i_L starts reducing.
- At 't_2', v_c reaches to its peak value and it becomes equal to $V_s + Z_o I_o$. At this instant $i_L = 0$. After 't_2', i_L becomes negative due to resonance effect of L_r and C_r. The voltage v_c starts reducing.

- At 't_3', i_L is at its negative peak and $v_c = V_s$ again.
- At 't_4', the capacitor voltage reaches to zero and i_L (which is negative), starts flowing through diode D_r. Note that C_r cannot charge to negative voltage due to diode D_r. The switch 'T' is given the base drive. But it does not conduct till 't_5' since diode 'D_r' is conducting.
- At 't_5', 'T' is turned on again at zero voltage and zero current. Then i_L increases linearly and it becomes I_o at t_6.
- After 't_6' the switch 'T' carries the current $i_L = I_o$ and $v_c = 0$.
- The cycle repeats when switch 'T' is turned off at 't_7' again.

Advantages

i) Switch turns-on and off at zero voltage.

ii) Switch current is limited to I_o.

iii) ZVS is better over ZCS at high switching frequencies.

Disadvantage

Switch has to withstand voltage $V_s + Z_o I_o$.

5.7.5 Advantages, Disadvantages and Applications of Resonant Converters

Advantages

i) Switching losses are reduced and efficiency is increased due to zero voltage or zero current switching.

ii) RFI/EMI is greatly reduced.

iii) Requirement of heat sink/cooling arrangement is reduced. Since losses and heating of the devices is reduced.

iv) High frequency harmonics in the output are eliminated.

Disadvantages

i) Heavy and bulky resonant inductors / capacitors are required. Therefore the overall circuit becomes bulky.

ii) Control of the circuit is complex compared to PWM control.

iii) Peak current drawn from the supply is increased, since the power flow is only for half of the cycle.

Applications

i) Induction heating applications, where load appears as a resistance.

ii) Low power DC supplies

5.7.6 Comparison between Linear Switched Mode and Resonant Converters

Sr. No.	Parameter	Linear regulator	Switched mode	Resonant converter
1.	Operating region of devices	Active	Saturation/cutoff	Saturation/cutoff
2.	Switching losses	Zero (no switching)	High	Low
3.	RFI/EMI	Absent	High	Minimum
4.	Power handling capacity	Very low	High	Medium
5.	Size and cost	High	Low	High
6.	Control circuit	Less complex	High	Highest
7.	Efficiency	Low	High	Medium

Table 5.7.1 Comparison between linear, switched and resonant power supplies

Review Questions

1. *With the help of circuit diagram and waveforms, explain the operation of SLR dc-dc converter.*
   SPPU : May-15,16,17 (End Sem.), Dec.-16 (End Sem), Marks 8
2. *Compare switched, linear and resonant converters.*
   SPPU : Dec.-15, May-17, Marks 8
3. *Explain with circuit diagram and neat waveforms ZCS reasonant converters.*
   SPPU : May-15,17 (End Sem.) Marks 10
4. *What are resonant converters ? Explain necessity of resonant converters. State its advantages.*
   SPPU : May-18 (End Sem), Marks 8
5. *Explain with the neat diagram and waveforms L-type ZCS resonant converters ?*
   SPPU : May-18 (End Sem), Marks 10
6. *Draw the neat diagram of ZCS resonant converter. Explain the operation through waveforms.*
   SPPU : May-16, Dec.-16,18 (End Sem), Marks 8
7. *What is resonant converter ? State necessity of the resonant converter ?*
   SPPU : May-19 (End Sem), Marks 8

8. *What is SLR ? Explain with circuit diagram and waveforms above resonant converter comment on Pf.* **SPPU : May-16 (End Sem), Marks 9**

9. *What is resonant converters ? Explain the concept of ZCS and ZVS. using circuit diagram and waveforms.* **SPPU : Dec.-15,19 (End Sem), Marks 10**

5.8 EMI and EMC

SPPU : May-15, Dec.-16,19

5.8.1 Difference between EMI and EMC

Definition : Power electronics circuits operate at very high frequencies. The switching of power devices at high frequencies generate conducted and radiated switching spikes or noise like signals. Such signals are called electromagnetic interference (EMI) or radio frequency interference (RFI).

Effect of EMI : The EMI/RFI interfere with nearby control circuits and cause its malfunctioning. It also disturb the functioning of communication circuits operating in the vicinity. EMI/RFI are carried over a along distance.

Electromagnetic compatibility (EMC) : When the system doesnot emit EMI above a gives level and not affected due to permissible external EMI is said to have electromagnetic compatibility (EMC).

The EMC can be achieved in following ways

i) By reducing the EMI levels from the source.

ii) By stopping the propagation of EMI signals.

iii) By reducing susceptibility of receiver to EMI signals.

5.8.2 Sources of EMI

Following are the sources of EMI :

i) Switching of realys, static switches, mechanical switches.

ii) Sparking of motor brushes.

iii) Mobile, pagers, television, radars and radio equipments.

iv) Atmospheric noise, lightening, ignition of engines.

v) Rapid variation of current in transformers reactors, motors and protection circuits.

vi) Power converters.

vii) Braking of relay contacts, circuit breakers, welding machines.

viii) Stray capacitance and inductance cause oscillations at high frequencies.

5.8.3 Minimizing Techniques of EMI

i) Shielding of EMI

ii) Suppressior filters

iii) Using high permeability material for transformers and reacters.

iv) Electrostatic shielding in transformers between primary and secondary.

v) Using freewheeling diodes, zener diodes to provide path for inductive currents.

vi) Smart layout of components and design of PCBs.

vii) Minimizing harmonics, soft switching of power devices. (Switching at zero voltage or current)

viii) Appropriate grounding and shielding.

5.8.4 Shielding Techniques for EMI

- The EMI can be radiated as electromagnetic wave or it can conduct as a current along the cable.
- The shield is a conducting material, that shunts the conducted or radiated EMI to ground. The shield is placed in the path of the EMI.
- The shield either absorbs the interfering EMI signal or reflects it back.
- The conducted EMI appears in the form of common mode and differential mode voltages and currents.
- These common mode voltages and currents can be minimized by suppression filters. These filters are mainly inductive and capacitive filters. These filters are normally placed very close to the source of EMI.

5.8.5 EMI and EMC Standards

- The FCC standards in US are listed below for conducted EMI. It is the maximum permissible RF line voltage in microvolts.

Frequency range (MHz)	Class A	Class B
0.45 - 1.6	1000 μV	250 μV
1.6 - 30	3000 μV	250 μV

- The FCC standard is shown below for radiated EMI limit. It is the field strength in μV/m

Frequency range (MHz)	Class A	Class B
30 - 88	30 μV/m	100 μV/m
88 - 216	50 μV/m	150 μV/m
216 - 1000	70 μV/m	200 μV/m

- In the above tables, class A is used for commercial purpose and class B is used for domestic purpose.
- The Indian standard IS14700-4-12 (2008) is the EMC standard followed in India. It mentions about test transient, its duration/amplitude, test generator, coupling/decoupling network specifications, test setup, test power supply, earthling, equipment under test, testing procedure, testing and climatic conditions. Test results evaluation and reports analysis are presented in detail in this standard.
- The European standard EN55022 also specifies EMI limits for class A and class B type of use similar to FCC.

Review Questions

1. *What is EMI ? Explain various sources and minimizing techniques of EMI.*
   SPPU : May-15, Dec.-16 (End Sem), Marks 6
2. *What is meant by electromagnetic interferance ? Explain it's sources and different minimization techniques in detail ?* **SPPU : Dec.-19, Marks 10**

5.9 Importance of Isolation Transformer

- Isolation transformers provide electrical isolation between the two circuits. The isolation transformers have following advantages and importance.
  i) Electrical isolation between high power converter circuit and low power control circuit.
  ii) Transfer of electrical power from AC power source to some equipment or device.
  iii) Reduces power surges and noise. Hence electrical equipment runs more smoothly.
  iv) Provides separation from the power line ground connection to eliminate ground loops.
  v) Protects circuits, equipment and people from shocks and short-circuits.
  vi) Blocks DC component in signals from one circuit to another, but allows AC components to pass.
  vii) Triggering circuits use isolation transformers to pass triggering signals from low power control circuit to high power triggering circuit.

5.10 Multiple Choice Questions

Q.1 di/dt protection is provided to the thryistor by __________.

a connecting an inductor in parallel across the load

b connecting an inductor in series with the load

c connecting an inductor in parallel across the gate terminal

d connecting an inductor in series with the gate

Q.2 The dv/dt protection is provided in order to __________.

a limit the power loss

b reduce the junction temperature

c avoid accidental turn-on of the device

d avoiding sudden large voltage across the load

Q.3 dv/dt protection is provided to the SCR by __________.

a connecting a capacitor in parallel with the load

b connecting an inductor in series with the load

c connecting a capacitor and resister in parallel with the device

d connecting an inductor and resister in parallel with the device

Q.4 The effect of over-voltages on SCR are minimized by using __________.

a RL circuits

b circuit breakers

c varistors

d di/dt inductor

Q.5 Over-current protection in SCRs is achieved through the use of __________.

a varistors

b snubber circuits

c F.A.C.L.F and C.B.

d zener diodes

Q.6 Thyristors are used in electronic crowbar protection circuits because it possesses __________.

a high surge current capabilities

b high amp^2 sec rating

c less switching losses

d voltage clamping properties

Q.7 What is the purpose of heat sink in power devices ?

a Provide sufficient heat for transistor

b Absorb excess heat from transistor

c Keep transistor at desired temperature range

d All of the mentioned

Q.8 What is the major principle behind heat sink action ?

a Avogadro's law

b Fourier's law

c Archimedes principal

d Faraday's law

Q.9 The performance of heat sink does not depend upon ___________.

a choice of material

b protrusion design

c surface treatment

d none of the mentioned

Q.10 The converter circuit which employs turn on and turn off when the voltage and/or current through the device is zero at the instant of switching is ____________.

a a conventional converter

b a resonant converter

c a zero switching circuit

d none of the mentioned

Q.11 Heat dissipation from heat sink take place primarily by ___________.

a conduction

b convection

c radiation

d all of the mentioned

Q.12 In ZCS converter ___________.

a inductor is connected in series with the switch

b inductor is connected in parallel with the switch

c capacitor is connected in parallel with the switch

d capacitor is connected in series with the switch

Q.13 In ZCS, _________________ oscillates.

a switch current

b switch voltage

c load current

d load voltage

Q.14 In ZVS, _______________ resonates.

a voltage across resonating capacitor
b current through resonating capacitor
c load voltage
d load current

Q.15 Zero-voltage switching is a more appropriate control strategy for ____________ resonant switch mode converters than zero-current switching control.

a high frequency
b low frequency
c zero frequency
d none of these

Q.16 ________________ is high-frequency EMI source.

a Radio
b Television
c Marine communication
d All of these

Q.17 Shielding is _______ to avoid unwanted noise from relating with a susceptible piece of equipment.

a wire shield
b none of these
c magnetic enclosure
d metal enclosure

Q.18 The ability of an electronic system to function properly in its intended electromagnetic environment and should not be a source of pollution to that electromagnetic environment is known as ___________.

a susceptibility
b emission
c interference
d electromagnetic compatibility

Q.19 A transformer is said to be isolation transformer if its primary to secondary ratio is ___________.

a equal to one
b more than one
c less than one
d equal to 0.5

Q.20 An RC snubber protects an SCR against ___________.

a supply over voltages
b false triggering
c breakover
d crowbarring

Explanation :

Q.1 Explanation : By placing the di/dt inductor (L) in series with the load, the change in the anode current can be limited to a small value.

Q.2 Explanation : Accidentally some voltage spike or noise may occur in the vicinity of the device, if the magnitude is large enough it may turn on the SCR.

Q.3 Explanation : Snubber circuit R-C in parallel with SCR is connected for dv/dt protection.

Q.4 Explanation : Varistors are non-linear voltage clamping devices, RC circuits across the loads can also be used.

Q.5 Explanation : FACLF stands for Fast Acting Current Limiting Fuse.

Q.6 Explanation : Crowbar protection circuits have high surge current capabilities.

Q.7 Explanation : Heat sink in a transistor circuit performs a major function of keeping temperature of transistor at a desired range and also absorbs excess heat. Self heating occurs in a transistor due to power dissipated at the collector junction. This can cause junction temperature to rise and further increases collector current, and such a process may damage the device.

Q.8 Explanation : Major principle behind heat sink is Fourier's law. Fourier's law of heat conduction, simplified to a one-dimensional form is, when there is a temperature gradient heat will be transferred from the higher temperature region to the lower temperature region. The rate at which heat is transferred by conduction is proportional to the product of the temperature gradient and the cross-sectional area through which heat is transferred.

Q.9 Explanation : The performance of the heat sink depends on the factors like the choice of material, protrusion design, surface treatment and air velocity. The material is preferred to have high conductivity and heat absorption. The shape and design also effect heat flow as well as coolant flow in the sink.

Q.11 Explanation : Heat dissipation from heat sink take place primarily by convection since there is no actual contact between heat sink and transistor. Heat dissipation also takes place by Radiation but it is comparatively low.

Answer Keys for Multiple Choice Questions :

Q.1	b	**Q.2**	c	**Q.3**	c	**Q.4**	c	**Q.5**	c
Q.6	a	**Q.7**	d	**Q.8**	b	**Q.9**	d	**Q.10**	b
Q.11	d	**Q.12**	a	**Q.13**	a	**Q.14**	a	**Q.15**	a
Q.16	d	**Q.17**	d	**Q.18**	d	**Q.19**	a	**Q.20**	a

❑❑❑

Notes

UNIT VI

6 Power Electronics Applications

Syllabus

AC Voltage Controller using IGBT & SCR, Fan Regulator, Electronic Ballast, LED Lamp driver, DC motor drive for single phase separately excited dc motor, BLDC motor drive, Variable voltage & variable frequency three phase induction motor drive, On-line and Off- line UPS, study of various selection criteria and performance parameters of batteries in battery operated power systems, battery charging models and modes for EVs, Architecture of EVs battery charger, PFC stage circuit topologies with details of Full-bridge boost rectifier and Full-bridge interleaved for EV battery charger, case study of power electronics in electric vehicle and photovoltaic solar system

Contents

6.1 AC Voltage Controller using IGBT and SCR

SPPU : Dec.-09,11,13,16,18,19, May-10,11,12,17,18,19

Fig. 6.1.1 shows the circuit diagram of 1ϕ full wave controller. It has two SCRs, T_1 and T_2. In the positive half cycle of the supply T_1 controls the power flow to the load. And in the negative half cycle of the supply T_2 controls the power flow to the load. The waveforms of this circuit are shown in Fig. 6.1.2 for resistive load.

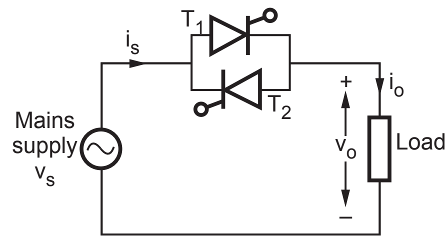


Fig. 6.1.1 1ϕ full wave (bidirectional) controller

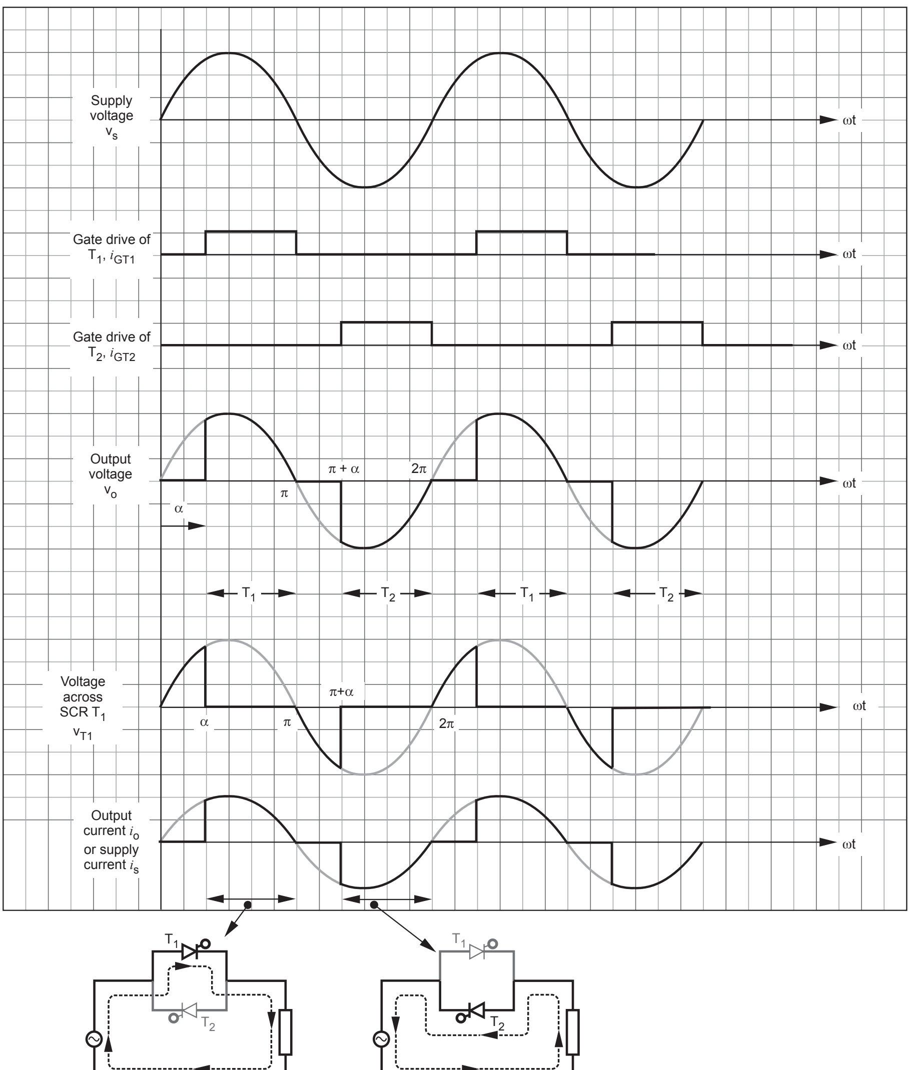


Fig. 6.1.2 Waveforms of 1ϕ full wave controller for resistive load

The output current waveform is shown for resistive load. It is similar to the voltage waveform. The output current and the supply current flow in the same loop. Hence $i_o = i_s$. Observe that the voltage and current waveforms are symmetric. Hence there is no dc component in v_o, i_o and i_s. Also, it is possible to control the output fully from zero to maximum value. The output is controlled in positive as well as negative half cycles due to two SCRs.

Examples for Understanding

Example 6.1.1 *Derive an expression for rms value of the output voltage for* 1ϕ *full wave (bidirectional) controller.* **SPPU : Dec.-09, Marks 8; Dec.-11, Marks 6; May-12, Marks 4**

Solution : We know that the rms value is given as,

$$V_{o(rms)} = \left[\frac{1}{T}\int_0^T v_o^2(\omega t)\, d\omega t\right]^{\frac{1}{2}} \quad \text{... (6.1.1)}$$

Whenever the SCRs conduct, the output voltage is same as supply voltage.

The supply voltage is given as

$$v_s(\omega t) = V_m \sin \omega t$$

From the output voltage waveform of Fig. 6.1.2 we can write equation (6.1.1) as,

$$V_{o(rms)} = \left\{\frac{1}{2\pi}\left[\int_\alpha^\pi v_o^2(\omega t)\, d\omega t + \int_{\pi+\alpha}^{2\pi} v_o^2(\omega t)\, d\omega t\right]\right\}^{\frac{1}{2}}$$

When SCRs conduct, $v_o(\omega t) = v_s(\omega t)$. Hence above equation will be,

$$V_{o(rms)} = \left\{\frac{1}{2\pi}\left[\int_\alpha^\pi V_m^2 \sin^2 \omega t\, d\omega t + \int_{\pi+\alpha}^{2\pi} V_m^2 \sin^2 \omega t\, d\omega t\right]\right\}^{\frac{1}{2}}$$

$$= \left\{\frac{V_m^2}{2\pi}\left[\int_\alpha^\pi \frac{1-\cos 2\omega t}{2}\, d\omega t + \int_{\pi+\alpha}^{2\pi} \frac{1-\cos 2\omega t}{2}\, d\omega t\right]\right\}^{\frac{1}{2}}$$

On simplifying the above integration, we get,

$$V_{o(rms)} = V_m \sqrt{\frac{\pi-\alpha+\dfrac{\sin 2\alpha}{2}}{2\pi}} \quad \text{... (6.1.2)}$$

In the above equation,

when $\alpha = 0 \quad V_{o\,(rms)} = \dfrac{V_m}{\sqrt{2}} = V_{s(rms)}$

when $\alpha = \pi \quad V_{o(rms)} = 0$

Thus the output can be controlled from zero to $V_{s\,(rms)}$ by varying firing angle from π to zero. Since the output current and voltage as well as supply current waveforms are symmetric, their dc/average values are zero. Hence transformer saturation problems are absent.

Example 6.1.2 *A single phase bidirectional regulator is feeding resistive load of $10\ \Omega$. The supply voltage is 230 V-50 Hz. If the firing angle is 45 degrees, calculate the power absorbed by the load. Derive necessary equations.*

Solution : Given data is,

$$R = 10\ \Omega$$

$$V_{s(rms)} = 230\ \text{V}$$

$$\alpha = 45^\circ \quad \text{or} \quad \frac{\pi}{4}$$

The rms value of output voltage is given by equation (6.1.2) as,

$$V_{o\,(rms)} = V_m \sqrt{\frac{\pi - \alpha + \dfrac{\sin 2\alpha}{2}}{2\pi}}$$

Here $V_m = \sqrt{2}\ V_{s(rms)} = \sqrt{2} \times 230 = 325.26$ V.

Hence above equation becomes,

$$V_{o\,(rms)} = 325.26 \sqrt{\frac{\pi - \dfrac{\pi}{4} + \dfrac{\sin \dfrac{\pi}{2}}{2}}{2\pi}} = 219.3 \ \text{volts}$$

The power absorbed by the load is given as,

$$P_o = \frac{V^2_{o(rms)}}{R} = \frac{(219.3)^2}{10} = 4.8 \ \text{kW.}$$

Example 6.1.3 *A voltage source $v_s = 100 \sin 377\,t$ supplies a resistive load of $100\ \Omega$ through a pair of back to back connected thyristors (ac regulator). Calculate the average power in the load, if the thyristor's firing angle is fixed at 45° with respect to the supply voltage.*

Solution : This is a 1ϕ full wave controller. The supply voltage is $v_s(\omega\, t) = 100 \sin 377\, t$.

Hence,

$$V_m = 100 \text{ volts}$$

$$\text{Load } R = 100 \ \Omega$$

$$\alpha = 45° \text{ or } \frac{\pi}{4}$$

The rms value of output is given by equation (6.1.2) as,

$$V_{o\,(rms)} = V_m \sqrt{\frac{\pi - \alpha + \frac{\sin 2\alpha}{2}}{2\pi}}$$

Putting values in this equation,

$$V_{o\,(rms)} = 100 \sqrt{\frac{\pi - \frac{\pi}{4} + \frac{\sin \frac{\pi}{2}}{2}}{2\pi}} = 67.42 \text{ volts}$$

The load power can be obtained as

$$P_o = \frac{V_{o(rms)}^2}{R} = \frac{(67.42)^2}{100} = 45.45 \text{ watts}$$

Example 6.1.4 *Find the power consumed in the heater element shown in Fig. 6.1.3, if both SCRs are triggered with delay angle of 45°. In the circuit of Fig. 6.1.3, if the load is 2 kW, 230 V heater and V_s = 230 V, 50 Hz,*

Calculate - i) $V_{o(rms)}$ and ii) Power dissipated in heater for $\alpha = 45^o$

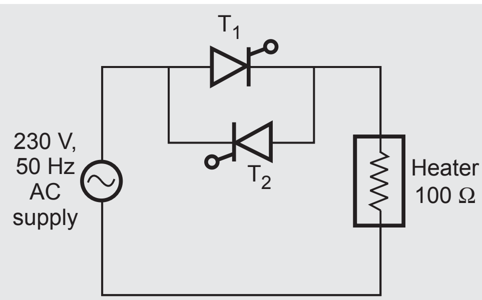


Fig. 6.1.3 AC controller of example 6.1.4

Solution : The given data is,

$$\alpha = 45° = \frac{\pi}{4}$$

$$V_s = 230 \text{ V}, \quad \therefore V_m = 230\sqrt{2}$$

Load resistance, R = 100 Ω

The rms value of output in bidirectional regulator is given by equation (6.1.2) as,

$$V_{o\,(rms)} = V_m \sqrt{\frac{\pi - \alpha + \frac{\sin 2\alpha}{2}}{2\pi}}$$

Putting values in above equation,

$$V_{o\,(rms)} = 230\sqrt{2}\sqrt{\frac{\pi - \frac{\pi}{4} + \frac{\sin\left(2\times\frac{\pi}{4}\right)}{2}}{2\pi}} = 219.3 \text{ V}$$

The power absorbed in the load can be calculated as

$$P_o = \frac{V_{o(rms)}^2}{R} = \frac{219.3^2}{100} = 480.92 \text{ W}$$

Solution to the second question :

RMS valve of output voltage is calculated as,

$$V_{o(rms)} = 219.3 \text{ V}$$

A heater is 2 kW, 230 V. This meas it dissipates 2 kW at 230 V. Therefore we can write,

$$P_{rated} = \frac{V_{rated}^2}{R}$$

Here $P_{rated} = 2$ kW and $V_{rated} = 230$ V.

Hence, $2 \times 10^3 = \frac{(230)^2}{R}$

$\therefore$ $R = 26.45\ \Omega$

Hence power dissipation at $V_{o(rms)} = 219.3$ V will be,

$$P_o = \frac{V_{o(rms)}^2}{R} = \frac{(219.3)^2}{26.45} = 1.818 \text{ kW}$$

Example 6.1.5 *For the AC voltage controller shown in Fig. 6.1.4, the delay angles of the thyristors T_1 and T_2 are equal, $\alpha_1 = \alpha_2 = \frac{2\pi}{3}$. Determine -*

i) rms output voltage

ii) input power factor

iii) average current of thyristors and

iv) rms current of thyristors

SPPU : Dec.-13, Marks 6

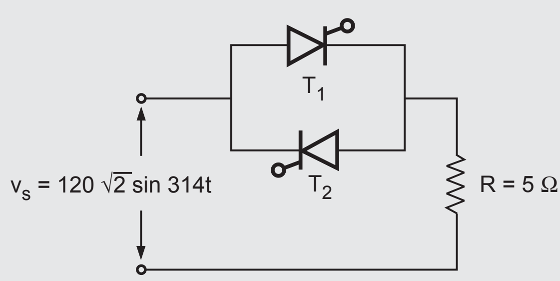


Fig. 6.1.4 Controller of example 6.1.5

Solution : Given data

$$v_s = 120\sqrt{2}\sin 314\ t$$

$$\therefore \quad V_m = 120\sqrt{2} = 169.7 \text{ V}$$

Firing angle $\alpha = \alpha_1 = \alpha_2 = \frac{2\pi}{3}$

Load resistance, R = 5 Ω

i) To obtain rms output voltage ($V_{o(rms)}$)

RMS valve of output is given by equation (6.1.1) as,

$$(V_{o(rms)}) = V_m \sqrt{\frac{\pi - \alpha + \frac{\sin 2\alpha}{2}}{2\pi}} = 169.7 \sqrt{\frac{\pi - \frac{2\pi}{3} + \frac{\sin\left(2 \cdot \frac{2\pi}{3}\right)}{2}}{2\pi}} = 53 \text{ V}$$

ii) To obtain input power factor

RMS valve of load current can be calculated as,

$$I_{o(rms)} = \frac{V_{o(rms)}}{R} = \frac{53}{5} = 10.6 \text{ A}$$

The active load power becomes,

Active load power = $I_{o(rms)}^2 R = (10.6)^2 \times 5 = 561.8$ W

In Fig. 6.1.2 observe that the supply current is same as the output current.

Hence rms value of supply current will be,

$$I_{s(rms)} = I_{o(rms)} = 10.6 \text{ A}$$

Therefore total rms input power will be,

Total rms input power = $V_{s(rms)} \times I_{s(rms)}$

Here the $V_m = 120\sqrt{2}$. Hence $V_{rms} = 120$ V.

Therefore above equation becomes,

Total rms input power = 120 × 10.6 = 1272 VA

Therefore input power factor is given as,

$$PF = \frac{\text{Active load power}}{\text{Total rms input power}} = \frac{561.8}{1272} = 0.4416 \text{ or } 44.16 \%$$

This is lagging power factor since load current lags behind the supply voltage.

iii) To obtain average current of thyristors

Fig. 6.1.5 shows the current waveform of thyristor T_1. This waveform is prepared from waveforms of Fig. 6.1.2.

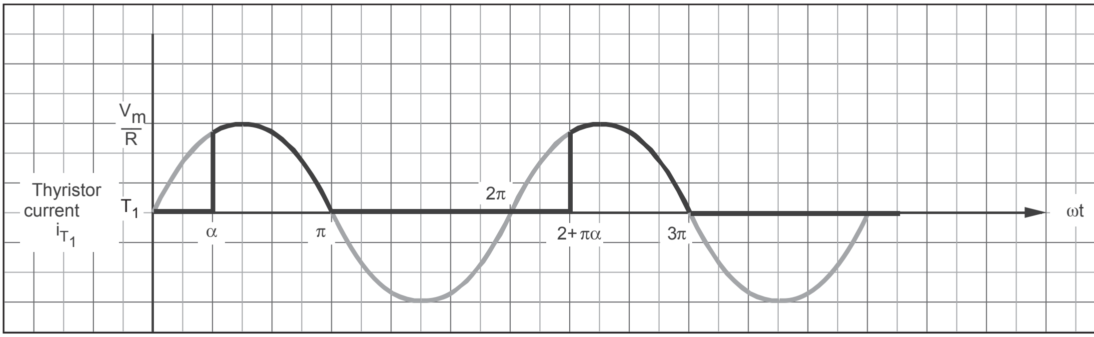


Fig. 6.1.5 Current waveform of thyristor in full wave phase control

The current waveform can be expressed as,

$$i(t) = I_m \sin \omega t$$

Peak value of current is, $I_m = \frac{V_m}{R}$. Average value of current in above figure can be given as,

$$I_{T(av)} = \frac{1}{2\pi}\int_{\alpha}^{\pi} I_m \sin(\omega t)\, d\omega t = \frac{1}{2\pi}\int_{\alpha}^{\pi} \frac{V_m}{R}\sin(\omega t)\, d\omega t$$

$$= \frac{V_m}{2\pi R}\left[-\cos\omega t\right]_{\alpha}^{\pi} = \frac{V_m}{2\pi R}(1+\cos\alpha)$$

Putting values in above equation

$$I_{T(av)} = \frac{169.7}{2\pi\times 5}\left(1+\cos\frac{2\pi}{3}\right) = 2.7 \text{ A}$$

iv) To obtain rms thyristor current

Let the rms currents of thyristors be $I_{T_1(rms)}$ and $I_{T_2(rms)}$. Since output rms current is made up of thyristor currents, we can write,

$$I_{o(rms)}^2 = I_{T_1(rms)}^2 + I_{T_2(rms)}^2$$

Both the thyristors conduct for same interval and they carry equal amount of current. Hence rms currents of both the thyristors will be same. i.e.,

$$I_{T_1(rms)} = I_{T_2(rms)} = I_{T(rms)}$$

$$\therefore \quad I_{o(rms)}^2 = I_{T(rms)}^2 + I_{T(rms)}^2$$

$$\therefore \quad I_{T(rms)} = \frac{I_{o(rms)}}{\sqrt{2}} = \frac{10.6}{\sqrt{2}} = 7.49 \text{ A}$$

Example 6.1.6 *The single phase full wave AC voltage controller operates on a single phase supply voltage of 230 V rms, at 50 Hz. If the triac is triggered at a delay angle of 45°, during each half cycle of input supply,*

Calculate, i) RMS value of output voltage ii) RMS value of current through heater iii) Averge value of triac current iv) RMS value of triac current v) Input PF

Derive any expressions used.

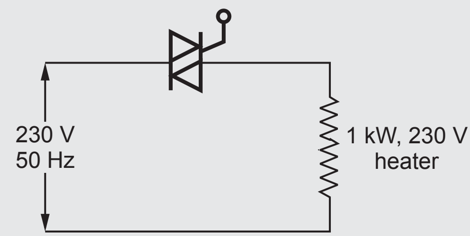


Fig. 6.1.6 AC controller of example 6.1.6

Solution : Given data

$$V_S = 230 \text{ V} \quad \therefore \; V_m = 230\sqrt{2}$$

$$\alpha = 45^{\circ} \text{ i.e. } \frac{\pi}{4}$$

i) To obtain $V_{o\,(rms)}$

The rms value of output voltage is given by equation (6.1.2) as,

$$V_{o\,(rms)} = V_m \sqrt{\frac{\pi - \alpha + \frac{\sin 2\alpha}{2}}{2\pi}} = 230\sqrt{2} \cdot \sqrt{\frac{\pi - \frac{\pi}{4} + \frac{\sin\left(2 \cdot \frac{\pi}{4}\right)}{2}}{2\pi}} = 219.3 \text{ volts}$$

ii) To obtain rms value of output current

The resistance of the heater will be,

$$R_L = \frac{(230)^2}{1000} = 53 \ \Omega$$

Hence rms current through heater will be,

$$I_{o(rms)} = \frac{V_{o(rms)}}{R_L} = \frac{219.3}{53} = 4.137 \text{ A}$$

iii) Average value of triac current

The output current, triac current and supply current waveforms are same. It is shown in Fig. 6.1.2. Since the positive and negative half cycles of current flowing through triac are symmetric, the average value is zero.

iv) RMS value of triac current

The triac current is same as output current. Hence rms value of triac current will be same as output current i.e.,

$$I_{T(rms)} = I_{o(rms)} = 4.137 \text{ A}$$

v) To obtain input PF

The active load power will be,

Active load power $= I^2_{o(rms)} R_L = (4.137)^2 \times 53 = 907$ W

The supply current is same as output current (See Fig. 6.1.2). Hence rms value of supply current will be same as that of output current i.e.

$$I_{s(rms)} = I_{o(rms)} = 4.137 \text{ A}$$

Therefore total rms input power will be,

Total rms input power $= V_{s(rms)} \times I_{s(rms)}$

$= 230 \times 4.137 = 951.5$ VA

Then input power factor will be,

$$\text{PF} = \frac{\text{Active Load Power}}{\text{Total Input Power}} = \frac{907}{951.5} = 0.953$$

Examples for Practice

Example 6.1.7 : *Calculate the rms current flowing through the heater element shown in Fig. 6.1.7. Both the SCRs are triggered with a delay angle of 30°.*

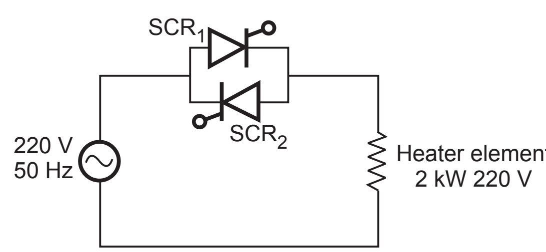


Fig. 6.1.7 AC regulator

[Ans. : $I_{o(rms)} = 9.23$ A]

Example 6.1.8 : *A single phase AC voltage controller has the resistive load of $R = 10\ \Omega$. It has the supply voltage of 230 V, 50 Hz. The triggering angle is $\alpha = \frac{\pi}{2}$. Determine (i) rms output voltage (ii) input power factor.*

[Ans. : $V_{o(rms)} = 162.63$ V, PF = 0.707]

Review Questions

1. *Explain the operation of 1ϕ full wave controller with the help of circuit diagram and waveforms. What are the different configurations of this circuit ?*
   SPPU : Dec.-09,13, May-11,12,17, Marks 8, May-10, Marks 10, Dec.-11, Marks 6
2. *Draw the circuit diagram and explain working of single phase full waves ac voltage controller using IGBT with R load, derive equation for rms output voltage ?*
   SPPU : May-18,19, Dec.-16,19, Marks 8
3. *Draw and explain the operation of single phase AC voltage controller using SCR or IGBT with necessary waveforms. Derive the expression of RMS voltage of output.*
   SPPU : Dec.-18, Marks 8
4. *Draw the circuit diagram of single phase AC voltage controller with R load. Explain its operation. Draw the waveform of output voltage.* **SPPU : May-17, Marks 9**
5. *Explain working of single phase full wave bidirectional controller using SCR with R load. Draw waveform and state equation of RMS output voltage.* **SPPU : May-19, Marks 8**

6.2 Fan Regulator

SPPU : May-18,19, Dec.-18,19

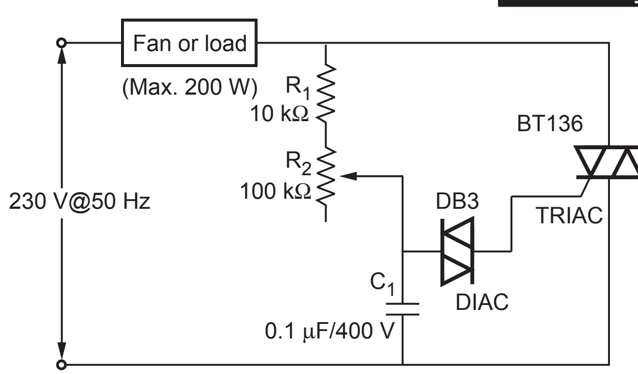


Fig. 6.2.1

Waveforms :

- Before giving the power supply to this simple fan regulator circuit, the variable resistor or potentiometer is kept in maximum resistance position so that no triggering is applied to TRIAC and hence the TRIAC will be in cutoff mode.
- Turn ON the power supply of the circuit and observe whether the fan is in standstill condition or not. The potentiometer

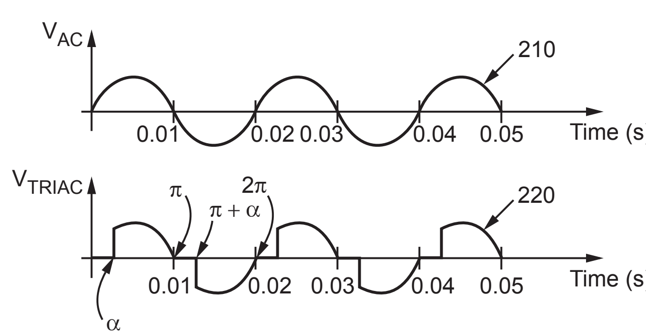


Fig. 6.2.2

position is changed slowly so that the capacitor starts charging. The time constant is determined by the values of R_1 and R_2.

- Once the voltage across the capacitor is more than the break over voltage of the DIAC, DIAC starts conducting. Thus, the capacitor starts discharging towards the gate terminal of TRIAC through DIAC.
- Therefore, TRIAC starts conducting and hence the main current starts flowing into the fan through the closed path formed by TRIAC.
- By varying the potentiometer R_2, the rate at which capacitor is going to be charged get varied this means that if the resistance is less, the capacitor will charge at a faster rate so the earlier will be the conduction of TRIAC.
- As the potentiometer resistance gradually increases, the conduction angle of TRIAC will be reduced. Hence the average power across the load will be varied.
- Due to the bidirectional control capability of both TRIAC and DIAC, it is possible to control the firing angle of the TRIAC in both positive and negative peaks of the input.

Advantages of simple fan regulator circuit

1. Continuous and step less control of the fan speed is possible
2. Power saving is achieved at all the speeds by minimizing the energy losses
3. Simple circuit which requires less number of components
4. Efficient as compared with resistive type due to lower power consumption
5. Cost-effective

Review Questions

1. *Draw and explain the operation fan regulator circuit using triac with neat waveforms at various points ?* **SPPU : May-18, Dec.-19, Marks 8**
2. *Draw and explain the fan regulator using Triac and Diac with waveform at various circuit points.* **SPPU : Dec.-18, Marks 6**
3. *With a circuit diagram, explain an application of Triac to control the domestic fan speed.* **SPPU : May-19, Marks 8**

6.3 Electronic Ballast

SPPU : May-15,17, Dec.-15,16,19

6.3.1 Characteristics of Fluorescent Lamps and Ballast

- Fluorescent lamps are four times energy efficient compared to incandescent lamps.
- If fluorescent lamps are operated at high frequencies, then their efficiency is further increased.

- Fluorescent lamps have negative resistance characteristics as shown in Fig. 6.3.1. Therefore inductive ballast is used in series for stable operation. In Fig. 6.3.1 observe that when the characteristics of fluorescent lamp and inductive ballast cross each other, stable operating point is established.

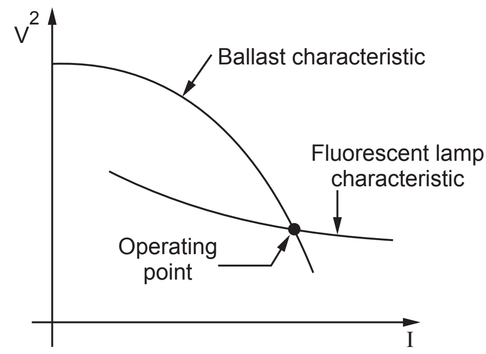


Fig. 6.3.1 Fluorescent lamp characteristic

6.3.2 Block Diagram and Operation of Electronic Ballast

- Fig. 6.3.2 shows the block diagram of electronic ballast.

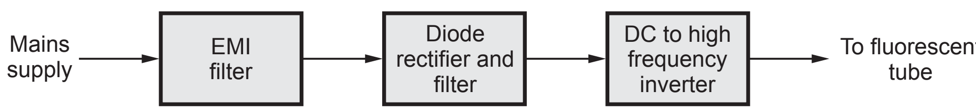


Fig. 6.3.2 Block diagram of electronic ballast

- The mains supply is passed through EMI filter and rectified. The d.c. voltage at the output of rectifier is filtered with capacitor filter.
- The DC voltage is then converted to a.c. with very high frequency. This frequency is 20-40 kHz. This high frequency a.c. voltage is given to the fluorescent tube.
- The fluorescent tube works efficiently at high frequency a.c. voltage. The voltage required is also low.
- EMI is generated due to high frequency inverter. EMI filter is used to suppress this EMI from being injected in the main supply.

6.3.3 Advantages/Disadvantages of Electronic Ballast

Advantages

i) Electronic ballast provides power saving upto 30 % .

ii) Fluorescent lights can work at low supply voltages with electronic ballast.

iii) Electronic ballast consume less power and hence heating is reduced.

iv) Life of fluorescent tube is increased due to electronic ballast since noise interference from mains supply is absent.

Disadvantages

i) Electronic ballast operate at poor power factor.

ii) Electronic ballast generate EMI, hence additional filters are required.

iii) Internal circuit and control of electronic ballast is complex.

iv) Electronic ballast is costlier than conventional ballast.

Review Questions

1. *Explain the operation of electronic ballast with the help of block diagram.* **SPPU : May-17, Dec.-19**
2. *State advantages and disadvantages of electronic ballast.*
3. *Explain electronic ballast. What are the advantages of flourescent lamp over conventional lamp ?* **SPPU : May-17, Marks 8**
4. *What are advantages of electronic ballast over conventional ballast ? Explain working of electronic ballast with block schematic.* **SPPU : May-15, Marks 8**
5. *Write short note on : i) Electronic ballast.* **SPPU : Dec.-15,16, Marks 4**

6.4 LED Lamp

SPPU : May-18,19

An LED lamp is a light-emitting diode (LED) product that is assembled into a lamp (or light bulb) for use in lighting fixtures. LED lamps have a lifespan and electrical efficiency which are several times greater than incandescent lamps, and are significantly more efficient than most fluorescent lamps. Like incandescent lamps and unlike most fluorescent lamps (e.g. tubes and compact fluorescent lamps or CFLs), LEDs come to full brightness without need for a warm-up time; the life of fluorescent lighting is also reduced by frequent switching on and off. The initial cost of LED is usually higher. Degradation of LED dye and packaging materials reduces light output to some extent over time.

Some LED lamps are made to be a directly compatible drop-in replacement for incandescent or fluorescent lamps. An LED lamp packaging may show the lumen output, power consumption in watts, color temperature in kelvins or description (e.g. "warm white"), operating temperature range, and sometimes the equivalent wattage of an incandescent lamp of similar luminous output.

Fig. 6.4.1

Most LEDs do not emit light in all directions, and their directional characteristics affect the design of lamps, although omnidirectional lamps which radiate light over a 360° angle are becoming more common. The light output of single LED is less than that of incandescent and compact fluorescent lamps; in most applications multiple LEDs are used to form a lamp. Following Fig. 6.4.1 shows A 230-volt LED light bulb, with an E27 base (10 watts, 806 lumens).

6.4.1 LED Driver Circuit Principle

The basic principle behind the LED driver circuit is transformer less power supply. The main component is the rated AC capacitor, which can reduce the supply current to a suitable amount. These capacitors are connected line to line and are designed for high voltage AC circuits. The rated capacitor reduces only the current and the AC voltage can be rectified and regulated in the later parts of the circuit. The high voltage and low current AC is rectified in to high voltage DC using a bridge rectifier. This high voltage DC is further rectified using a zener diode to a low voltage DC. Finally, the low voltage and low current DC is given to an LED.

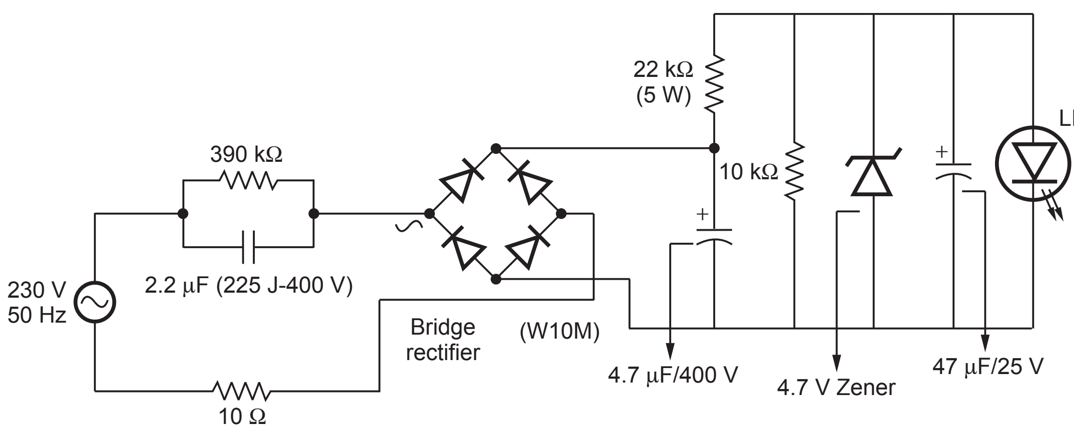


Fig. 6.4.2

The main components of this project are the rated capacitor, the zener diode and the resistor which limits the current in the zener diode. First, the rated capacitor (225J - 400 V) will limit the AC current from the mains supply. This total current enters the bridge rectifier. Now, output of the bridge rectifier is filtered using a capacitor. It is important to select an appropriated voltage rating for this capacitor. The rectified DC voltage is high voltage. This must be brought down to a usable range for lighting up the LED. Hence, the zener diode is used.

There are three important factors associated with the zener diode that is acting as a regulator. This series resistor connected will limit the current flowing through the zener diode. The power rating of the series resistor has to be taken into consideration as it determines the amount of power the resistor can dissipate. Then the zener diode is used as regulator. The rectified and regulated voltage with limited current is given to the LED.

6.4.2 Advantages, Limitations and Applications

Advantages

- With the help of this LED driver circuit, we can drive LEDs directly from the main supply.
- Transformer less power supply. Hence, small in size.

Applications of LED driver circuit

1. This circuit can be used for home lightening systems.
2. It can be used as an indicator circuit.
3. One can fix this circuit with the door-bell to give indication.

Limitations of LED Driver Circuit

1. Since AC supply is being directly used here, this circuit can be dangerous.
2. This circuit is best suited for domestic applications using single phase supply. This is because, in case of three phase supply, if any of the phases accidently touches the input terminal, it can prove to be quite dangerous.
3. The capacitor can produce spikes at mains fluctuations.

Review Questions

1. *With the help of block diagram, explain the working of LED lamp driver circuit used for domestic lightening applications.* **SPPU : May-18, Marks 8**
2. *Explain working of LED lamp driver circuit used as a domestic tube light.* **SPPU : May-19, Marks 10**

6.5 Single Phase Separately Excited DC Motor Drive

SPPU : May-17, Dec.-15,18

6.5.1 Equivalent Circuit and Torque-speed Characteristics of Separately Excited DC Motor

Fig. 6.5.1 shows an equivalent circuit of separately excited DC motor. We can write following steady state equations for this motor,

$$V_a = E_b + I_a R_a \quad \dots (6.5.1)$$

$$E_b = K_a \phi_f \omega \quad \dots (6.5.2)$$

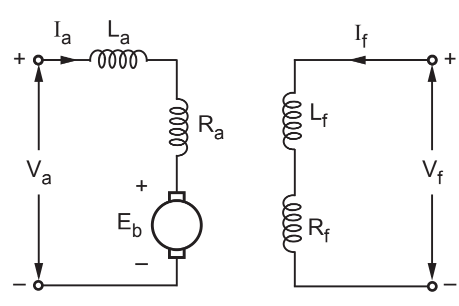


Fig. 6.5.1 Equivalent circuit of separately excited DC motor

Here V_a is the armature voltage

E_b is the back e.m.f. of the motor

R_a is the armature resistance

K_a motor armature constant

ω is the speed of motor in rad/sec

ϕ_f field flux per pole in webers

The torque of the motor is given as,

$$T = K_a \phi_f I_a \qquad \dots (6.5.3)$$

Here I_a is the armature current. Putting for E_b from equation (6.5.2) in equation (6.5.1),

$$V_a = K_a \phi_f \omega + I_a R_a$$

$$\therefore \quad \omega = \frac{V_a - I_a R_a}{K_a \phi_f} = \frac{V_a}{K_a \phi_f} - \frac{I_a R_a}{K_a \phi_f}$$

Since $I_a = \dfrac{T}{K_a \phi_f}$ from equation (6.5.3), then above equation can be written as,

$$\omega = \frac{V_a}{K_a \phi_f} - \frac{R_a}{(K_a \phi_f)^2} T \qquad \dots (6.5.4)$$

This equation gives speed torque characteristics of the motor.

Here observe that $K_a \phi_f$ is the constant. Hence speed-torque characteristic will be almost straight line as shown in Fig. 6.5.2.

The speed decreases with increased torque due to $R_a T$ drop in equation (6.5.4). The no load speed ($T = 0$) depends upon field flux and armature voltage.

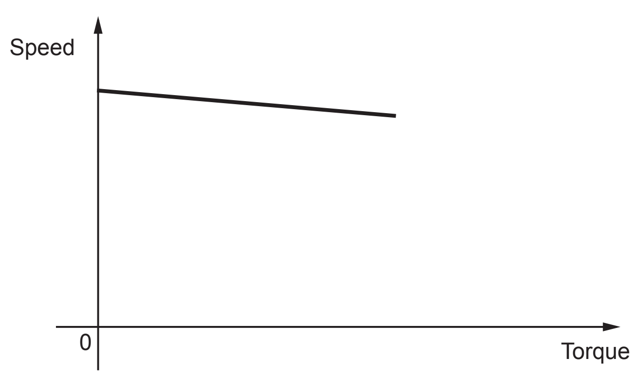


Fig. 6.5.2 Speed-torque characteristics

6.5.2 Speed Control Methods

In equation (6.5.4) observe that the two parameters can vary the speed of the motor. They are

i) Armature voltage (V_a)

ii) Field current control (ϕ_f)

The armature voltage of the DC motor can be varied by putting controlled rectifier in the armature circuit. By changing the firing angle, the armature voltage and hence speed can be varied. For constant torque and flux, it is clear from equation (6.5.4) that the speed is proportional to armature voltage.

Form equation (6.5.4), observer that the speed is inversely proportional flux (ϕ_f) for constant torque and armature voltage. Flux depends upon the field current. As the field current is reduced, the field flux reduces. Hence motor speed increases. The field current can be varied by putting a controlled rectifier in the field circuit. The field current is given as,

$$I_f = \frac{V_f}{R_f}$$

Value of field voltage (V_f) can be changed by changing the firing angle. Hence field current and flux can be changed.

6.5.3 Constant Torque and Constant Power Regions

The DC motor can be operated in constant torque or constant power region. Fig. 6.5.3 shows these two regions on speed torque characteristics.

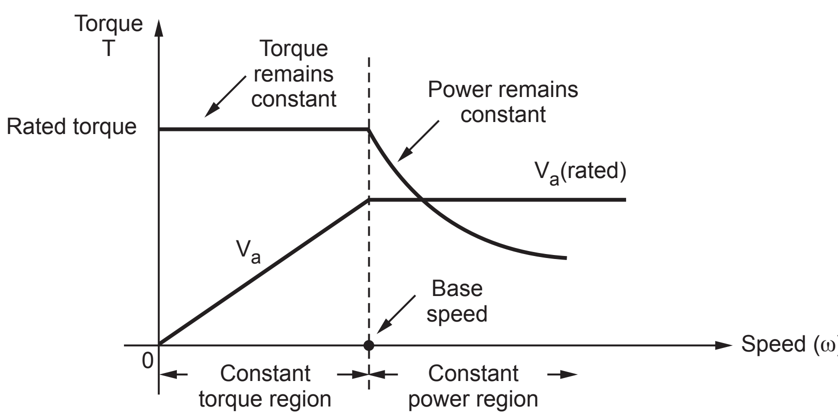


Fig. 6.5.3 Constant torque and constant power operation

6.5.3.1 Constant Torque Region

The torque remains constant in constant torque region. As the speed increases, armature voltage V_a also increases. Hence the power also increases. The constant torque region ends when rated armature voltage is applied to the motor. The speed at rated V_a is called base speed of the motor. The motor speed can be controlled in this region using armature voltage control.

6.5.3.2 Constant Power (HP) Region

The power suplied to the motor remains constant in this region. Hence observe that armature voltage remains constant in this region. As the speed increases, the maximum available torque reduces. In this mode, the speeds more than base speed can be obtained. Motor speed can be controlled in this region using field current control.

Review Questions

1. *Explain with circuit diagram working of single phase seperately excited DC motor drive. Draw neat waveforms across load.* **SPPU : May-17, Marks 10**
2. *What are the methods of speed control of DC motor ?* **SPPU : Dec.-18, Marks 3**
3. *Draw and explain torque speed characteristics of DC drive and explain the constant power and constant speed operation of DC motor.* **SPPU : Dec.-18, Marks 10**
4. *What are speed control techniques of DC Motors ?* **SPPU : Dec.-15, Marks 4**

6.6 Armature Voltage Control

SPPU : May-16,17,18, Dec.-15,18

The armature voltage of the separately excited DC motor can be controlled by controlled converters. In this section we will study these techniques in detail.

6.6.1 Speed-Torque Characteristics

Fig. 6.6.1 shows the speed torque characteristics of separately excited DC motor having armature voltage control. It is assumed that the field flux remains constant. In these characteristics $V_{a1} < V_{a2} < V_{a3} < V_{a4} < V_{a5}$. This means for a constant torque, speed increases with increasing armature voltage. This means $\omega_1 < \omega_2 < \omega_3 < \omega_4 < \omega_5$.

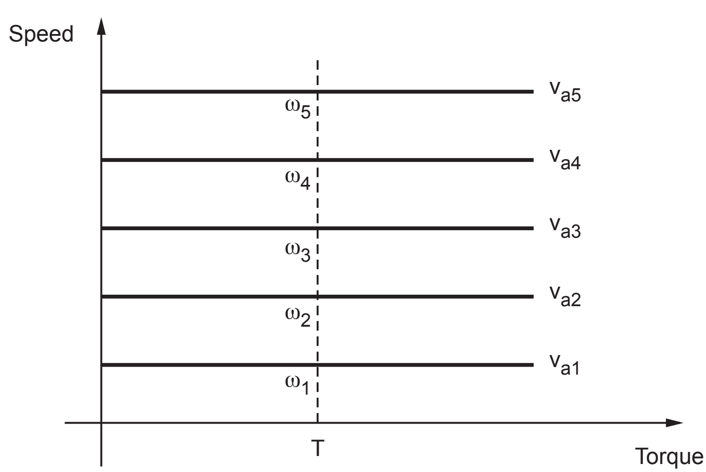


Fig. 6.6.1 Speed-torque characteristics for armature voltage control

6.6.2 1ϕ Semiconverter Based DC Motor Drive

Fig. 6.6.2 shows the circuit diagram having 1ϕ semiconverter for the armature voltage control.

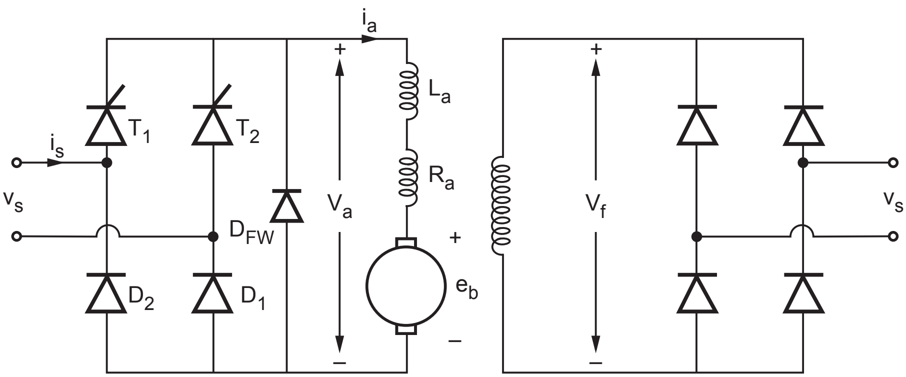


Fig. 6.6.2 1ϕ semiconverter based DC drive

In the circuit observe that, the field supply is given by uncontrolled rectifier. Hence field flux is fixed. The armature voltage can be varied by controlling the firing angles of T_1 and T_2 in semiconverter. The load current can be continuous or discontinuous depending upon armature inductance.

6.6.2.1 Continuous Load Current Mode

The armature current is continuous in this mode. Fig. 6.6.3 shows the waveforms for this mode. (See Fig. 6.6.3 on next page)

The supply voltage and the back emf is shown in Fig. 6.6.3 (a). In Fig. 6.6.3 (b) observe that the output voltage is zero from π to $\pi+\alpha$ due to free wheeling operation. Fig. 6.6.3 (c) shows that the armature current is continuous. The ripple in this current depends upon the armature inductance of the motor.

Fig. 6.6.3 (d) shows the supply current i_s observe that supply current is basically part of armature current i.e.,

$$i_s = i_a \quad \text{when } T_1\, D_1 \text{ conducts}$$

$$i_s = -i_a \quad \text{when } T_2\, D_2 \text{ conducts}$$

and $$i_s = 0 \quad \text{when freewheeling diode conducts}$$

The waveform of Fig. 6.6.3 (e) shows the freewheeling diode current. (See Fig. 6.6.3 on next page)

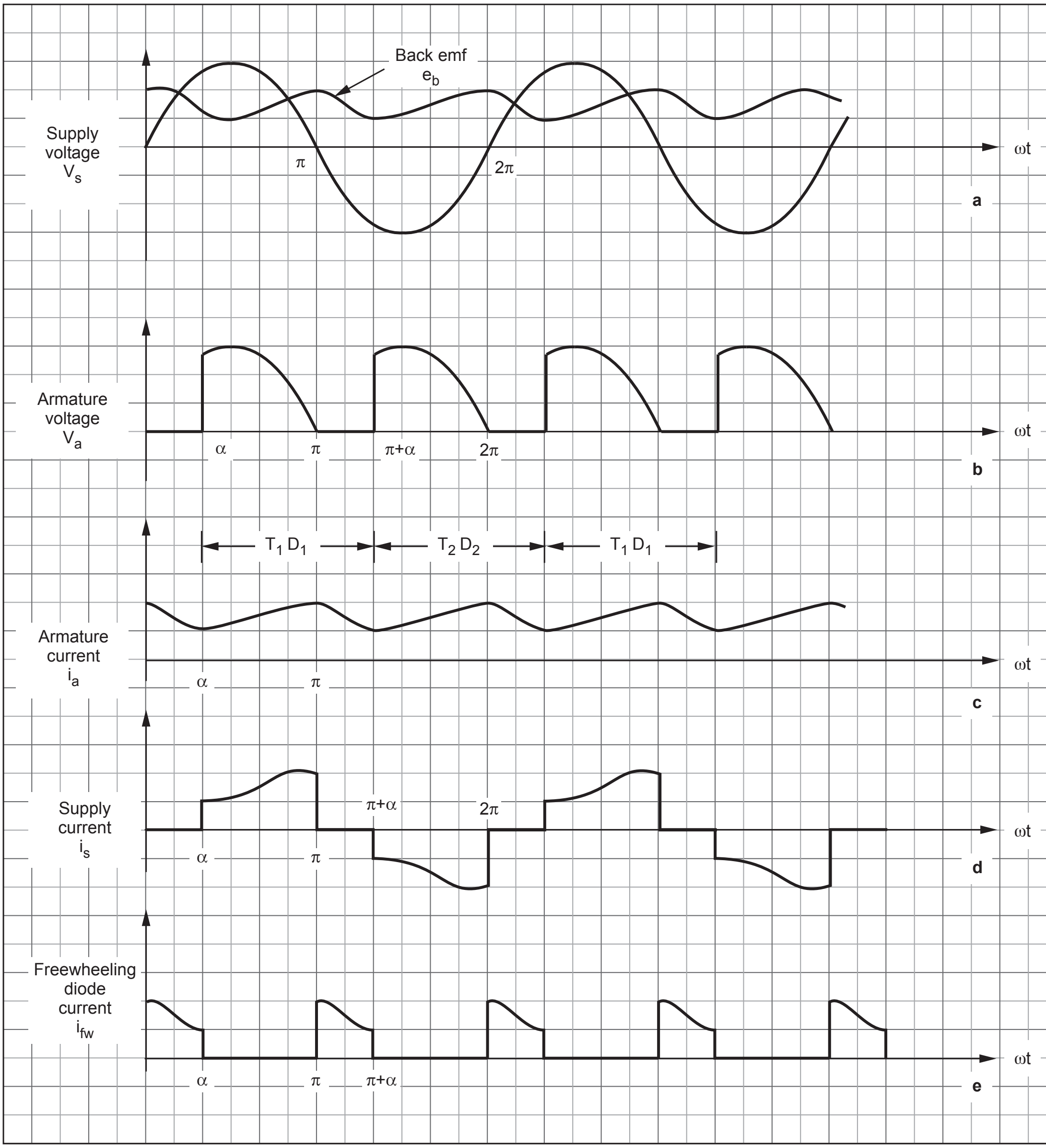


Fig. 6.6.3 Waveforms of 1φ semiconverter based separately excited DC motor drive

Mathematical analysis

We know that speed of the separately excited DC motor is given as,

$$\omega = \frac{V_a - I_a R_a}{K_a \phi_f} \qquad \dots (6.6.1)$$

Here V_a is the output voltage of 1ϕ semiconverter. It is given as $\frac{V_m}{\pi}(1+\cos\alpha)$. Hence above equation will be,

$$\omega = \frac{\frac{V_m}{\pi}(1+\cos\alpha)-I_a R_a}{K_a \phi_f} \quad \dots (6.6.2)$$

$$= \frac{V_m (1+\cos\alpha)}{\pi K_a \phi_f}-\frac{I_a R_a}{K_a \phi_f}$$

This equation relates the speed with firing angle of semiconverter.

6.6.2.2 Discontinuous Load Current Mode

The motor current can be discontinuous if armature inductance is small. Fig. 6.6.4 shows the waveforms of discontinuous current mode.

Observe the armature current waveform of Fig. 6.6.4 (c). It is discontinuous. SCR T_1 is triggered at α. Then current flows till β beyond π. At β, $i_a = 0$. The next SCR T_2 is triggered at $\pi+\alpha$. Therefore i_a again starts increasing from zero. The armature current again goes to zero at $\pi+\beta$. In the waveform of Fig. 6.6.4 (e) observe that freewheeling diode conducts from α to β and 2π to $\pi+\beta$. In the waveform of Fig. 6.6.4 (c) observe that armature current is zero. But the motor rotates due to inertia. Hence the back emf of $e_b = k_a \phi N$ is generated across the terminals of the motor. Therefore 'e_b' is shown in the armature voltage waveform of Fig. 6.6.4 (b). Observe that 'e_b' appears across the armature whenever current is zero. That is e_b appears at β to $(\pi+\alpha)$, $(\pi+\beta)$ to $(2\pi+\alpha)$ and so on. The motor is open circuited when we observe e_b across the motor terminals. (Refer Fig. 6.6.4 on next page)

Mathematical analysis

The average of output voltage of the semiconverter for discontinuous mode is given as,

$$V_{o(av)} = \frac{V_m}{\pi}(\cos\alpha-\cos\beta)$$

This $V_{o(av)}$ is armature voltage (V_a) of the motor. Hence from equation (6.6.1) we get,

$$\omega = \frac{\frac{V_m}{\pi}(\cos\alpha-\cos\beta)-I_a R_a}{K_a \phi_f} \quad \dots (6.6.3)$$

Disadvantages of discontinuous current mode

i) Speed regulation is poor.

ii) Motor performance is deteriorated

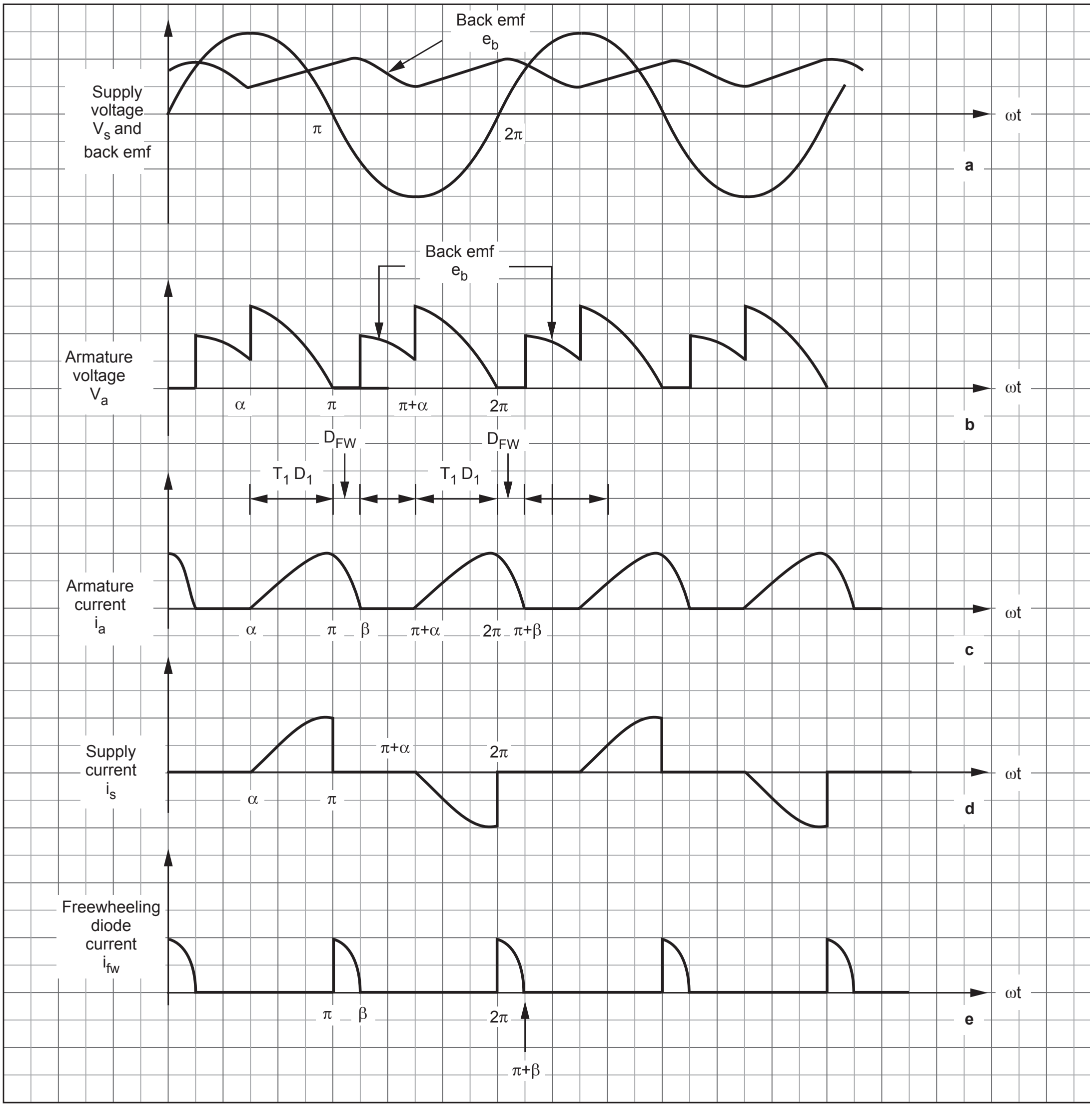


Fig. 6.6.4 Waveforms of 1ϕ semiconverter drive for discontinuous mode

iii) Peak current of the motor increases.

iv) Dynamic response is slow.

v) Motor efficiency is reduced.

6.6.3 1ϕ Full Converter Based DC Motor Drive

Full converters are better suitable for DC motors. Fig. 6.6.5 shows the circuit diagram of such drive.

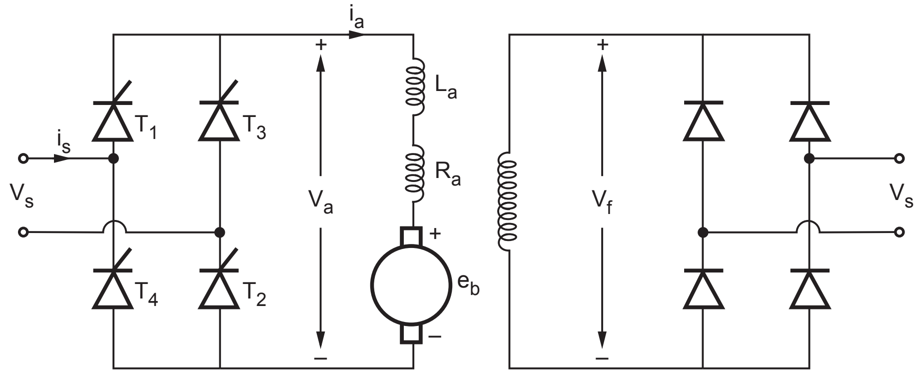


Fig. 6.6.5 1ϕ full converter based DC drive

Observe that the armature is supplied by 1ϕ fully controlled bridge. The field is supplied with uncontrolled rectifier. Hence field flux remains constant. The operation of this drive can also be described for continuous mode and discontinuous mode.

6.6.3.1 Continuous Load Current Mode

Fig. 6.6.6 shows the waveforms for continuous armature current, SCRs T_1 and T_2 conduct in a positive half cycle. Since the load is inductive, the SCRs continue to conduct till next pair $T_3 T_4$ is triggered at $\pi+\alpha$. Observe that armature voltage is negative from π to $\pi+\alpha$. This is second quadrant operation and it takes place due to inductive load. The armature current is shown in Fig. 6.6.6 (c). (See Fig. 6.6.6 on next page) It is continuous. The ripple in armature current depends upon motor armature inductance. Fig. 6.6.6 (d) shows the supply current i_s. It is given as,

$$i_s = \begin{cases} i_a & \text{when } T_1 T_2 \text{ conduct} \\ -i_a & \text{when} T_3 T_4 \text{ conduct} \end{cases}$$

Mathematical analysis

We know that average output voltage of the fully control bridge for continuous output current is given as,

$$V_{o(av)} = \frac{2V_m}{\pi}\cos\alpha$$

Putting this value of $V_{o(av)}$ for V_a in equation (6.6.1) we get,

$$\omega = \frac{\frac{2V_m}{\pi}\cos\alpha - I_a R_a}{K_a \phi_f} \qquad \dots (6.6.4)$$

This equation gives the speed interms of firing angle (α).

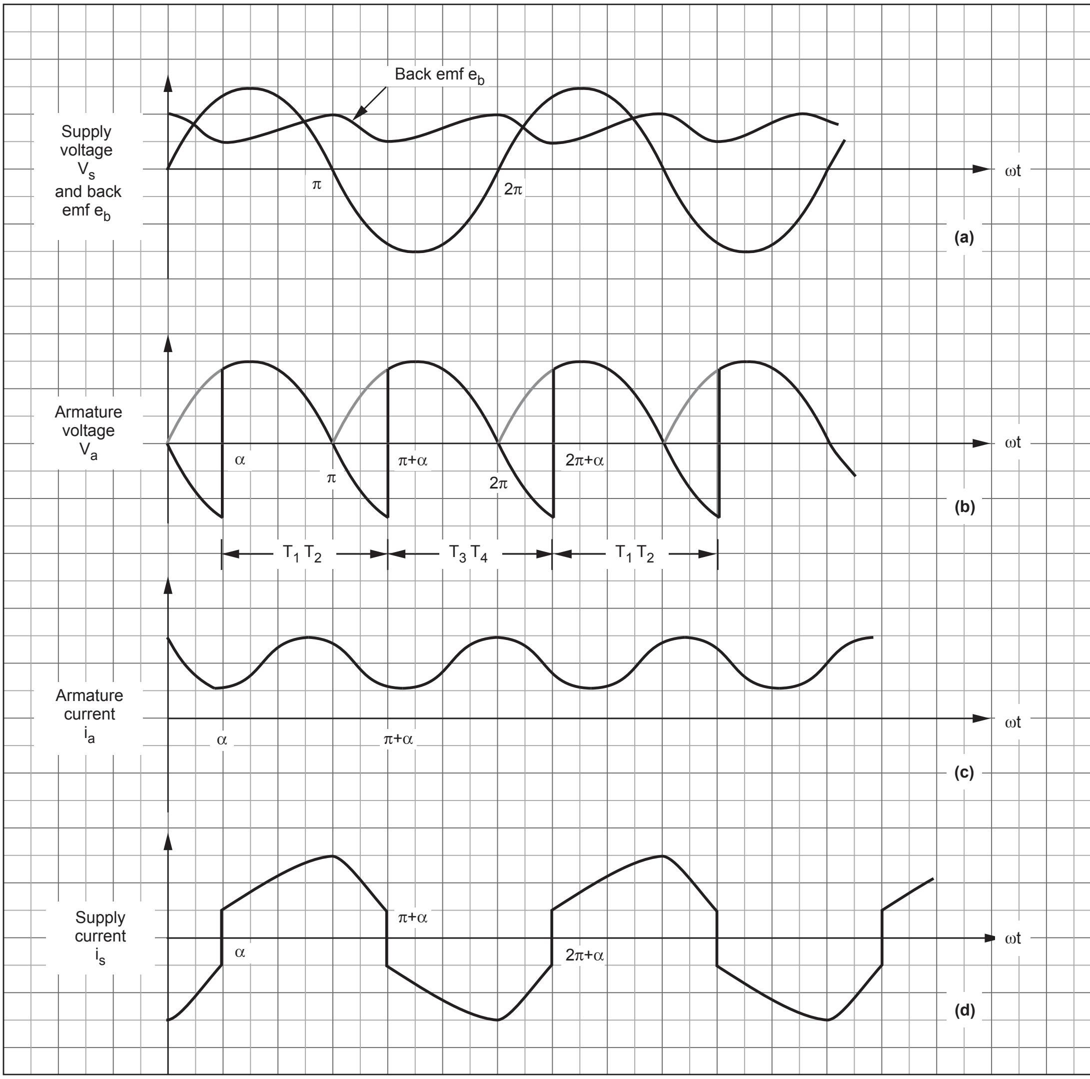


Fig. 6.6.6 Continuous mode waveforms of 1ϕ FCB drive

6.6.3.2 Discontinuous Load Current Mode

Fig. 6.6.7 shows the waveforms of fully control bridge drive for discontinuous operation. Fig. 6.6.7 (c) shows the armature current waveform.

The current is discontinuous from β to π+α. During this period the motor is open and no current flows. Since the motor is rotating due to inertia, a back emf of $e_b = K_a \phi_f N$ is developed across its terminals. The back emf appears across the motor terminals when armature current is zero. This is shown in the waveform of Fig. 6.6.7 (b). The supply current is shown in Fig. 6.6.7 (d). The discontinuous mode has similar drawbacks as discussed for semiconverter drive in last subsection.

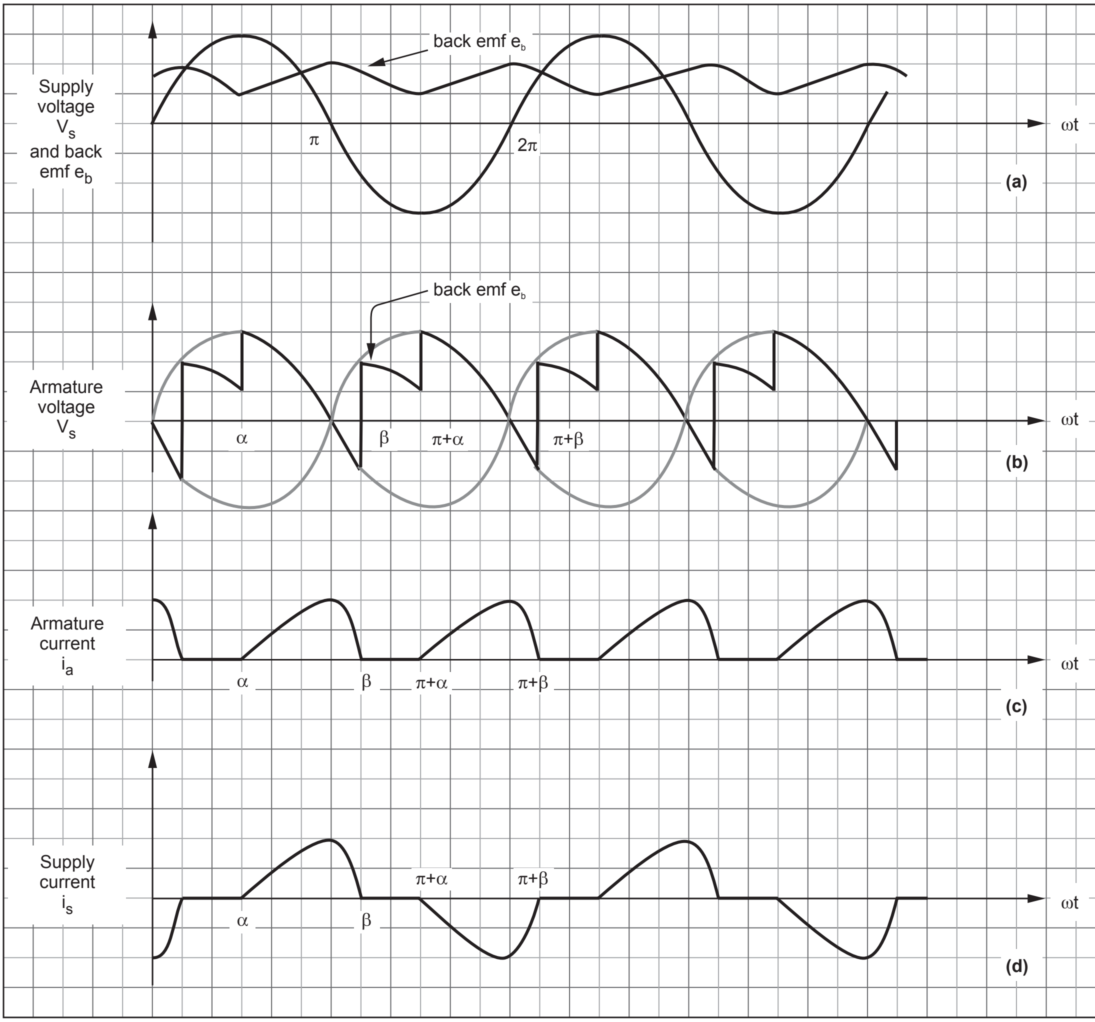


Fig. 6.6.7 Discontinuous mode waveforms of 1φ FCB based drive

Example 6.6.1 *A separately excited dc motor is operated from a single phase semiconverter and has following parameters :* $R_a = 0.05\ \Omega$, $K_a \phi_f = 1$ *N-m/A. The supply voltage is 230 V/50 Hz. Calculate the speed of the motor for a torque of 8 N-m and firing angle of 60°.*

Solution :

Here $K_a \phi_f = 1$ N-m/A

$T = 8$ N-m

$R_a = 0.05\ \Omega$

$V_m = 230\sqrt{2}$ V

For semiconverter, speed of the motor is given by equation (6.6.2) as,

$$\omega = \frac{\frac{V_m}{\pi}(1+\cos\alpha) - I_a R_a}{K_a \phi_f}$$

We know that $I_a = \frac{T}{K_a \phi_f}$. Hence above equation will be,

$$\omega = \frac{\frac{V_m}{\pi}(1+\cos\alpha) - \frac{T R_a}{K_a \phi_f}}{K_a \phi_f} = \frac{\frac{230\sqrt{2}(1+\cos 60°)}{\pi} - \frac{8 \times 0.05}{1}}{1}$$

$$= 155 \text{ rad/sec} = 155 \times \frac{60}{2\pi} \text{ rpm} = 1480 \text{ rpm}$$

Example 6.6.2 *The speed of 10 HP, 200 V, 1500 rpm separately excited DC motor is controlled by a semiconverter. The rated armature current is 40 A. The motor parameters are $R_a = 0.5\ \Omega$, $L_a = 10$ mH, $K_a \phi_f = 0.2$ V/rpm. Assume that the motor current is continuous and ripple free. The supply voltage is 230 V / 50 Hz. Determine i) Motor torque ii) Motor speed and iii) Supply power factor for $\alpha = 30°$ and rated motor current.*

Solution :

Here $K_a \phi_f = 0.2 \text{ V/rpm} = 0.2 \times 60 \text{ V/rps}$

$$= 0.2 \times \frac{60}{2\pi} \text{ V/rad/sec} = 1.91 \frac{\text{V}}{\text{rad/sec}}$$

i) To obtain motor torque

Motor torque is given as,

$$T = K_a \phi_f I_a = 1.91 \times 40 = 76.4 \text{ N-m}$$

ii) To obtain motor speed

Armature voltage of the motor will be,

$$V_a = V_{o(av)} = \frac{V_m}{\pi}(1+\cos\alpha) = \frac{230\sqrt{2}}{\pi}(1+\cos 30°) = 193.2 \text{ V}$$

In the steady state back emf is given as,

$$E_b = V_a - I_a R_a = 193.2 - 40 \times 0.5 = 173.2 \text{ V}$$

The back emf and motor speed are related as,

$$E_b = K_a \phi_f \omega$$

$$\therefore \quad \omega = \frac{E_b}{K_a \phi_f} = \frac{173.2 \text{ V}}{0.2 \text{ V/rpm}} = 866 \text{ rpm.}$$

iii) **To obtain supply power factor**

The supply power factor of 1 ϕ semiconverter is given as,

$$PF = \sqrt{\frac{8}{\pi(\pi-\alpha)}}\cos^2\frac{\alpha}{2} = \sqrt{\frac{8}{\pi\left(\pi-\frac{\pi}{6}\right)}}\cos^2\left(\frac{30}{2}\right) = 0.92$$

Example for Practice

Example 6.6.3 : *A separately excited DC motor is operated from a single phase HCB and has following parameters : $R_a = 0.1\ \Omega$, $K_a\phi_f = 0.75$ N-m/A, The supply voltage is 230 V/ 50 Hz. Assume the armature current to be continuous and ripple free.*

i) Calculate the firing angle to obtain a speed of 1400 rpm at a load torque of 5 N-m.

ii) If the load torque drops to 1 N-m, calculate the new firing angle to maintain the speed constant.

iii) If the supply voltage rises to 250 V, calculate the firing angle to maintain the speed constant with a load torque of 5 N-m.

[Hints and Ans. : $\omega = \dfrac{\frac{V_m}{\pi}(1+\cos\alpha) - I_a R_a}{K_a\phi_f}$, $I_a = \dfrac{T}{K_a\phi_f}$, **$\alpha$ = 1.502 rad or 86.07°, For $T = 1$ N - m, $\alpha = 86.37°$, For V_s = 250 V, 90.98°]**

Review Questions

1. *Draw the circuit diagram and waveforms for speed control of separately excited DC motor using armature voltage control.* **SPPU : May-17**
2. *Explain with circuit diagram working of single phase seperately excited DC motor drive. Draw neat waveforms across load.* **SPPU : Dec.-15, May-17, Marks 10**
3. *Explain how the speed of the separately excited dc motor can be controlled by DC drive system ?* **SPPU : Dec.-18, Marks 6**
4. *What are DC drives ? Explain with circuit diagram working of 1 ϕ separately excited DC Motor with inductive load. Suggest power factor improvement techniques.* **SPPU : May-16, Marks 8**

6.7 Field Current Control

The speed of the motor can be controlled by varying the field flux. The field flux can be changed by changing the field current. The motor operates in constant power mode if field current control is used.

6.7.1 1ϕ Half Converter Based Control

Fig. 6.7.1 shows the circuit diagram of separately excited DC motor drive having field control using 1ϕ half converter. The armature of the motor can be controlled using any type of converter.

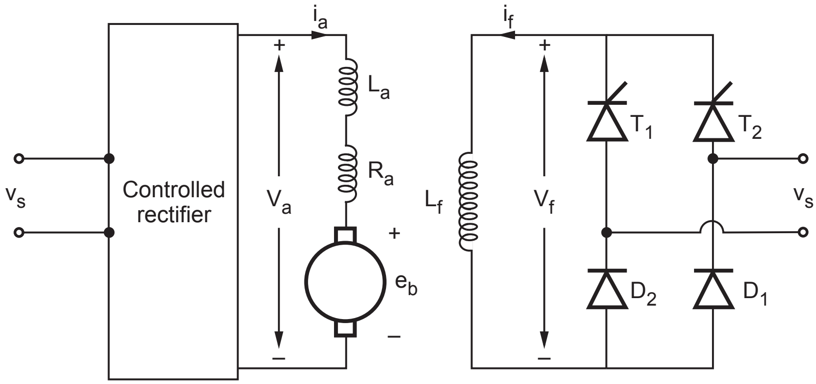


Fig. 6.7.1 Field current controlled drive

The firing angle of semiconverter controls the field voltage V_f. The field current $i_f = \frac{V_f}{R_f}$ flows in the circuit. The field flux is produced depending upon the field current. In other words, the flux can be controlled by controlling the firing angle of semiconverter. Hence the speed of the motor can also be controlled by the firing angle of the semiconverter.

6.7.2 Torque Speed Characteristics

Fig. 6.7.2 shows the torque-speed characteristics of the separately excited DC motor drive having field control.

Here the field flux $\phi_{f1} > \phi_{f2} > \phi_{f3} > \phi_{f4}$. And for the constant torque, the speeds $\omega_1 < \omega_2 < \omega_3 < \omega_4$. This means speed incereases as the field flux is reduced.

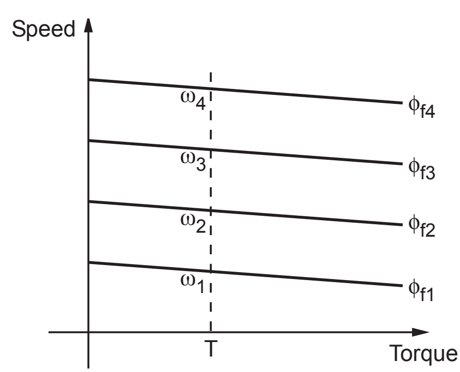


Fig. 6.7.2 Torque-speed characteristics for field current control

6.7.3 Advantages, Disadvantages and Applications

Advantages

i) Easier method of control ii) Good dynamic response

iii) Constant power operation iv) Speeds higher than base speeds can be obtained.

Disadvantages

i) Torque does not remain constant

ii) Motor becomes unstable at higher speeds.

Application

Field current control is used for obtaining speeds higher than base speed of the motor.

Review Question

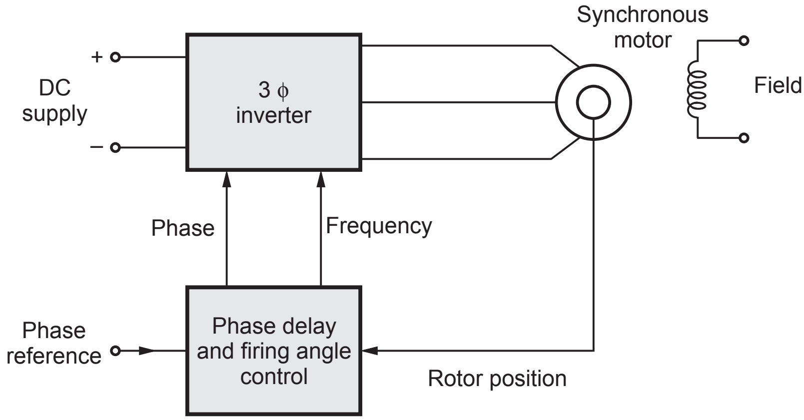
1. *What is the difference between armature control and field control ? Compare them.*

6.8 Brushless DC (BLDC) Motors

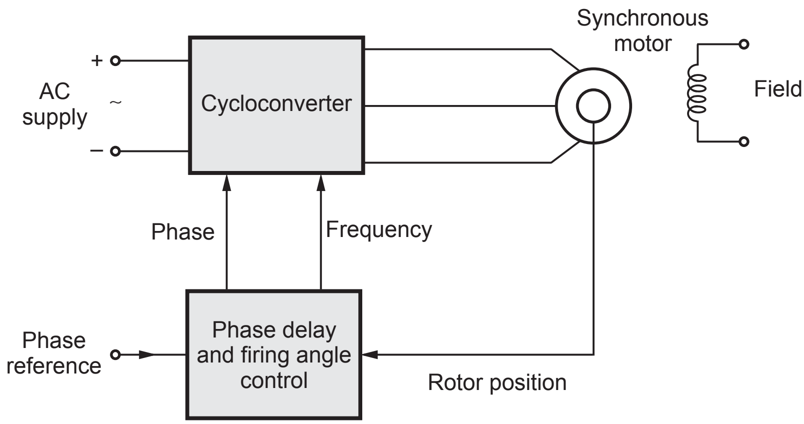
Principle of operation : The synchronous motors are operated as DC motors. The armature supply frequency is changed according to rotor speed changes. Therefore armature field always moves at the same speed as rotor. The characteristics of DC motor can be obtained by synchronous motors and there are no brush or commutators. Hence synchronous motors are also called brushless DC motors under such control. This control is called self control mode.

Explanation of the drive

- Fig. 6.8.1 shows the block diagram of brushless DC and AC motor drives. Observe that the drive can operate from AC or DC source. The DC source uses 3 ϕ inverter to drive the synchronous motor. It is then called brushless DC motor drive. The AC source uses cycloconverter to drive the synchronous motor. It is then called brushless AC motor drive.
- The three phase inverter or cycloconverter generate an output ; whose frequency is changed in proportion to the speed, such that armature and rotor mmf waves revolve at the same speed. This operation produces steady torque at all speeds smilar to dc motor.
- The rotor position is monitored continuously. The phase reference is also taken. This information is used to generate the drives of 3 ϕ inverter or cycloconverter. The drives are used to control the output frequency and phase of armature.
- Since the operation is similar to dc motor but there is no need of commutator or brushes, it is called brushless DC or AC motor drive.



(a) Brushless DC motor drive



(b) Brushless AC motor drive

Fig. 6.8.1 Brushless DC and AC motor drive

Advantages

1. The characteristics of dc motors are obtained but there are no limitations of dc motors.
2. These drives can operate in explosive environments since there are no brush or commutator contacts.
3. Both AC and DC supply can be used.

Applications

1. Brushless dc motors are used in servo drives.
2. Brushless ac motors are used in high power compression, blowers, fans, converyers, steel rollingmills, large, ship steering and cement plants.
3. Starting of large synchronous motors in gas turbine and pump storage power plants.

Review Questions

1. *Explain the current fed AC drives and state its advantages.*
2. *What are the advantages of brushless ac and dc motor drives ? Also state its advantages.*
3. *Explain the brushless ac and dc drives with the help of block diagram.*

6.9 Variable Voltage Variable Frequency *(v/f)* Control of 3 ϕ Induction Motors

SPPU : May-15,16,19, Dec.-16

6.9.1 Principle of Control

The torque-speed equation of squirrel cage motor can be written as,

$$T = \frac{3P}{2\pi}\left(\frac{v_s}{f_s}\right)^2 \cdot \frac{f_r R_r}{[(s R_s + R_r')^2 + s^2 (X_s + X_r')^2]}$$

i.e.

$$T \propto \left(\frac{v_s}{f_s}\right)^2$$

Above equations show that the torque is proportional to voltage to frequency ratio of the stator supply. It shows that maximum available torque can be maintained constant by keeping v_s/f_s ratio constant. The stator flux depends upon v_s/f_s ratio. As long as v_s/f_s ratio remains constant, the stator flux remains constant. And due to constant flux, torque remains constant. Since this method ensures constant flux throughout the speed range, there is no chance of core saturation. Hence other effects such as heating of windings and circulating currents are minimized.

6.9.2 How Speed is Controlled ?

We know that speed depends upon frequecy i.e. $N_s = \frac{120 f_s}{p}$. This means if stator frequency is changed, synchronous speed of the motor also changes. Slip is given as,

$$s = \frac{N_s - N}{N_s} = 1 - \frac{N}{N_s}$$

$$\therefore \quad N = (1-s) N_s = \frac{(1-s)\,120 f_s}{p}$$

Above equation shows that as long as slip of the motor is constant,

$$N \propto f_s$$

Thus speed of the motor is proportional to frequency. Therefore by increasing or decreasing the frequency, speed of the motor can be varied.

6.9.3 Significance of *v/f* Ratio

The stator voltage to frequency ratio determines the flux. To avoid saturation or heating of the motor, the air gap flux must be maintained constant. The constant air gap flux ensures constant torque operation at any speed. Therefore *v/f* ratio must be maintained constant to maintain constant flux. For example, if '*f*' is reduced to reduce the speed, then '*v*' should also be reduced such that new *v/f* ratio remains constant.

This means increase or decrease in frequency also increases or decreases voltage proportionately. Therefore *v/f* ratio remains constant.

6.9.4 Speed Torque Characteristics

Fig. 6.9.1 shows the speed-torque characteristics of induction motor for various frequencies.

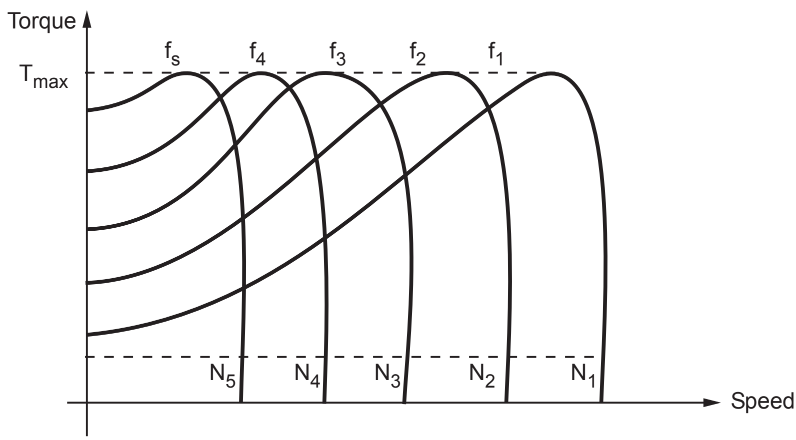


Fig. 6.9.1 Speed-torque characteristics for constant v/f control

In Fig. 6.9.1 $f_1 > f_2 > f_3 > f_4 > f_5$ and the corresponding speeds $N_1 > N_2 > N_3 > N_4 > N_5$. Thus by varing the frequency speed of the motor can be varied. In the figure observe that the maximum torque (T_{max}) available in each frequency characteristic is the same. Thus motor can be operated at its rated torque over the wide range of speed with this method.

6.9.5 Controllers-for-*v/f* Method

Fig. 6.9.2 shows various schemes which can be used for *v/f* control of the induction motor.

In the scheme shown in Fig. 6.9.2 (a) , the 3 ϕ converter obtains variable DC voltage and frequency is varied by an inverter. In the scheme shown in Fig. 6.9.2 (b), the diode rectifier gives fixed DC voltage. The chopper converts fixed DC to variable DC voltage. Then the 3 ϕ inverter obtains variable frequency AC output voltage.

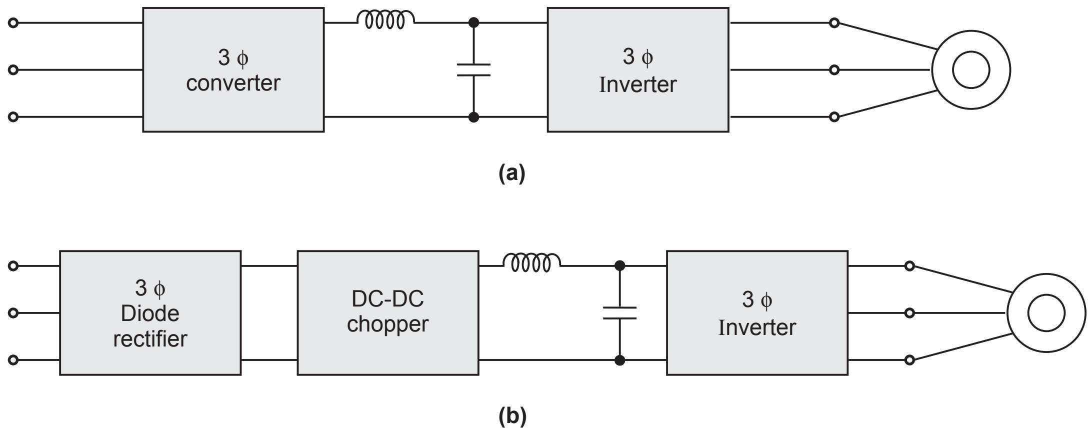


Fig. 6.9.2 Schemes for v/f control of induction motor

6.9.6 Advantages and Disadvantages of *v/f* Scheme

Advantages

i) *v/f* scheme ensures constant torque operation over wide speed range.

ii) The control is constant, precise and speed range is wide.

Disadvantages

i) Starting and breakdown torques are reduced considerably at low frequencies.

ii) At low frequencies motor gets saturated and magnetizing current is very large.

Review Questions

1. *What are drives ? Explain the working of variable frequency three phase induction motor drive.* **SPPU : May-19, Marks 8**
2. *Explain voltage and frequency control method for 3-φ induction motor drive in detail.* **SPPU : May-15, Marks 8**
3. *What are AC drives ? Explain with block diagram, speed control technique of 3 φ Inductor motor by using* $\frac{V}{F}$ *method.* **May-16, Dec.-16, Marks 8**

6.10 Uninterruptible Power Supply (UPS)

SPPU : Dec.-09,11,13,15,16,19, May-10,11,15,16,17,18,19

- An UPS is used to provide the power when mains is not available. In the present days of load shading, UPS is playing major role. UPS is being used along with computers.

- There are three types of UPS as follows :
  i) Online UPS ii) Offline UPS
  iii) Line interactive UPS
  The block diagrams and working of these UPS is discussed next.

6.10.1 Online UPS

- The online UPS is also called inverter preferred UPS. Fig. 6.10.1 shows the block diagram of online UPS.

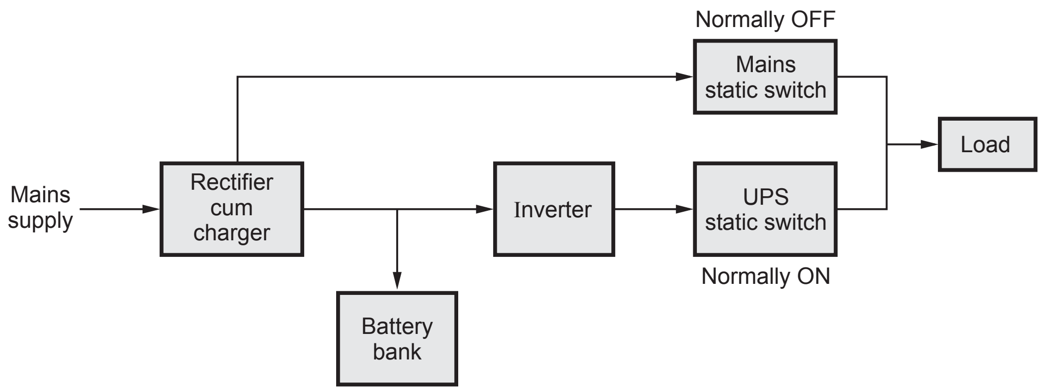
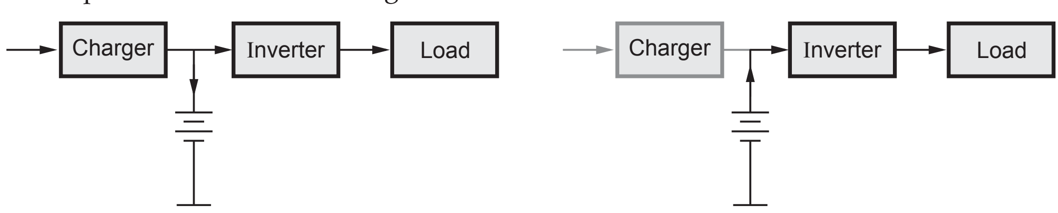


Fig. 6.10.1 Block diagram of online UPS system

- When the main supply is present, the rectifier/charger provides power to an inverter as well as battery (See Fig. 6.10.2 (a)). The battery is charged. The inverter is on and feeds power to the load through UPS static switch.



(a) When mains is present **(b) When mains is absent**

Fig. 6.10.2 Power flow in online UPS

- The UPS static switch is always on and connects load to inverter output.
- The mains static switch is always off. But when the UPS fails, then load is connected directly to the mains directly through mains static switch.
- When the mains supply is not available, then battery bank supplies power to an inverter (See Fig. 6.10.2 (b)). Thus an inverter is always on and it takes power from rectifier or battery.
- Fig. 6.10.2 shows the power flow when mains is present and mains is absent.

6.10.2 Offline UPS

- The offline UPS is also called line preferred UPS. Fig. 6.10.3 shows the block diagram of an offline UPS. Observe that this diagram appears similar to that of online UPS, but it is functionally different.

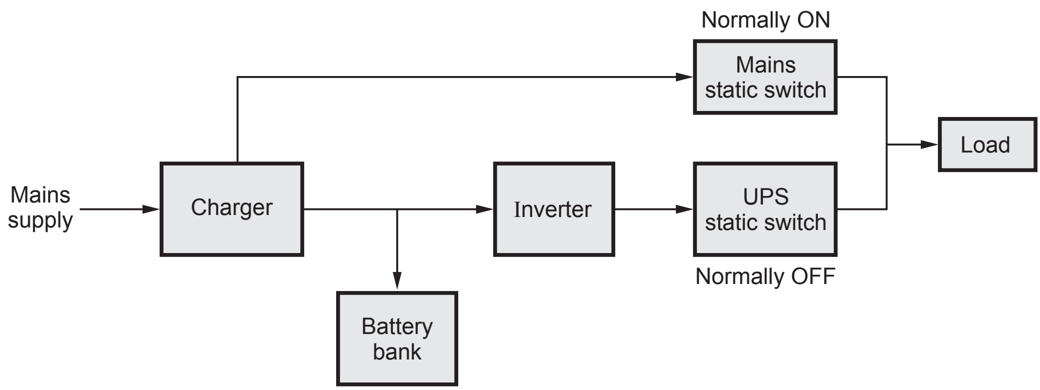
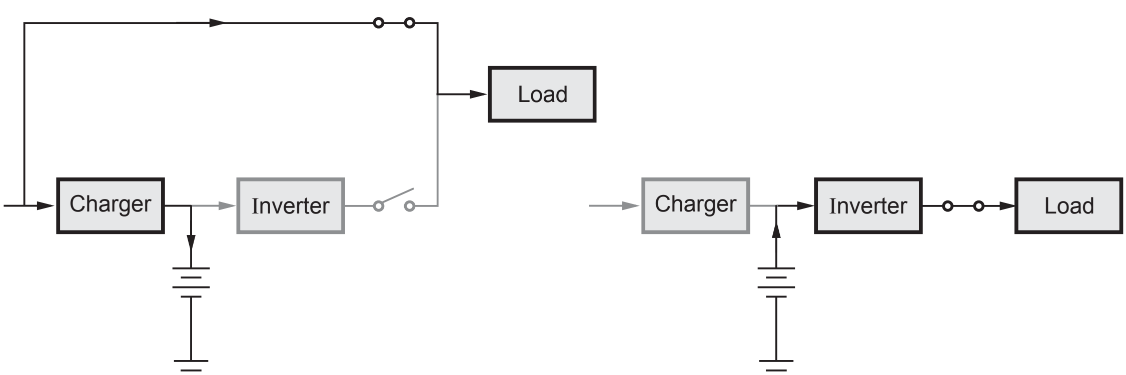


Fig. 6.10.3 Block diagram of offline UPS

- When mains supply is present, then charger charges the battery. Inverter is off and UPS static switch is off. The load is connected to mains through mains static switch. The power flow is shown in Fig. 6.10.4 (a).



(a) When mains is present **(b) When mains is absent**

Fig. 6.10.4 Power flow in offline UPS

- When mains supply is not available, then inverter is turned on.
- Inverter takes power from the battery. The load is connected to inverter output through UPS static switch. The power flow diagram is shown in Fig. 6.10.4 (b).
- The mains static switch is always on and keeps load connected to mains. The mains static switch is turned off when mains is not available.
- The charger feeds power only to the battery. Hence its power handling capacity is reduced.

6.10.3 Line Interactive UPS

- Fig. 6.10.5 shows the block diagram of line interactive UPS system.

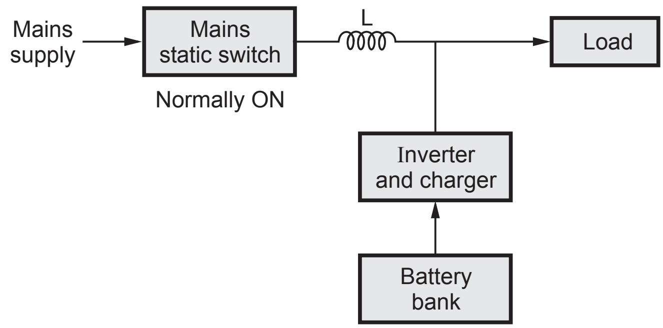
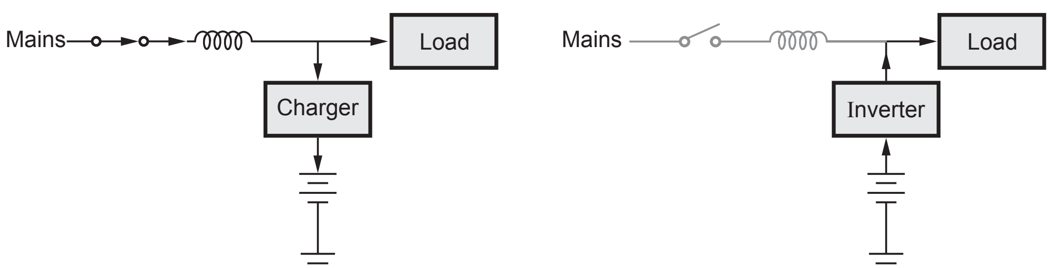


Fig. 6.10.5 Block diagram of line interactive UPS

- When the mains supply is present, the static switch is 'on'. The static switch connects load to mains supply through inductor L. The batteries are charged through the charger block. Fig. 6.10.6 (a) shows the power flow diagram.



(a) When mains is present **(b) When mains is absent**

Fig. 6.10.6 Power flow in line interactive UPS

- When mains is absent, the mains static switch is open. The inverter then turns on and supplies power to the load.
- The charger/inverter block operates as charger when mains is available and as an inverter when mains is not available.

6.10.4 Selection of the Battery and AH Rating

- While designing UPS system, slection of the battery is critical part. The battery has to provide estimated backup and it should be charged properly.
- **AH rating :** AH rating of the battery tells about how much amount of current it can supply for one hour. For example 80 AH means the battery will supply 80 A for 1 hour.

Efficiency of the battery

i) AH efficiency : An ampere-hour efficiency is defined as the ratio of AH taken from the battery while discharging to AH given to the battery while charging i.e.

$$\text{AH efficiency} = \frac{\text{AH (discharging)}}{\text{AH (charging)}} \quad \ldots(6.10.1)$$

AH efficiency varies from 90 to 95 %.

ii) WH efficiency : WH efficiency is the ratio of energy obtained from battery while discharging to energy given to the battery while charging i.e.,

$$\text{WH efficiency} = \frac{\text{Energy (discharging)}}{\text{Energy (charging)}} \quad \ldots(6.10.2)$$

$$= \frac{\text{AH (discharging)} \times \text{Average voltge (discharging)}}{\text{AH (charging)} \times \text{Average voltage (charging)}} \quad \ldots(6.10.3)$$

$$= \text{AH efficiency} \times \frac{\text{Average voltage on discharging}}{\text{Average voltage on charging}} \quad \ldots(6.10.4)$$

WH efficiency varies from 70 to 80 %.

Selection of the battery

The capacity of the battery is given as,

$$\text{Battery kW} = \frac{\text{Load kVA} \times \text{Power factor}}{\text{Inverter efficiency}} \quad \ldots(6.10.5)$$

Examples for Understanding

Example 6.10.1 *An online UPS is driving 800 W, 0.8 lagging PF load, an inverter efficiency is 80 % and dc link voltage and battery voltage is 48 V dc. Assuming batteries are ideal,*

Find i) VA rating of an inverter ii) Wattage or peak power requirement of rectifier.

iii) AH capacity of batteries required for backup time of 30 minutes.

Solution : Given data

$$P_{o(UPS)} = 800 \text{ W}, \quad \text{PF} = 0.8, \ \eta_{(inverter)} = 0.8, \quad V_{dc} = 96 \text{ V}$$

i) To obtain VA rating of an inverter

- PF of inverter is given as,

$$\text{PF} = \frac{\text{Active power output}}{\text{Total rms power (kVA)}}$$

$$\therefore \text{Total rms power (kVA)} = \frac{\text{Active power output}}{\text{PF}}$$

$$= \frac{800}{0.8} \quad \text{Here active power is } P_{o(UPS)} = 1000 \text{ VA}$$

ii) To obtain wattage of rectifier

- Assuming that there is separate battery charger and rectifier supplies power only to an inverter, then

$$\text{Rectifier wattage} = \frac{\text{Active power supplied by inverter}}{\text{Inverter efficiency}}$$

$$= \frac{P_{o(UPS)}}{\eta_{(\text{inverters})}} = \frac{800}{0.8} = 1000 \text{ W}$$

iii) To obtain AH capacity

- Here rectifier wattage is 1000 W. When mains fails, the battery must supply 1000 W to an inverter.

$$\text{Battery wattage} = \text{Battery voltage} \times \text{Battery current} = V_{dc} \times I_{dc}$$

$$1000 = 48 \times I_{dc}$$

$$\therefore \quad I_{dc} = 20.83$$

- Since the battery is ideal, the AH rating for 30 minutes $\left(\frac{1}{2}\text{Hr}\right)$ backup will be,

$$\text{AH rating} = I_{dc} \times \text{Backup(Hrs)} = 20.83 \times \frac{1}{2} = 10.41 \text{ AH}$$

$$\approx 11 \text{ AH}$$

Example 6.10.2 *A 1 kVA, 230 V, 50 Hz UPS feeds a 0.8 power factor load and operates from 96 V DC bus, the inverter efficiency being 90 %. Calculate backup time available if battery has the capacity of 100 AH. Also calculate the peak output power of input rectifier cum battery charger if batteries must be restored with six hours of mains supply becoming available. Assume the following :*

i) Battery float voltage is 110 V

ii) Battery voltage at start of discharge is 100 V.

iii) Battery voltage at end of discharge is 88 V.

iv) Capacity derating factor of battery upto 10 hour discharge is 0.5.

v) Battery voltage during charging is 106 V. vi) Battery charging efficiency is 75 %.

Solution : Given : UPS ratings : 1 kVA 230 V, 50 Hz

$$\text{Load PF} = 0.8, \quad V_{dc} = 96 \text{ V}$$

$$\eta_{(inverter)} = 0.9, \text{ AH rating} = 100$$

$$\text{Charging time} = 6 \text{ Hrs.}$$

i) To obtain backup time

$$\text{Battery kW} = \frac{\text{Load kVA} \times \text{PF}}{\text{Inverter efficiency}} = \frac{1\,\text{kVA} \times 0.8}{0.9} = 0.8889 \text{ kW}$$

Battery voltage at the end of discharge is 88 V. Hence the discharge current will be maximum at the end of discharge i.e.

$$\text{Battery kW} = \text{Battery voltage} \times I_{dc}$$

$$0.8889 \times 10^3 = 88 \times I_{dc}$$

$$\therefore \quad I_{dc} = 10.10 \text{ A}$$

The capacity derating factor is given as 0.5. This means even though the capacity of the battery is 100 AH, it should be discharged with 50 AH capacity. Therefore backup time will be,

$$\text{Backup time} = \frac{\text{AH capacity (after derating)}}{I_{dc}} = \frac{50}{10.10} = 5 \text{ Hrs.}$$

To obtain rectifier cum charger output power

$$\text{Battery charging efficiency} = \frac{\text{AH output}}{\text{AH input}}$$

$$0.75 = \frac{100 \text{ AH}}{\text{AH input}}$$

$$\therefore \quad \text{All input} = 133.33 \text{ AH.}$$

$$\text{Charging current} = \frac{\text{AH input}}{\text{Charging time}} = \frac{133.33}{6} = 22.22 \text{ A}$$

The rectifier cum charger has to supply current to the inverter as well as battery in case of on line UPS. The input kW to the inverter is 0.8889 kW. The DC voltage during charging is 106 V.

Therefore the input current to inverter is, $I_{dc} = \frac{0.8889 \text{ kW}}{106 \text{ V}} = 8.3858$ A. Therefore the total current that the rectifier cum charger that must supply is,

$$\text{Rectifier current} = \text{Battery charging current} + \text{Inverter input current}$$

$$= 22.22 \text{ A} + 8.3858 \text{ A} = 30.6 \text{ A}$$

$$\therefore \text{Peak output power of rectifier} = \text{Rectifier voltage} \times \text{Rectifier current}$$

$$= 106 \times 30.6 = 3244.22 \text{ watts}$$

6.10.5 Comparison between Online and Offline UPS

Advantages of online UPS

i) It provides isolation between main supply and load.

ii) Since inverter is always on, the quality of load voltage is free from distortion.

iii) All the disturbances of supply such as blackout, brownout, spikes etc are absent in the output.

iv) Voltage regulation is better.

v) Transfer time is practically zero since inverter is always on.

Disadvantages of online UPS

i) Overall efficiency of UPS is reduced since inverter is always on.

ii) The wattage of the rectifier is increased since it has to supply power to inverter as well as charge battery.

iii) Online UPS is costlier than other UPS systems.

Applications of online UPS

i) Induction motor drives and similar other motor control applications.

ii) Intensive care units, medical equipments.

Advantages of offline UPS

i) Offline UPS has high efficiencies, since charger is not continuously on.

ii) The power handling capacity of charger is reduced.

iii) Offline UPS are not very costly.

iv) Internal control is simpler in offline UPS.

Disadvantages of offline UPS

i) Since offline UPS provides mains supply when it is present, the output contains voltage spikes, brownouts, blackouts.

ii) There is finite transfer time from mains to inverter when mains supply fails.

iii) Output of offfline UPS is not perfectly reliable.

Applications of offline UPS

i) Computers, printers, scanners etc use offline UPS.

ii) Emergency power supplies, EPABX.

Sr. No.	Parameter	Online UPS	Offline UPS
1.	Inverter	Always on	Turned on when mains fails
2.	Rectifier cum charger	Supplies power to inverter as well as charges battery	Charges only battery
3.	Output waveform	sine wave	Quasi square wave
4.	Harmonic distortion	Low	High
5.	Efficiency	Low	High
6.	Load	Isolated from supply	Not isolated from supply
7.	Cost	High	Low

Table 6.10.1 Comparison between online and offline UPS

Review Questions

1. *Explain the operation of offline UPS with the help of block diagram.*
SPPU : Dec.-09, Marks 8, May-11, Marks 4
2. *Compare offline and online UPS.* **SPPU : May-10,17 Marks 4**
3. *How battery is selected for the UPS system ?*
4. *State the advantages and disadvantages of online UPS over offline UPS.*
5. *With the help of block diagram, explain the working of online UPS.*
SPPU : Dec.-11, Marks 4; Dec.-13, May-17, Marks 6
6. *Explain On-line UPS with neat block-diagram. State its specifications and applications.*
SPPU : May-17, Marks 6
7. *Compare ON-line and OFF-line UPS. Justify why ON-line UPS is better.*
SPPU : Dec.-15,May-17, Marks 8
8. *What are the various types of UPS systems ? With the help of block diagram, explain function of each block of on line UPS system ?* **SPPU : May-18, Marks 8**
9. *Explain working of on line UPS. State four important commercial specifications.*
SPPU : May-19, Marks 10
10. *Explain with block schematic working of On-line and off-line UPS.*
SPPU : May-15, Marks 8
11. *Explain with block schematic working of off-line UPS. State its specifications and applications.*
SPPU : Dec.-15,16, Marks 8
12. *What is need of uninterruptable power supplies in industries ? Explain with block diagram working of On-line UPS state its specifications.* **SPPU : May-16, Marks 8**
13. *What is online ? Offline ups ? Explain block diagram and applications ?*
SPPU : Dec.-19, Marks 8

6.11 Selection Criteria and Performance Parameters for Batteries in Electric Vehicles (EVs)

- Batteries are the source of energy in electric vehicles. Hence their selection, performance evaluation and charging are important aspects.

6.11.1 Selection Criteria

Following are the selection criteria for batteries in electric vehicles and other power systems :

i) Power requirement of the electric vehicle.

ii) Charging time and charging method.

iii) Operating environment such as temperature, depth of discharge and operating current.

iv) Characteristics of the electric vehicle.

v) Energy density (Amount of energy stored per unit volume or weight).

vi) Life, cost and safety.

vii) Manufacturing ease and maintenance.

viii) Availability of charging stations.

ix) Trade off between energy, power, cost, life and safety.

x) Commercial availability.

6.11.2 Performance Parameters for Batteries

i) Energy measured in watt hours per kg.

ii) Energy density in watt hours per litre.

iii) Rate of discharge or c - rate, which is the portion of battery's total charge capacity.

iv) Specific power and power density.

v) Depth of discharge and pulse duration.

vi) Cost, life, temperature and safety.

vii) Rate of self discharge.

viii) Reactivity between electrolyte and electrode.

ix) Battery operating voltage is decided by electrode materials. Fig. 6.11.1 shows the different types of batteries and their voltages with respect to percentage of capacity discharge. (See Fig. 6.11.1 on next page.)

x) Type and mode of discharge.

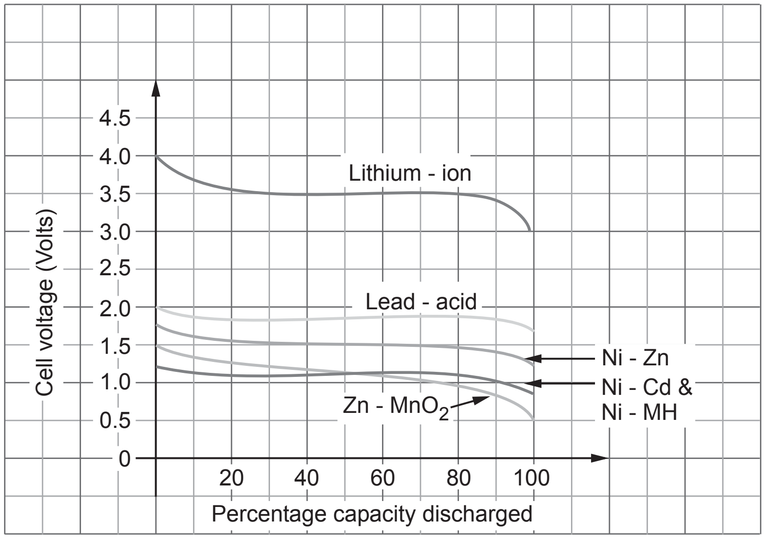


Fig. 6.11.1 Various types of batteries and their voltages with discharged

6.12 Battery Charging Models and Modes for EV

6.12.1 Battery Charging Models

- **Inductive charging :** These are wireless charging systems (WCS). This charging can be used when the car is parked or when it is in motion. Inductive charging provides reliability, durability and user friendliness. But it suffers due to limited power transfer, short range, reduced efficiency cost and size.
- **Unidirectional or bidirectional power flow :** The battery charger can allow unidirectional or bidirectional power flow. The bidirectional power flow can send power from vehicle to grid. In case of system failure, vehicles can supply energy to grid.
- **Electrochemical Li-ion battery model :** It calculates amount of battery aging and decides charging current and voltage. This charging model is complex to implement.

6.12.2 Battery Charging Modes

- **Constant current constant voltage (CC/CV) charging :** This is the most popular charging method used to recharge Li-ion batteries. The battery is charged initially with constant current (CC) and then finally with constant voltage (CV).
- Full charge of the battery is reached when charging current reduces 3 to 5 % of the rated current. Trickle charge or float charge is not applied for Li-ion battery. Instead, topping charge is applied when battery voltage drops below set value.

- **Five step charging method :** The constant current (CC) charging time is divided into five steps. In each stage, the charging current is set to specific threshold value. The voltage of the battery increases in each stage and the stage is changed when battery voltage reaches pre-set voltage.
- **Pulse charging method :** The charging current is injected in the battery in the form of pulses. In the absence of the pulse, ions diffuse and neutralize in the battery. The charging rate can be controlled by varying the width of the pulses.

6.13 Architecture of Electric Vehicles Battery Charger

- Fig. 6.13.1 shows the classification of electric vehicles battery charging architectures. These architectures are classified depending upon factors such as structure, power rating, charging times, type of connection, location, etc.

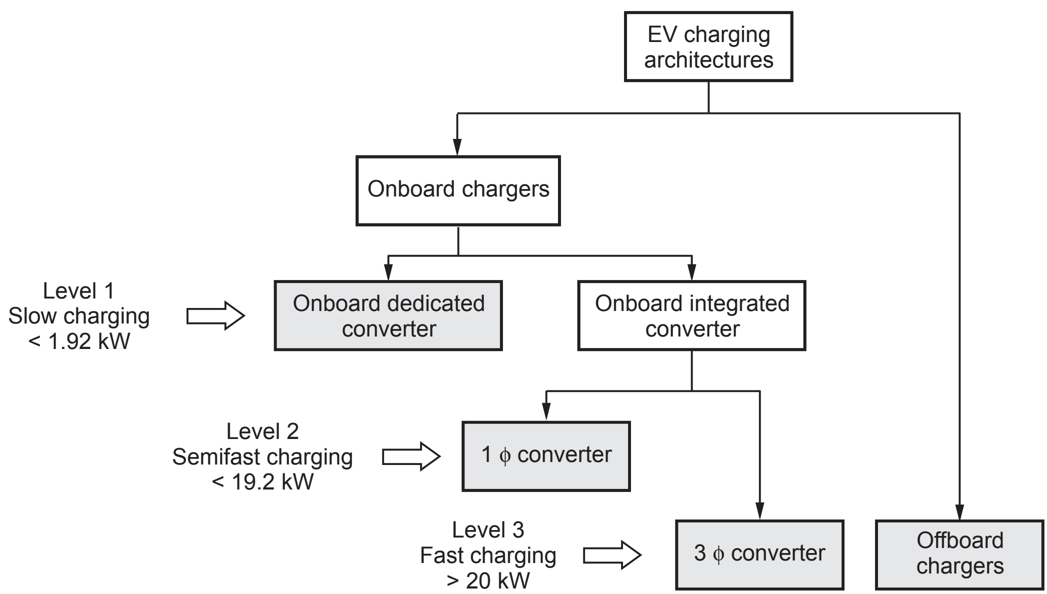


Fig. 6.13.1 EV charging architectures

- The three levels in above architecture are capable of supplying different capacities of power. Level 1 can supply power upto 1.92 kW, Lever 2 can supply power up to 19.2 kW and Level 3 can supply powers more than 20 kW.
- Level 1 provides flexible and simple way of recharging battery. It uses a dedicated power converter for battery charging. It uses full bridge converter with interleaved boost PFC. It is discussed in detail in next section.
- Level 2 configuration provide higher power and fast charging but the charger is larger and bulkier. It was 1ϕ converter.

- Level 3 provides fastest charging with onboard integrated converter such as 3ϕ converter or offboard chargers. The offboard chargers consists of two energy conversion stages. First stage is AC to DC converter, which performs grid integration and generates regulated DC voltage. The second stage is DC to DC converter that performs current shaping to charge batteries.
- **Onboard chargers (OBC) :** These chargers are implemented inside the vehicle. These chargers have small size, small weight and limited power for charging. Hence charging is slow. These are used with level 1 and level 2 and have unidirectional power flow.
- **Onboard chargers have two stages :** The front end AC to DC and back end is DC to DC converter. The front end rectifier contains boost power factor correction (PFC) converter to achieve good power factor.
- The onboard chargers can be two stage (AC to DC converter followed by DC to DC converter), single stage (AC to DC rectifier combined with DC to DC converter) integrated (reuse of drive train components) or multifunctional (some components of charger perform other tasks also).
- **Offboard battery charger :** These chargers are usually installed outside of the vehicle. Normally level 3 chargers are offboard type. It consists of grid facing AC to DC converter followed by DC to DC converter.
- Offboard battery chargers allow bidirectional power flow, low harmonic input currents and power factor correction.

6.14 PFC Stage Circuit Topologies

- The power factor correction (PFC) in battery charging circuits can be achieved through various types (topologies) of circuits.
  i) **Full bridge converter with interleaved PFC :** In this topology, AC to DC converter is followed by boost converter. It provides unity power factor correction. Then DC to DC converter is used to provide charging current to the battery.

  ii) **Interleaved bridgeless boost PFC :** The AC grid is integrated with bridgeless boost converter. It regulates output voltage and improves input power factor by a feedback system of outer voltage loop and inner current loop. The DC link capacitor voltage is then converted to appropriate charging current by phase shifted full bridge DC to DC converter.

  iii) **Single phase totem pole PFC :** It is conventional boost PFC, in which half portion of the diode bridge is replaced with active switches such as IGBTs or MOSFETs. Hence it is called totem pole PFC. It provides improved efficiency. The totem pole switches are driven synchronously with complementary PWM to provide PFC.

iv) **Three phase two level PFC :** There is six switch boost type rectifier along with bulky inductor filter on each line of AC grid. The six switches must block high voltage of the DC link.

v) **Three phase vienna PFC :** It uses vienna rectifier power topology. The vienna rectifier is used in high power, three phase power factor correction applications. The vienna rectifier operates in continuous conduction mode, it has multilevel switching ability and reduced voltage stress on power devices.

6.15 Full Bridge Converter with Interleaved Boost PFC

- Fig. 6.15.1 shows the level 1 on board charger which consists of full bridge rectifier, DC boost and DC to DC converter. (See Fig. 6.15.1 on next page.)
- This configuration consists of DC boost circuit between full bridge rectifier and DC to DC converter. Hence it is called interleaved boost.
- This charger maintains power factor close to unity, hence it is called power factor correction (PFC) charger.
- The full bridge converter is connected to AC grid. It generates DC intermediate voltage. It generates supply current with least distortion at unity power factor.
- The switch T_b along with boost inductance L_b and diode D_b forms a DC to DC boost converter. The capacitor C_{dc} maintains constant boosted DC voltage at the input of DC to DC converter.
- The DC to DC converter provides electric isolation and generates filtered DC battery charging current. L_o and C_o are the LC filter components at output.
- This is a two stage battery charger that offers interleaved boost and power factor correction (PFC).

6.16 Case Studies

6.16.1 Power Electronics in Electric Vehicles

- Fig. 6.16.1 shows the block diagram of electric vehicle along with different power electronic converters. (See Fig. 6.16.1 on page 6.40)
- Below system has onboard charger that contains 1ϕ AC - DC converter and DC - DC converter with interleaving boost PFC. It is shown by shaded region on the right side. The AC supply can be taken from home or public.
- The DC link drives DC - AC converter (inverter) that further drives AC motor of the vehicle. The DC link also drives SMPS or DC - DC converter, that supplies power to various electronic loads on the vehicle.

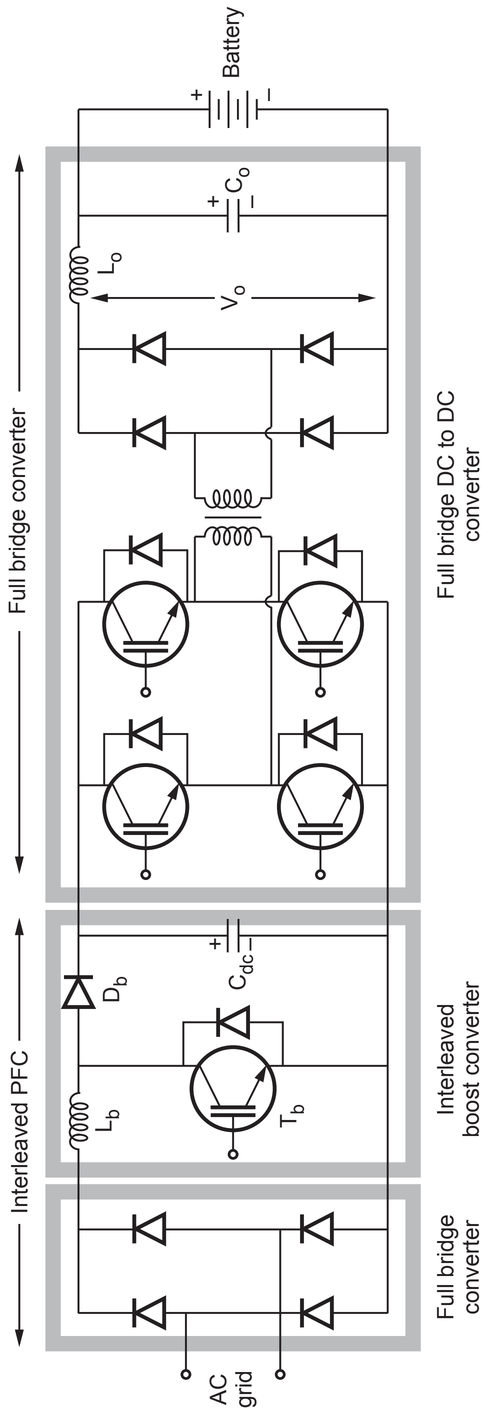


Fig. 6.15.1 Full bridge converter with interleaved boost PFC

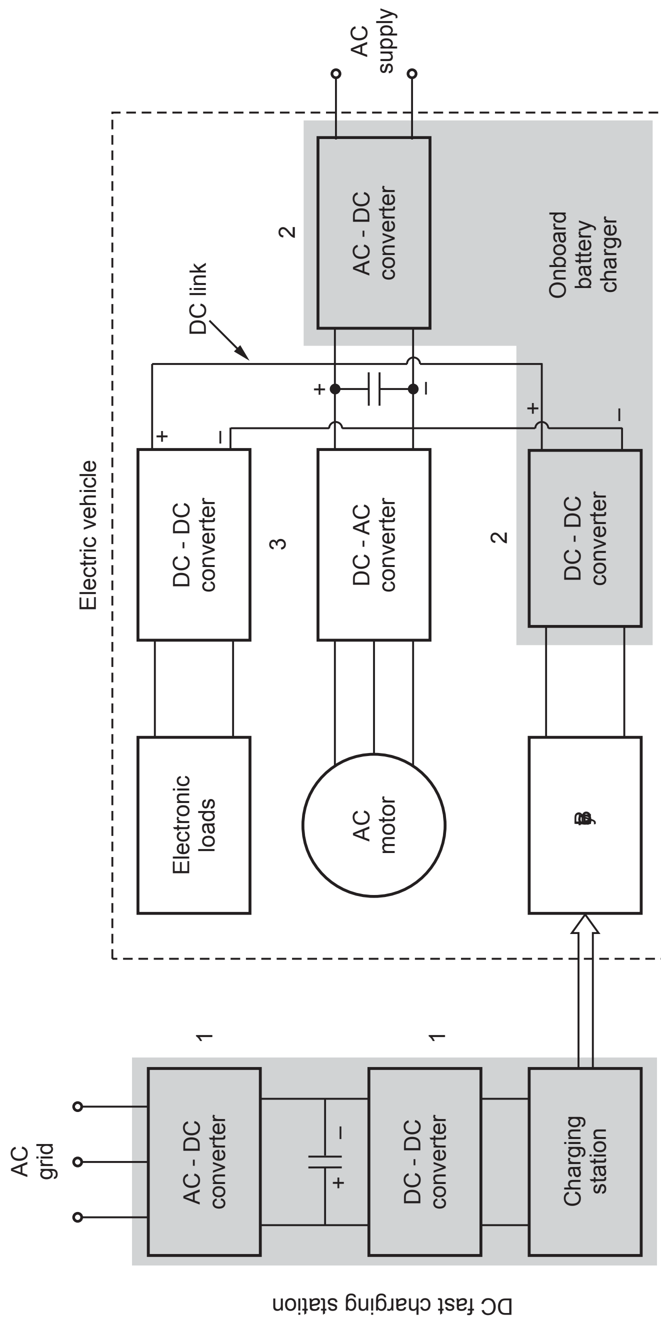


Fig. 6.16.1 Block diagram of electric vehicle

- The DC - DC converter - 2 is bidirectional. It charges the battery from onboard battery charger as well as supplies power to the DC link.

- The battery can also be charged from the charging station. It is shown in the shaded region on left side. The AC - DC converter connects to AC grid and provides DC voltage with boost converter to DC - DC converter. The output of DC - DC converter is used to charge the battery fast.
- Following are important specifications of Tata Motors Nexon EV car :

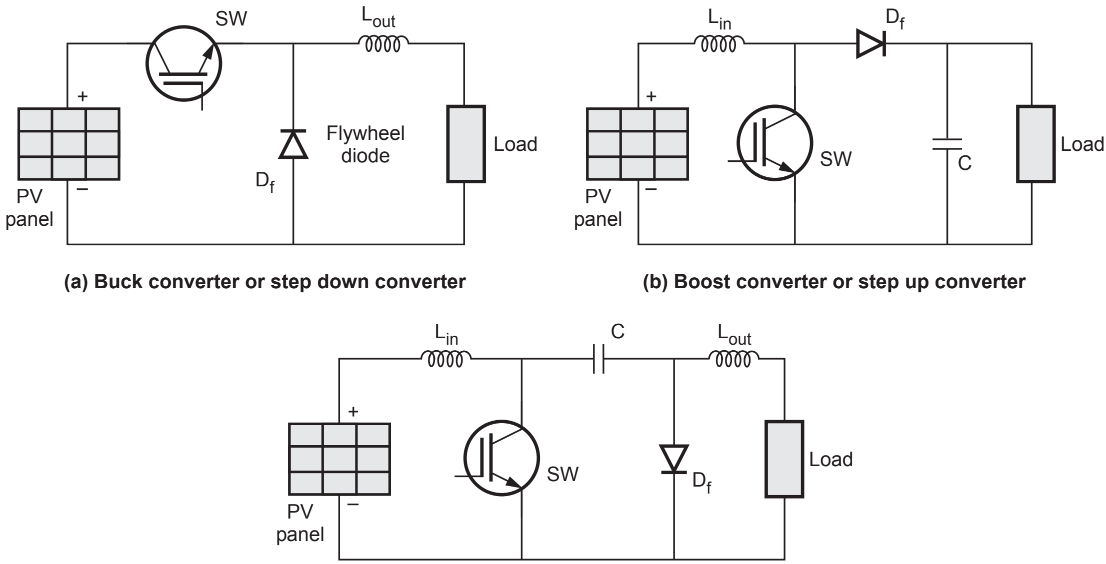
Battery rating	30.2 kWh
Nominal voltage	320 V
Temperature range	– 5 to 45 °C
Electric motor	Permanent magnet synchronous motor
Power	129 PS
Torque	245 N-m
Range on single charge	300+ km
Charging modes	Fast and regular
Onboard charger	3.3 kW AC
Fast charging time	60 min
Regular charging time	8 Hour

6.16.2 Power Electronics in Photovoltaic Solar System

- The photovoltaic cell or solar cell converters light energy into electricity by means of photovoltaic effect.
- A solar cell or PV cell is the building block of photovoltaic (PV) system. Number of PV cells are joined together to form a photovoltaic (PV) panel. The PV panel is also called solar panel. It provides more power.

PV panel to charge battery

A typical D.C. - D.C. converter use an electronic switch, inductor which stores energy, a flywheel diode. Such type of converters reduce charge current so that the battery voltage is maintained at a specified value continuously. There are three main types of converters used namely **Step down or Buck converter** (as shown in the Fig 6.16.2 (a), **Step up or Boost converter** (as shown in the Fig. 6.16.2 (b)) and the **Step down/up or Buck-Boost converter.**



(a) Buck converter or step down converter

(b) Boost converter or step up converter

(c) Boost-buck converter or step up-down converter

Fig. 6.16.2 Various types of DC to DC converter type charge regulators

6.17 Multiple Choice Questions

Q.1 AC voltage controllers convert ________.

a fixed ac to fixed dc

b variable ac to variable dc

c fixed ac to variable ac

d variable ac to fixed ac

Q.2 The AC voltage controllers are used in ______ applications.

a power generation

b electric heating

c conveyor belt motion

d power transmission

Q.3 A single-phase half wave voltage controller consists of ________.

a one SCR is parallel with one diode

b one SCR is anti parallel with one diode

c two SCRs in parallel

d two SCRs in anti parallel

Q.4 Single phase half wave AC voltage controller has V_s = 230 V and R = 20 Ω. Find the value of the average output voltage at the R load for a firing angle of 45°.

a 224 V

b – 15.17 V

c 15.17 V

d – 224 V

Q.5 A single phase voltage controller has input of 230 V and a load of 15 Ω resistive. For 6 cycles on and 4 cycles off, determine the rms output voltage.

a 189 V
b 260 V
c 156 V
d 178 V

Q.6 _________ is used for critical loads where temporary power failure can cause a great deal of inconvenience.

a SMPS
b UPS
c MPS
d RCCB

Q.7 Static UPS requires __________

a only rectifier
b only inverter
c both inverter and rectifier
d none of the mentioned

Q.8 Usually __________ batteries are used in the UPS systems.

a NC
b Li-On
c Lead acid
d All of the mentioned

Q.9 Following is true for electronic ballast

a Electronic ballast is used in series with fluorescent lamp
b Electronic ballast provides high frequency ac
c Electronic ballast consists of EMI filter, rectifier and inverter
d All of these

Q.10 In constant torque region of the separately excited DC motor, _____________.

a armature voltage can be increased
b speed can change
c field current remains constant
d all of these

Q.11 In v/f control of induction motor _____________

a v/f ratio remains constant
b speed of motor is proportional to frequency
c flux remains constant
d all of these

Q.12 Following type of battery is used in electric vehicles

a Lead-acid
b Nickel-cadmium
c Lithium-ion
d Nickel-zinc

Q.13 In electric vehicles which of the following method provides fast charging

a Onboard charging
b Offboard charging
c Full bridge converter with PFC
d All of these

Q.14 Full bridge converter with interleaved boost PFC provides _____________.

a power factor correction
b fast battery charging
c two stage charging with interleave boost
d all of these

Explanations :

Q.1 Explanation : Voltage controllers convert the fixed ac voltage to variable ac by changing the values of the firing angle.

Q.6 Explanation : Uninterruptible Power Supply is used where loads where temporary power failure can cause a great deal of inconvenience.

Q.7 Explanation : Rectifier to converter the dc from the battery to ac. Inverter to charge the battery from mains.

Q.8 Explanation : Lead acid batteries are cheaper and have certain advantages over the other types. NC batteries would however be the best, but are three to four times more expensive than lead acid.

Answer Keys for Multiple Choice Questions :

Q.1	c	**Q.2**	b	**Q.3**	b	**Q.4**	b	**Q.5**	d
Q.6	b	**Q.7**	c	**Q.8**	c	**Q.9**	d	**Q.10**	d
Q.11	d	**Q.12**	c	**Q.13**	b	**Q.14**	d		

❑❑❑

April - 2015 Power Electronics T.E. (E&Tc) Semester - II [In Sem. Exam]	SPPU Solved Paper

Time : 1 Hour] **[Maximum Marks : 30**

Note :

i) Answer Q.1 or Q.2, Q.3 or Q.4, Q.5 or Q.6.

ii) Neat diagrams must be drawn wherever necessary.

iii) Figures to the right side indicate full marks.

iv) Use of nonprogrammable calculator is allowed.

v) Assume suitable data, if necessary.

Q.1 a) *Explain construction and steady state characteristics of SCR.*
(Refer section 1.1.1 and Fig. 1.2.1) **[6]**

b) *A UJT relaxation oscillator is designed to trigger a SCR, UJT has following data :* $\eta = 0.72$, $I_p = 0.6$ *mA*, $V_p = 18$ *V*, $V_v = 1$ *V*, $I_v = 2.5$ *mA*, $R_{BB} = 5$ *kΩ, leakage current = 4.2 mA. If triggering frequency is 2 kHz and C = 0.04 μf, calculate R,* R_1 *and* R_2. **[4]**

Ans. : Let $R_c = R, \; R_{B1} + R_{B2} = R_{BB}$

$$T = R_c \, C \ln\left(\frac{1}{1-\eta}\right)$$

Here $T = \frac{1}{f} = \frac{1}{2\times 10^3}$ since f = 2 kHz and putting other values,

$$\frac{1}{2\times 10^3} = R_c \times 0.04 \times 10^{-6} \ln\left[\frac{1}{1-0.72}\right]$$

$$R_c = 9.82 \text{ k}\Omega$$

The peak voltage is given as,

$$V_p = \eta V_{BB} + V_D \quad \text{putting values}$$

$$18 = 0.72 \, V_{BB} + 0.7 \quad \text{let } V_D = 0.7$$

$$\therefore \quad V_{BB} = 24.028 \text{ V}$$

The value of R_2 is given by as,

$$R_2 = \frac{0.7\times R_{BB}}{\eta V_{BB}} = \frac{0.7\,(5\times 10^3)}{0.72\times 24.028}$$

$$R_2 = 202.310\ \Omega$$

Value of R_1 can be calculated as,

$$V_{BB} = I_{leakage}\,(R_1 + R_2 + R_{B1} + R_{B2})$$

$$24.028 = 4.2\times 10^{-3}\,(R_1 + 202.310 + 5000)$$

$$\therefore \quad R_1 = 518.64\ \Omega$$

OR

Q.2 a) *Draw and explain synchronized UJT triggering circuit for SCR with waveforms.* **(Refer section 1.10.5)** **[6]**

b) *Compare power MOSFET with IGBT.* **(Refer section 1.6.7)** **[4]**

Q.3 a) *Draw and explain single phase fully controlled bridge converter for R-L load with various o/p voltage waveforms.*
(Refer section 2.3.2) **[6]**

b) *A single phase semi converter is operated from 230V, 50Hz AC supply. The load is resistive having resistance of 100 Ω. If the firing angle (α) is 60°, calculate*
i) Average output voltage ii) RMS output voltage **(Refer example 2.2.3)** **[4]**

OR

Q.4 a) *Draw and explain three phase fully controlled bridge converter for R load with o/p voltage waveforms.* **(Refer section 2.8)** **[7]**

b) *What is commutation ? Explain natural commutation with forced commutation for SCR.* **(Refer sections 1.3.3 and 2.1.2)** **[3]**

Q.5 a) *Draw and explain single phase full bridge inverter for R-L load with o/p voltage and current waveforms.*
(Refer section 3.3.2) **[5]**

b) *Single phase full bridge inverter is operated from 48V dc supply, it has a resistive load of R = 2.4 Ω. Find its rms o/p voltage at fundamental frequency.*
(Refer example 3.3.5) **[2]**

c) *Compare free wheeling diode and feedback diode ?* **[3]**

Ans. :

1)	Used for circulating load energy in load it selt.	Used for transfering load energy to surve.
2)	Used in controlled rectifiers.	Normally used in choppen and inverters.
3)	Improves power feature.	Improves power efficiency.

OR

Q.6 *Explain 180° mode in three phase inverters for balanced star R load with circuit diagram in detail.* **(Refer section 3.4.1)** **[10]**

May - 2015 **Power Electronics** **T.E. (E&Tc) Semester - II [End Sem. Exam]**	**SPPU** **Solved Paper**

Time : $2\frac{1}{2}$ Hours] **[Maximum Marks : 70]**

Note :

i) ***Answer Q.1 or Q.2, Q.3 or Q.4, Q.5 or Q.6 and Q.7 or Q.8.***

ii) ***Neat diagrams and waveforms must be drawn wherever necessary.***

iii) ***Figures to the right side indicate full marks.***

iv) ***Using of nonprogrammable calculator is allowed.***

v) ***Assume suitable data if necessary.***

Q.1 a) *Draw two transistor analogy of SCR and derive an expression for its anode current I_A?* **(Refer section 1.2.5)** **[7]**

b) *Draw and explain single phase fully controlled rectifier (full converter) for R-L load with various output voltage waveforms.* **(Refer section 2.3.2)** **[7]**

c) *Single phase full bridge inverter is operated from 48 V dc supply, it has a resistive load of R = 2.40 Ω. Find :*

i) rms output voltage at fundamental frequency (V_{o1}) **(Refer example 3.3.5)**

ii) rms output power **(Refer example 3.3.5)**

iii) rms output voltages at second and third harmonic (V_{o2} and V_{o3}) **[6]**

Ans. : iii) rms output voltages of second and third harmonic (V_{02} and V_{03}).

The rms value of n^{th} harmonic is given as,

$$V_{n(rms)} = V_{on} = \frac{0.9\ V_s}{n}$$

$$\therefore \quad V_{o2} = \frac{0.9\ V_s}{2} = \frac{0.9 \times 48}{2} = 21.6\ V$$

And, $$V_{o3} = \frac{0.9\ V_s}{3} = \frac{0.9 \times 48}{3} = 14.4\ V$$

OR

Q.2 a) *Draw construction diagram of n-channel enhancement type MOSFET and explain its steady state characteristics.* **(Refer sections 1.5.1 and 1.5.2)** **[7]**

b) *Draw and explain three phase half controlled bridge converter for R load with output voltage waveforms.* **(Refer section 2.7)** **[7]**

c) *Compare 120° mode with 180° mode in three phase inverter for balanced star R load.* **(Refer section 3.4.3)** **[6]**

Q.3 a) *Explain operation of step up chopper with circuit diagram and derive an $V_o = V_s$ expression for its output voltage : $V_o = \frac{V_s}{(1-D)}$ where D is duty cycle.*

(Refer section 4.3 and example 4.3.1) **[6]**

b) *A DC chopper with R-L load is operated from 220 V dc supply. The load parameters are R = 5 Ω , L = 7.5 mH and chopping frequency F_c = 1 KHz. If peak to peak load ripple current is maximum, calculate : i) Maximum instantaneous load current ii) Minimum instantaneous load current iii) Peak to peak load ripple current iv) Average load current* **[6]**

Ans. : Here peak to peak ripple current is given as maximum. This ripple current is maximum in step down chopper when duty cycle is 0.5. Hence δ = 0.5.

Refer example 4.2.9 for rest of the part.

c) *Explain various control strategies in DC chopper.* **(Refer section 4.1.1)** **[6]**

OR

Q.4 a) *Explain operation of four quadrant chopper with circuit diagram.*
(Refer section 4.4.5) **[6]**

b) *Explain with block schematic working of SMPS. What are its advantages over linear power supply.* **(Refer section 4.6)** **[6]**

c) *A single phase full wave ac voltage controller has a resistive load of R = 10 Ω and the input voltage is V_s = 120 V(rms), 50 Hz. The delay angles of thyristors T_1 and T_2 are equal : $\alpha_1 = \alpha_2 = \pi/2$. Determine i) The rms output voltage ii) The rms output current iii) The input PF* **[6]**

Ans. : Given data, $V_s = 120$, $V_m = 120\sqrt{2}$

Firing angle $\alpha = \alpha_1 = \alpha_2 = \pi/2$

Load resistance R = 10 Ω

i)To obtain rms output voltage $V_{o(rms)}$

RMS value of output is given by,

$$V_{o(rms)} = V_m \sqrt{\frac{\pi - \alpha + \frac{\sin 2\alpha}{2}}{2\pi}}$$

$$= 120\sqrt{2} \times \sqrt{\frac{\pi - \pi/2 + \frac{\sin 2\pi/2}{2}}{2\pi}}$$

$$V_{o(rms)} = \frac{120}{\sqrt{2}} = 84.85 \text{ V}$$

ii) RMS value of load current calculated as,

$$I_{o(rms)} = \frac{V_{o(rms)}}{R} = \frac{84.85}{10} = 8.485 \text{ A}$$

$$\text{Now active load power} = I_{o(rms)}^2 R = (8.485)^2 \times 10 = 719.95 \text{ W}$$

As supply current is same as output current RMS value of supply current will be,

$$I_{s(rms)} = I_{o(rms)} = 8.485 \text{ A}$$

$$\therefore \quad \text{Total rms input power} = V_{s(rms)} \times I_{s(rms)}$$

$$= 120 \times 8.485 = 1018.2 \text{ VA}$$

iii) Input power factor is given as,

$$PF = \frac{\text{Active load power}}{\text{Total rms input power}} = \frac{719.95}{1018.2} = 0.707$$

This is lagging power factor since load current lags behind supply voltage.

Q.5 a) *Explain with block schematic working of on-line and off-line UPS.*
(Refer sections 6.10.1 and 6.10.2) **[8]**

b) *The speed of a separately excited dc motor (armature) is controlled by a 1 - ϕ semi-converter. The field current is also controlled by a 1 - ϕ semi-converter and is set to its maximum possible value. The ac supply to both armature and field converters is single phase 208 V, 60 Hz. The armature resistance R_a = 0.25 Ω, field resistance R_f = 147 Ω. The motor voltage constant K_v = 0.7032 V/A. rad/s, the armature and field currents are continuous and ripple free. If load torque T_L = 45 N-m at 1000 rpm, calculate : i) Field current I_f ii) Back emf E_g iii) Firing angle of converter in armature circuit iv) Input power factor of armature circuit converter.* **[8]**

Ans. : Here $V_m = 208\sqrt{2}$ V, $R_a = 0.25\ \Omega$, $R_f = 147\ \Omega$

$$T = T_L = 45 \text{ N-m}, \; k_v = 0.7032 \text{ V/A-rad/sec}$$

$$\omega = 1000 \times \frac{2\pi}{60} = 104.72 \text{ rad/sec.}$$

i) To obtain field current (I_f)

Maximum field current is given as,

$$V_f = \frac{V_m}{\pi}(1+\cos 0), \text{ since } \alpha_f = 0 \text{ for max voltage}$$

$$= \frac{2\,V_m}{\pi} = 187.25 \text{ V.}$$

$$\therefore \text{ Field current, } I_f = \frac{V_f}{R_f} = \frac{187.25}{147} = 1.274 \text{ A}$$

ii) Back emf, E_b

$$\text{Torque, } T = k_a\,\phi_f\,I_a$$

$$\therefore \quad I_a = \frac{T}{k_a\,\phi_f} = \frac{45}{0.7032 \times 1.274}, \text{ Here } k_a\,\phi_f = k_v\,I_f$$

$$= 50.23 \text{ A}$$

$$E_b = k_a\,\phi\omega = k_v\,I_f\,\omega = 0.7032 \times 1.274 \times 104.72 = 93.82 \text{ V}$$

iii) Firing angle of converter

$$V_a = E_b + I_a R_a = 93.82 + 50.23 \times 0.25 = 106.38 \text{ V}$$

We know that output voltage of the semi-converter is given as,

$$V_{o(av)} = V_a = \frac{V_m}{\pi}(1+\cos\alpha)$$

$$\therefore \quad 106.38 = \frac{208\sqrt{2}}{\pi}(1+\cos\alpha)$$

$$\therefore \quad \alpha = 82.2^\circ = 1.435 \text{ radians}$$

iv) Output power factor

Output power, $P_o = V_a I_a = 106.38 \times 50.23 = 5343.467$

The rms value of supply current for armature converter is given as,

$$I_{s(rms)} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} I_a^2 \, d\omega\right]^{\frac{1}{2}}$$

$$= I_a \sqrt{\frac{\pi-\alpha}{\pi}}$$

(Refer Fig. 1 for current waveform)

$$= 50.23 \sqrt{\frac{\pi-1.435}{\pi}} = 37.02 \text{ A}$$

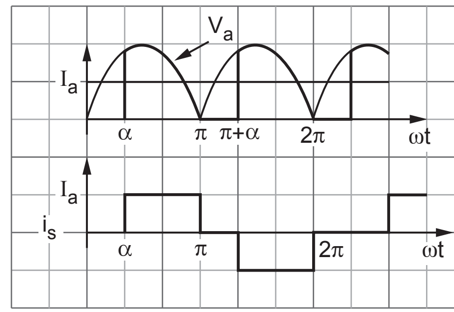


Fig. 1 Supply Current

Supply power, $P_s = V_s I_s = 208 \times 37.02 = 7700.16$ VA

$\therefore$ Power factor, PF $= \dfrac{P_o}{P_s} = \dfrac{5343.467}{7700.16} = 0.694.$

OR

Q.6 a) *Explain voltage and frequency control method for 3-φ induction motor drive in detail.* **(Refer section 6.9)** **[8]**

b) *What are advantages of electronic ballast over conventional ballast ? Explain working of electronic ballast with block schematic.*
(Refer sections 6.3.2 and 6.3.3) **[8]**

Q.7 a) *What is EMI ? Explain various sources and minimizing techniques of EMI.*
(Refer section 5.8) **[6]**

b) *For a thyristor, maximum junction temperature is 125 °C. The thermal resistances are $\phi_{JC} = 0.16$, $\phi_{CS} = 0.08$ °C/W for heat sink temperature of 70 °C, calculate total average power loss in thyristor - sink combination. If heat sink temperature is reduced to 60 °C, find new total average power loss in thyristor - sink combination.* **[4]**

Ans. : i) Power loss for sink temperature of 70 °C

Here $R_{\theta js} = 0.16 + 0.08 = 0.24$ °C/W

$$P = \frac{T_j - T_s}{R_{\theta js}} = \frac{125-70}{0.24} = 229.17 \text{ W}$$

ii) Power loss for sink temperature of 60 ºC

$$P = \frac{125-60}{0.24} = 270.83 \text{ W}$$

c) *Write a note on "over voltage protection" in power electronics.* **(Refer section 5.1.2)** **[6]**

OR

Q.8 a) *What is the need of resonant converter ? Explain ZCS resonant converter with circuit and waveforms.* **(Refer sections 5.7.1 and 5.7.3)** **[8]**

b) *Explain SLR half bridge dc-dc converter in low frequency with suitable waveforms.* **(Refer section 5.7.2)** **[8]**

December - 2015 **Power Electronics** T.E. (E&Tc) Semester - II (2012 Course) [End Sem. Exam][4858] - 1048	**SPPU** **Solved Paper**

Time : 2 $\frac{1}{2}$ Hours] **[Maximum Marks : 70**

Note :

1) ***Neat diagrams must be drawn wherever necessary.***
2) ***Figures to the right indicate full marks.***
3) ***Your answers will be valued as a whole.***
4) ***Use of logarithmic tables slide rule, Mollier charts, electronic pocket calculator and steam table is allowed.***
5) ***Assume suitable data, if necessary.***

Q.1 a) *What are phase controlled converter? Explain with circuit diagram working of 1 ϕ half controlled converter with suitable load. Draw suitable waveforms and comment on p.f.* **[7]**

Ans. : Refer sections 2.1.1, section 2.2.

Comment on power factor : The converter has lagging power factor. It is given as,

$$PF = \sqrt{\frac{8}{\pi(\pi-\alpha)}} \quad \cos^2\frac{\alpha}{2}$$

As the firing angle increases, the power factor becomes poor. The highest value of power factor is 0.9 for $\alpha = 0$.

b) *What is inverter ? Explain with diagram 3ϕ voltage controlled inverter with star load (R). Comment on waveforms and duty cycle.* **[7]**

Ans. : Refer section 3.4.

Inverter : It is DC to AC converter. The input can be fixed or variable DC voltage. The output can be fixed or variable voltage and frequency. The switching times of the devices are controlled in inverters to control the output voltage.

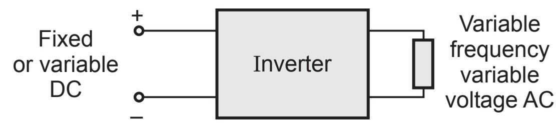


Fig. 1 Inverter

Duty cycle : The ratio of on time to total period of the switch is called duty cycle. Duty cycle is varied to control the rms value of output voltage. Single pulse modulation, multiple pulse modulation, sinusoidal PWM are the various duty cycle control techniques.

c) *What is IGBT ? Explain with characteristics.* **(Refer sections 1.6 and 1.6.3)** **[6]**

OR

Q.2 a) *What is the need of dual converters in the industries ? Explain with diagram and waveforms, working of 1ϕ dual converter with highly inductive load.* **[7]**

Ans. : Need of dual converters in industries : i) Reversible DC drives (ii) High power applications (iii) Rectification and inversion of DC power (iv) Four quadrant operation of DC drives (v) Regenerative breaking.

Working of 1ϕ dual converter with highly inductive load

Fig. 2 shows the circuit diagram of 1ϕ practical dual converter. The P-converter has the output V_{o1} and it operates in rectification mode (i.e. $\alpha < 90°$). The N-converter has the output V_{o2} and it operates in the inversion mode (i.e. $\alpha > 90°$). For $\alpha > 90°$, the average output V_{o2} of N-converter is negative. The two outputs V_{o1} and V_{o2} appear across the load. The two converters operate on inductive load. Hence their average values are given as,

$$V_{o1(av)} = \frac{2V_m}{\pi} \cos \alpha_1$$

and $$V_{o2(av)} = \frac{2V_m}{\pi} \cos \alpha_2 \quad \text{... (1)}$$

Since one converter operates in rectifying mode and other converter operates in inversion mode, their average values must be equal and opposite in sign. i.e.,

$$V_{o1(av)} = -V_{o2(av)} \quad \text{... (2)}$$

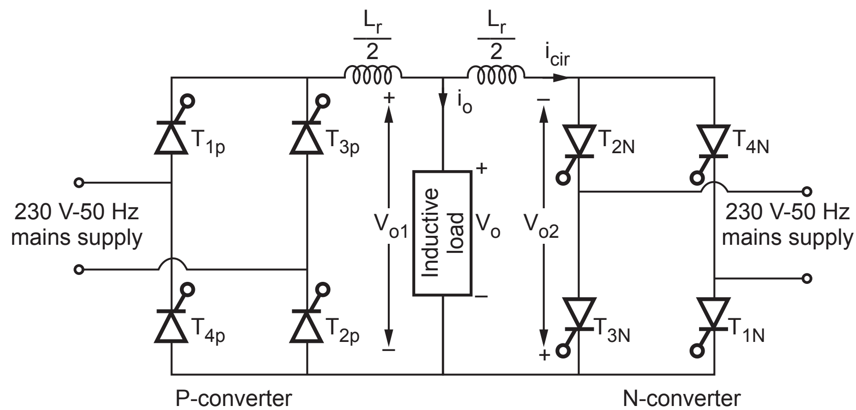


Fig. 2 1 ϕ dual converter

Putting for $V_{o1(av)}$ and $V_{o2(av)}$ from equation (1) in above equation,

$$\frac{2\,V_m}{\pi}\cos\alpha_1 = -\frac{2\,V_m}{\pi}\cos\alpha_2$$

$$\therefore \qquad \cos\alpha_1 = -\cos\alpha_2$$

$$\therefore \qquad \alpha_2 = \pi-\alpha_1 \quad \text{or} \quad \alpha_1+\alpha_2 = \pi \qquad \text{... (3)}$$

Thus if $\alpha_1 < 90°$, then $\alpha_2 > 90^o$ and their sum is 180^o or π. Fig. 3 shows the waveforms of 1 ϕ dual converter.

Observe that P-converter is triggered at α_1 which is less than 90°. The N-converter is triggered at α_2 which is greater than 90. Hence the average values of V_{o1} and V_{o2} are equal but opposite in sign. In Fig. 3 observe that the instantaneous values of V_{o1} and V_{o2} are not same. Hence a small amount of circulating current flows between the two converters. This current does not flow through the load. The circulating current is limited by the circulating current reactor L_r. The circulating current reactor is connected between the two converters as shown in Fig. 2.

Four quadrant operation

By controlling the firing angles α_1 and α_2 it is possible to change the polarity of output voltage completely. Consider that V_o is positive when $\alpha_1 < 90^o$ and $\alpha_2 > 90^o$. Then V_o is negative when $\alpha_1 > 90^o$ and $\alpha_2 < 90^o$. Similarly direction of output current i_o will also be changed. Thus 1ϕ dual converter operates in 4 quadrants of V_o and i_o.

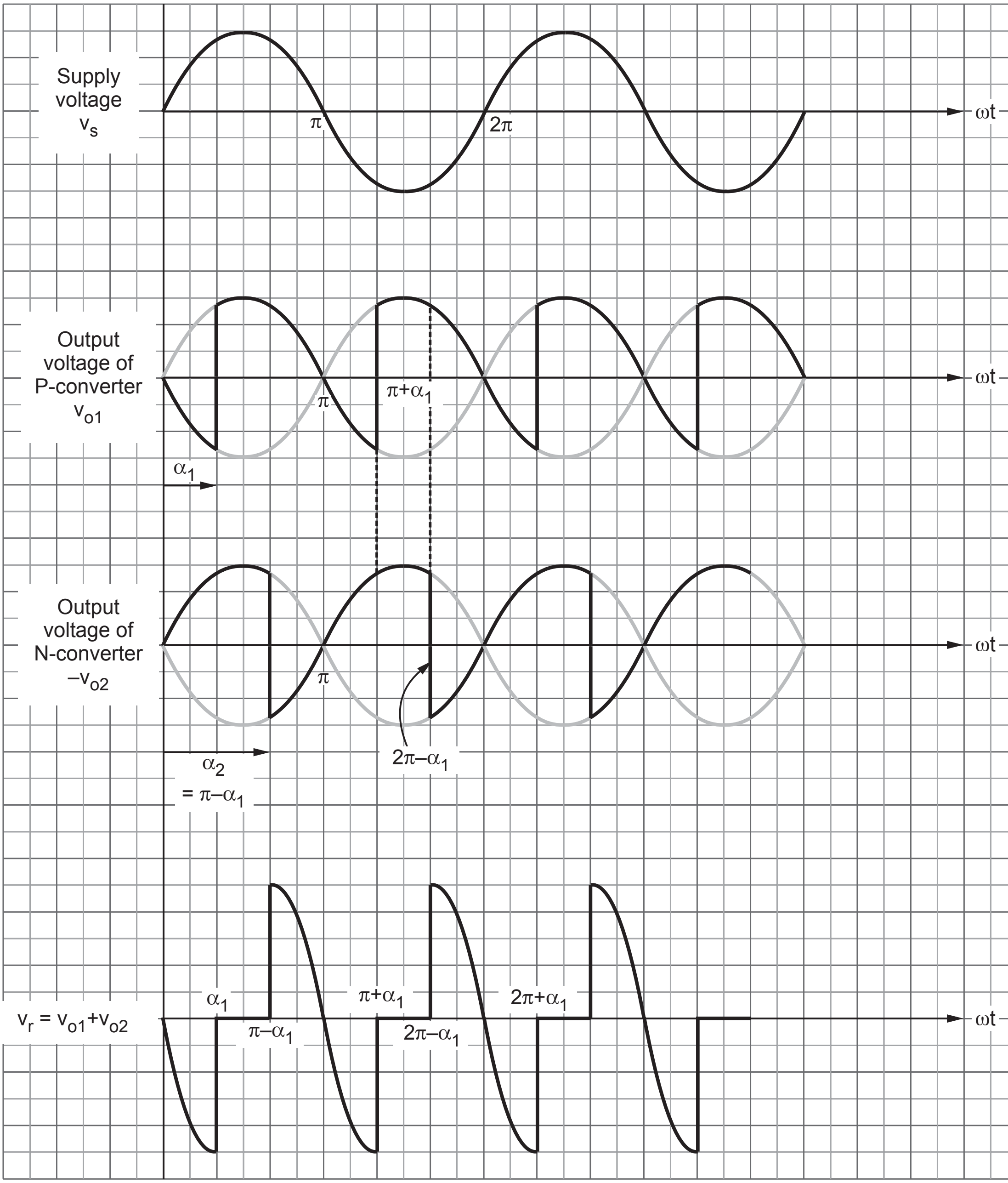


Fig. 3 Waveforms of 1 ϕ dual converter

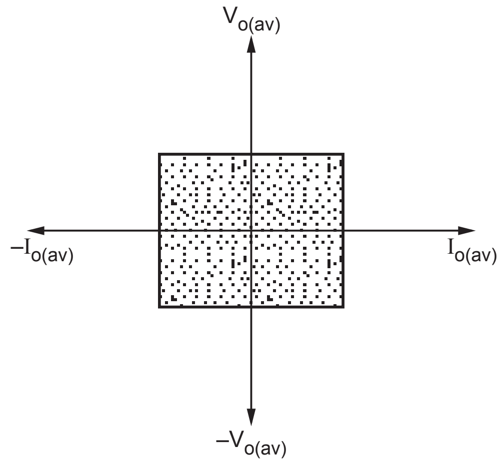


Fig. 4 4-Quadrant operation of 1φ dual converter

b) *Explain with circuit diagram and waveforms working of 1φ Full controlled converter with RL load ? Justify what is inversion and rectification mode with waveforms.* **(Refer sections 2.3.2 and 2.3.3)** **[7]**

c) *What is bridge inverter ? Explain with circuit diagram and waveforms.* **(Refer sections 3.3 and 3.3.1)** **[6]**

Q.3 a) *What are DC-to-DC converters ? Explain with circuit diagram and waveforms working of 4 quadrant chopper ? State its applications.* **[9]**

Ans. : Refer sections 4.4.5 and 4.5.

DC to DC converters : They are also called choppers. The input to the chopper is fixed or variable voltage DC supply. And the output of the chopper is also fixed or variable voltage DC.

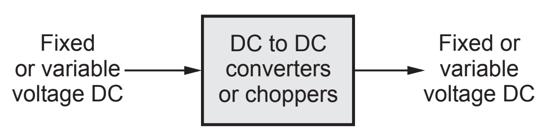


Fig. 5 DC to DC Converter

The input to the chopper can be from controlled rectifier or battery. The output of the chopper is used to Drive DC motor.

b) *What is AC to AC controller ? Explain with circuit diagram working of 1φ AC full wave AC to AC controller with balanced star Load (R)* **[9]**

Ans. : Refer section 6.1.

AC to AC controller : It is also called AC voltage regulater. The input is fixed or variable voltage AC. Normally frequency of input is fixed.

The output has variable voltage as well as frequency. The input normally comes from AC mains supply. The output is used to drive induction moters, pumps, fains, heaters etc.

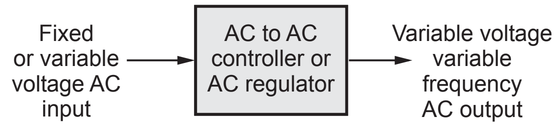


Fig. 6 AC to AC Controller

OR

Q.4 a) *i) What is chopper ? Explain in brief.*

(Refer section 4.1 and Q.3 (a) of same paper)

ii) A DC chopper has a resistance of 10 Ω *and input voltage is 220 V. When the chopper switch remains ON its voltage drops to 2 V and chopping frequency is 1 kHz. If the Duty cycle is 50 % Determine,*

1) Average o/p volt 2) Rms o/p voltage 3) Chopper efficiency 4) Input resistance of chopper **[10]**

Ans. : Given data : $V_s = 220$ V, $R = 10\ \Omega$, $V_{ch} = 2$ V, $\delta = 0.5$

1. $$V_{o(av)} = \delta(V_s - V_{ch}) = 0.5\ (220 - 2) = 109 \text{ V}$$

2. $$V_{o(rms)} = \sqrt{\delta}\,(V_s - V_{ch}) = \sqrt{0.5}\,(220-2) = 154.15 \text{ V}$$

3. $$P_o = \frac{\delta(V_s - V_{ch})^2}{R} = \frac{0.5\,(220-2)^2}{10} = 2376.2 \text{ W}$$

$$P_s = \frac{\delta V_s (V_s - V_{ch})}{R} = \frac{0.5 \times 220\,(220-2)}{10} = 2398 \text{ W}$$

$$\therefore \quad \eta = \frac{P_o}{P_s} = \frac{2376.2}{2398} = 0.9909 \text{ or } 99.09\ \%$$

4. $$R_{in} = \frac{1}{\delta} R = \frac{1}{0.5} \times 10 = 20\ \Omega$$

b) *Explain with circuit diagram and waveforms working of triac based AC power controller circuit. Comment on p.f. Justify why SCR based controllers are prefered over triac based controllers.* **[8]**

Ans. : Triac based AC power controller : We know that antiparallel SCRs can be replaced by triac. The triac conducts in both the directions with single gate control. Fig. 7 shows the circuit diagram of the 1 ϕ controller that uses triac. The triac is triggered in both the positive as well as negative half cycles. The waveforms of this circuit will be same as those shown in the Fig. 7.

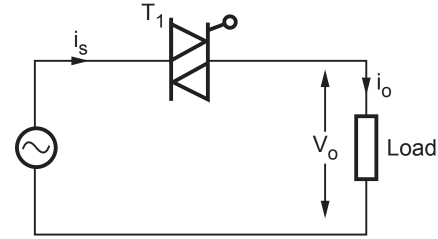


Fig. 7 Triac based controller

Why triacs are not used for inductive loads ?

1. For inductive load the triac must turn-off when voltage becomes zero in positive half cycle, before negative voltage is reapplied to triac. This negative voltage also forward biases triac for negative half cycle.
2. With inductive load, the triac conducts after π and due to application of negative voltage in next cycle, it does not turn-off at all.
3. Thus commutation of triac is not successful for inductive loads.

Advantages of triac controller

i) Triac controller is simple, since there is only one drive.

ii) It is best device for resistive low power loads.

Disadvantages

i) Triac is not suitable for inductive load, since it does not turn-off properly when load is inductive.

Comment on pf : Power factor of triac based AC power controllers is poor for inductive load compared to resistive loads.

Q.5 a) *Explain with block schematic working of off-line UPS. State its specifications and applications.* **[8]**

Ans. : Refer sections 6.10.2 and 6.10.5.

Specifications of offline UPS : Typical specifications of offline UPS are as follows :

Capacity	:	10 kVA
Technology	:	MOSFET - PWM
Input - Output	:	Single phase - single phase
Input Voltage	:	230 V ± 20% and 50 Hz ± 5%
Output Voltage	:	230 V ± 5 % and 50 Hz ± 1.5 %
Waveform	:	sine wave
Power factor	:	0.8
Efficiency	:	More than 80 %
Recharge time	:	8 to 10 Hours
Temperature	:	0 to 40ºC
Noise	:	< 60 dB

b) *What are speed control techniques of DC Motors ? Explain with circuit diagram working of* 1ϕ *seperately excited DC Motor with Inductive Load. Comment on p.f.* **[8]**

Ans. : Refer sections 6.5.2 and 6.6.2 and

Comment on pf : The motor draws lagging current, hence power factor of 1ϕ seperately excited DC motor drive is lagging. Power factor becomes poor as firing angle increases (i.e. speed reduces). Power factor of half converter is better compared to full converter.

OR

Q.6 a) *Compare ON-Line UPS with Off-Line UPS. Justify why ON-Line is better than Off-Line with technical reasons.* **(Refer section 6.10.5)** **[8]**

b) *Write short notes on : i) Battery charger ii) Electronic Ballast* **[8]**

Ans. : i) Battery Charger : Fig. 8 shows the circuit diagram of a battery charger.

Operation of the charger

It uses half controlled converter for battery charging. The firing angle of the SCRs T_1 and T_2 is continuously adjusted to maintain constant current charging of the battery. The battery voltge is sensed by the control circuit. The triggering angles of T_1 and T_2 are adjusted depending upon battery voltage. Fig. 8 shows the block diagram of triggering circuit for one of the SCR.

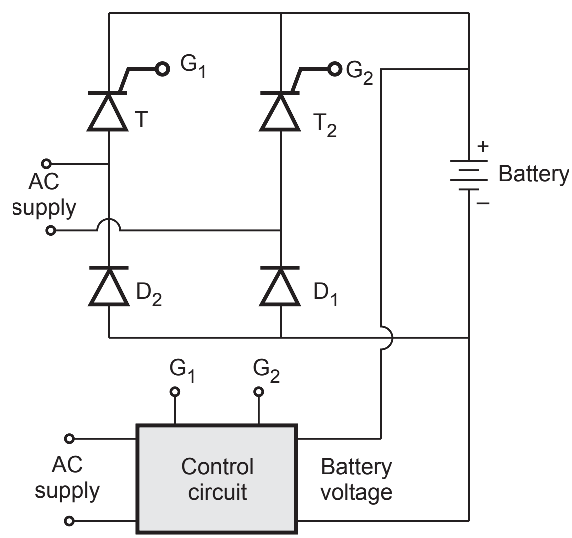


Fig. 8 Battery charger

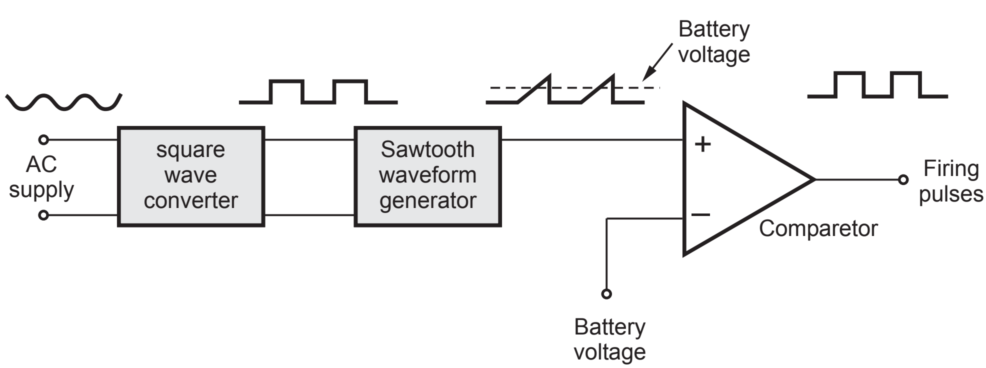


Fig. 9 Control circuit for battery charger

Operation of the control circuit

The AC voltage is given to the square wave converter. It is simple comparator that generates square wave at its output. This square wave is given to the sawtooth generator. It generates sawtooth waveform with battery voltage. This is shown in

Fig. 10. The output of the comparator is firing pulses for the SCR. From the waveforms observe that as the battery voltage increases, the firing angle is increased. Hence output voltage of semiconverter is reduced. Therefore the charging voltage for the battery is also reduced. Thus the battery is charged at constant current rate. This is done by maintaining constant voltage difference between semiconverter output and battery voltage.

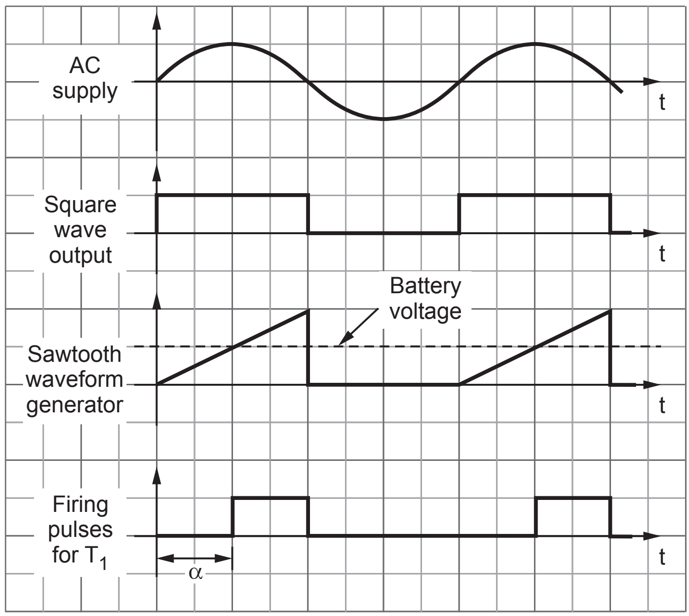


Fig. 10 Waveforms of control circuit

Advantages :

i) Dynamic charger allows constant current charging of the battery.

ii) It is capable of supplying high charging currents.

iii) It increases life of the battery.

Applications :

i) Battery charging in UPS systems.

ii) Battery charging in back up systems for tractions, vehicles, medical equipments.

ii) Electronic Ballast : Refer section 6.3

Q.7 a) *What are resonant converters? Explain with circuit diagram and waveform working of ZVS ?* **(Refer sections 6.10.4 and 6.10)** **[8]**

b) *A Snubber circuit is used in SCR circuit for protection of di/dt, dv/dt. The value of RLC being* 4 Ω, 6 μH, *and* 6 μF *respectively and Supply being 400 V. Find the maximum permissible value of dv/dt. Assume the load resistance to be* 10 Ω **[8]**

Ans. : Given data, $V_s = V_m = 400\ V,\ L = 6\ \mu H,\ R = 4\ \Omega,\ C = 6\ \mu F,\ R_L = 10\ \Omega$

Maximum permissible value of dv/dt is given by, equation

$$C = \frac{1}{2L}\left[\frac{0.564\ V_m}{dv\ /\ dt}\right]^2 \quad \text{putting values}$$

$$6 \times 10^{-6} = \frac{1}{2 \times 6 \times 10^{-6}}\left[\frac{0.564 \times 400}{dv/dt}\right]^2$$

$$\therefore \quad \frac{dv}{dt} = 26587214.97\ \ V\ /\ sec = 26.58\ V/\mu sec$$

OR

Q.8 a) *Compare Linear, switched mode and resonant converter based power supplies.* **(Refer section 5.7.6)** **[6]**

b) *Write short notes on : i) HVDC ii) Induction heating iii) Protection circuits* **[10]**

Ans. : i) High Voltage DC (*HVDC*) Transmission

- The transmission of electric energy with minimum losses is of great importance now a days. This saves great amount of energy.
- The electric energy is normally transmitted at very high voltages to reduce losses. High voltage *AC* as well as *DC* transmissions are possible.
- High voltage *DC* (*HVDC*) transmission proves to be economical and efficient over High Voltage *AC* (*HVAC*) transmission.

Basic HVDC Transmission System

- Fig. 11 shows the block diagram of *HVDC* transmission system. The 3 ϕ *AC* supply is first passed through *AC* filter to remove harmonics and then stepped up through step up transformer. This gives high *AC* voltage which is ready for transmission.
- This high *AC* voltage is converted to high *DC* voltage by series connected converter. The series connected converters are used to increase the voltage rating. Normally these are 12-pulse converters to reduce ripple voltage.
- The *DC* voltage of the converter is then filtered by the smoothing inductors. Thus ripple free high *DC* voltage is obtained. This high *DC* voltage is then transmitted over the *DC* transmission line.

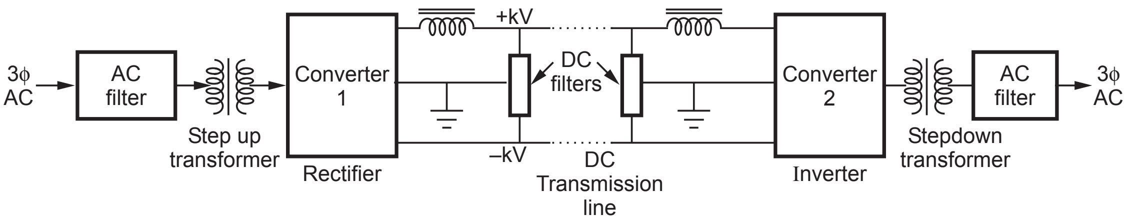


Fig. 11 Block diagram of HVDC transmission system

- Observe that the *DC* transmission line has *+kV* and *–kV* with respect to ground. This is purposely done to balance the voltage of two transmission lines with respect to earth.
- At the receiving station again the *DC* voltage is filtered and given to converter-2 which acts as an inverter.
- The output of the converter-2 is stepped down and passed through *AC* filters. Thus the 3 ϕ *AC* supply is finally obtained at the receiver side.

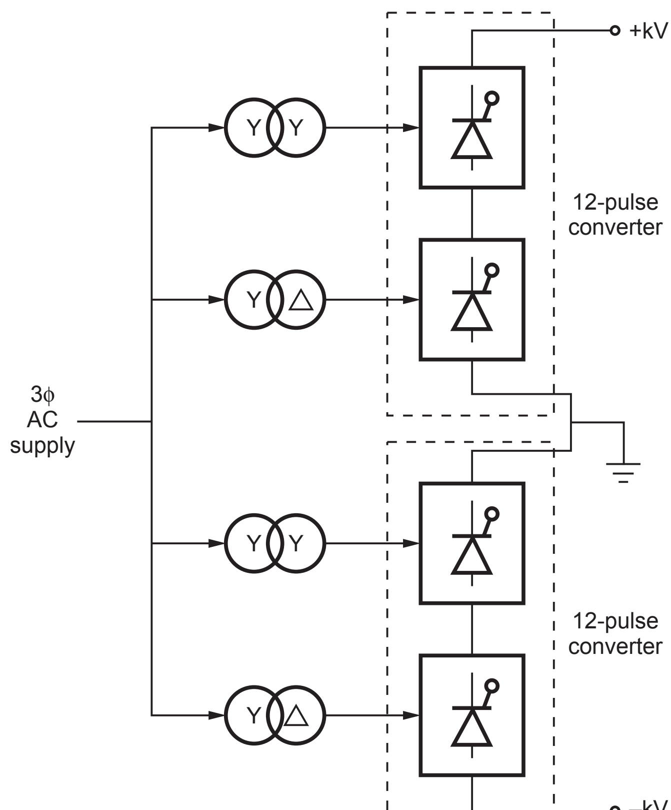


Fig. 12 Circuit diagram of converter used for HVDC transmission

- Note that converter-1 as well as converter-2 are series connected 3ϕ controlled rectifiers. The transmitting side converter-1 acts as a rectifier and receiving side converter acts as an inverter. The advantage of this system is that, the *HVDC* link becomes bidirectional.

Twelve-Pulse Converter Arrangement

Fig. 12 (Refer Fig. 12 on previous page) shows the circuit diagram of converter used for *HVDC* transmission. In this diagram observe that there are two 12-pulse converters which are connected in series. It gives *+kV* and *–kV* with respect to common earth. The *AC* supply is given to these converters through star-star and star-delta transformers.

Circuit diagram of 12-pulse converter

- Fig. 13 shows the circuit diagram of 3ϕ 12-pulse converter used in above diagram. Observe that there are two converters '*A*' and '*B*'. These two converters are connected in series.
- The supply to converter '*A*' is given through star-star connected transformer and supply to converter '*B*' is given through star-delta connected transformer.

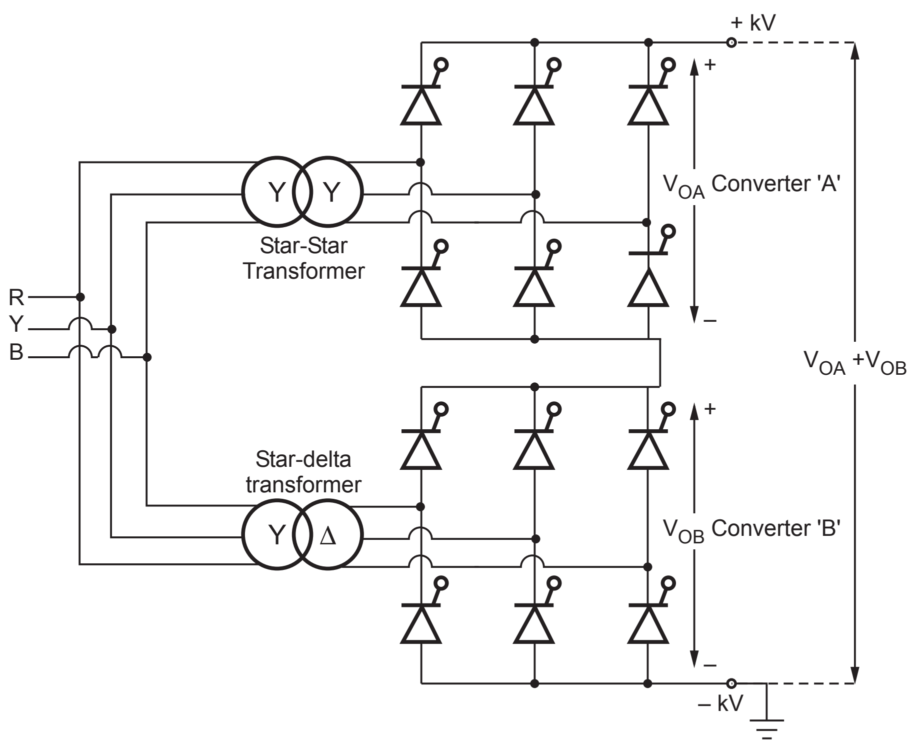


Fig. 13 Circuit diagram of 12-pulse converter

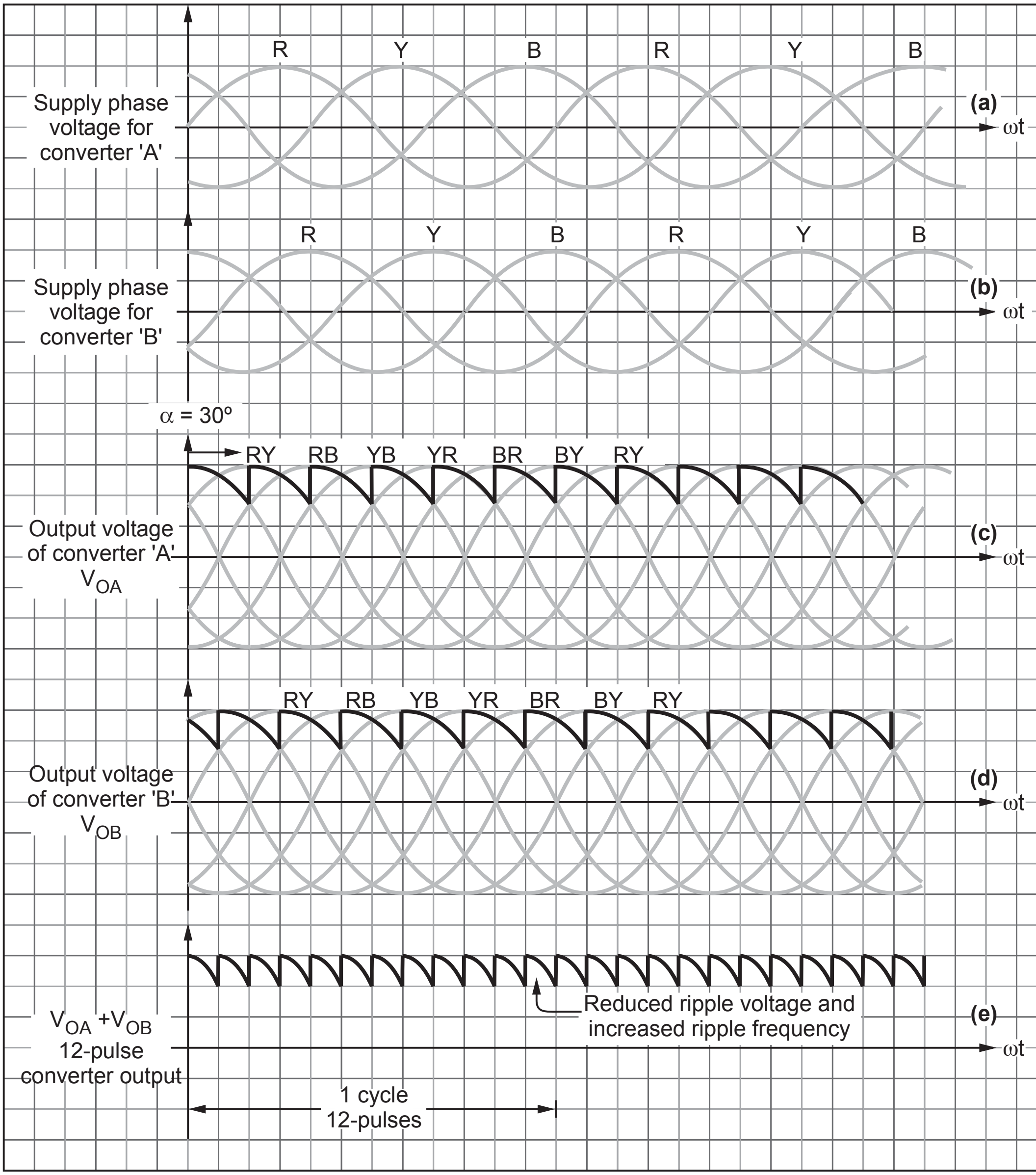


Fig. 14 Waveforms of 12-pulse converter

- Fig. 14 shows the waveforms of above 12-pulse converter. There is phase shift of 30° in the input supply voltages of converter '*B*'. This is due to star-delta transformer connection for converter '*B*'.
- Fig. 14 (c) shows the output of converter-*A*. Observe that it is 6-pulse output. The ripple frequency is 6 × 50 = 300 Hz. Fig. 14 (d) shows the output of converter-*B*. It is the 6-pulse output. The ripple frequency is 6 × 50 = 300 Hz.

- Fig. 14 (e) shows the output of 12-pulse converter. It is obtained by adding the waveforms of Fig. 14(c) and (d). Observe that there are 12-pulses in the output-waveform. The ripple frequency is $12 \times 50 = 600$ Hz. The ripple voltage is also reduced.

Advantages of 12-pulse converters

1. The ripple frequency and ripple voltage amplitude is reduced.
2. The size of filtering components is reduced due to increased ripple frequency.
3. Due to series connection of converters, the voltage rating of devices is reduced.

Advantages over *HVAC* Transmission

The *HVDC* transmission have several advantages over the *HVAC* transmission.

1. Only two conductors are used for transmission, hence cost of transmission is less.
2. Losses of transmission are reduced since there is no reactive power.
3. Due to high voltage transmission, current is less for same power. Hence I^2R loss is very small.
4. Due to *DC* transmission, there is no skin effect. Hence thin conductors can be used. But in *AC* transmission, the conductors must be thick to take care of skin effect.
5. *HVAC* induces body currents in the vicinity of the conductors. This is absent in *HVDC*.
6. Two *ac* systems of different frequencies can be connected through *HVDC* system. This is not possible in *HVAC*.
7. *HVDC* uses electronic converters. Hence protections can be implemented faster than *HVAC*.
8. *HVDC* do not have any dielectric loss heating problems in an insulation of conductors.
9. *HVDC* have minimum audible noise, radio and *TV* interference.
10. Power levels on *HVDC* can be electronically controlled in case of faults.
11. *DC* cables are cheaper than ac cables used for transmission.
12. Due to bipolar transmission, the voltage levels are balanced with respect to an earth.
13. Line charging and electric resonance effects are absent in *HVDC*.

Disadvantages of *HVDC* transmission

1. The cost of converters is high.
2. Converters control is quite complex.
3. Additional filters are required that increases the cost.

Comparison of *HVAC* and *HVDC* transmission

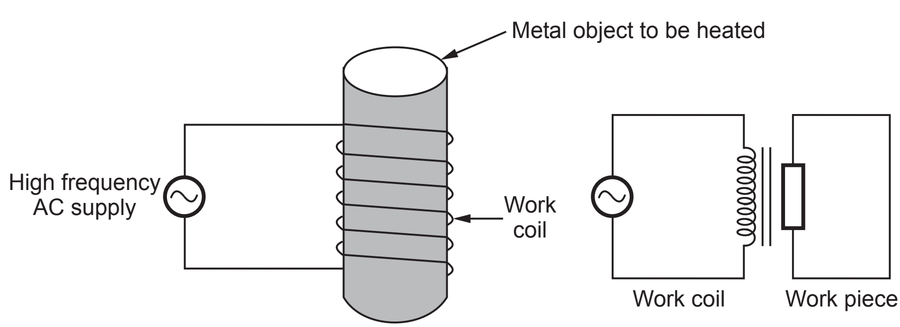
Table 1 shows the comparison between *HVAC* and *HVDC* transmission.

Sr. No.	Parameter	*HVAC*	*HVDC*
1.	Type of transmission	*AC*	*DC*
2.	Overall losses	High	Low
3.	Cost of transmission (conductors and poles)	High	Low
4.	Cost of equipment	Low	High
5.	Power control	Power cannot be controlled	Power can be controlled
6.	Directionality of link	Unidirectional	Bidirectional
7.	Transmitted power and distance	Depends upon distance	Independent of distance.

Table 1 Comparison between *HVAC* and *HVDC* transmission

ii) Induction Heating :

- Fig. 15 shows the induction heating setup used for metal object.



(a) Basic induction heating setup **(b) Equivalent circuit**

Fig. 15 Principle of induction heating

- The high frequency *AC* supply drives the coil, which is wound around the object to be heated.
- When current flows through the coil, it induces magnetic flux in the metal object. This flux generates eddy currents in the metal object.

- The eddy currents flow in circular connected paths in the metal object. Due to internal resistance of the metal object, heat is produced. Thus the metal object starts heating.
- Fig. 15 (b) shows an equivalent circuit of the induction heating. The work coil acts as primary and work piece acts as shorted secondary. The object heats up due to current flow in shorted path.

Advantages of Induction Heating

i) Induction heating provides very high heating ratios (up to 5 kW/cm^2).

ii) Temperature can be controlled automatically with the help of feedback.

iii) The heat transferred to the metal object can be controlled with the help of electronic timers.

iv) Heat is not wasted since it is generated internally in the metal object.

v) Surface hardening of steel is possible due to skin effect of eddy currents.

vi) Induction heating can take place in vaccum, inert gases as well as other gases.

Disadvantages of Induction Heating

i) Heating is not even. It is more in regions that are closer to heating coil.

ii) The shape of the work piece and coil should match.

iii) Heating is more in the corners of work piece.

iv) Cost of the heating equipment is very high.

v) Efficiency of heating is poor.

Applications of Induction Heating

i) Surface hardening of steel.

ii) Soldering and brazing.

iii) Annealing of brass and bronze items.

iv) Induction cooking using metal pans and pots.

v) Drying points on metals, sintering powdered metals.

vi) Sterilizing surgical instruments.

vii) Welding and bonding clutch facing.

iii) Protection circuits :

Over Voltage Conditions

Over voltage can arrive in power electronic circuits because of following conditions :

i) Incorrect selection of power devices.

ii) Voltage surges or spikes from load or supply side.

iii) Imbalance in the load.

iv) Failure of one or more power devices in the same circuit.

v) Insufficient snubber components.

vi) Insufficient cooling of power devices.

vii) Inappropriate mounting of power devices.

All the above situations lead to average or repetitive over voltage in the circuit. It damages the power device.

Over Voltage Protection Circuit

Overvoltage protection can be achieved in different ways. Fig. 16 shows the overvoltage protection circuit using SCRs. T_1 and T_2 are antiparallel SCRs used to bypass the voltage transients in case of overloads. Thus the load is protected. R_1 is used to limit the current through T_1 and T_2 in case of overvoltage zener diode D_5 and R_2 form the voltage sensing circuit. These components also work as a trigger circuit for the SCRs along with diodes D_1 to D_4.

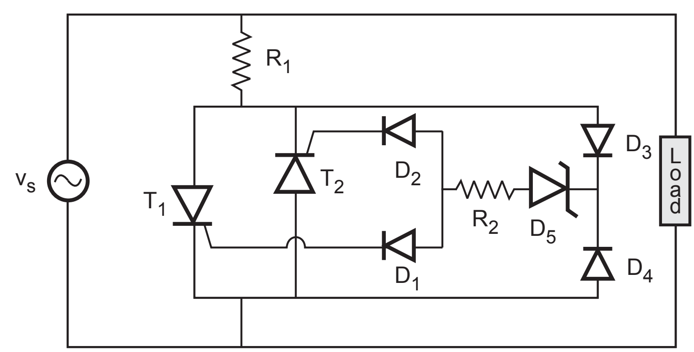


Fig. 16 Overvoltage protection circuit

Circuit Operation

When there is overvoltage, the values of R_2 is set such that zener diode D_5 breaks. This applies gate drive to T_1 and T_2. For positive half cycle T_1 conducts and the overvoltage is reduced by drawing heavy current through R_1 and T_1. Then T_1 turns off by natural commutation at the end of positive half cycle.

If over voltage persists, zener diode again breaks in negative half cycle and applies gate drive to T_2. Heavy current flows through T_2 and R_1 and the load is protected.

As soon as the voltage returns to its safe value, the zener diode D_5 doesnot break and no current flows through it. Hence T_1 and T_2 are turned off and supply voltage appears across the load.

The value of R_1 is selected such that enough current is drawn through the supply or load and overvoltage is returned to its safe limit.

This circuit provides overvoltage protection arised due to either supply or load.

April - 2016 **Power Electronics** T.E. (E&Tc) Semester - II (2012 Course) [In Sem. Exam] [23]	SPPU **Solved Paper**

Time : 1 Hour] **[Maximum Marks : 30**

Note :

1) Answer Q.1 or Q.2, Q.3 or Q.4, Q.5 or Q.6.

2) Neat diagrams and waveforms must be drawn wherever necessary.

3) Figures to the right indicate full marks.

4) Use of nonprogrammable calculator is allowed.

5) Assume suitable data, if necessary.

Q.1 a) *Draw and explain two transistor analogy of SCR.* **(Refer section 1.2.5)** **[6]**

b) *For an SCR, the gate cathode characteristics has straight line slope of 130. For triggering source voltage of 15 V and allowable gate power dissipation of 0.5 W, calculate the gate series resistance (R_g).* **[4]**

Ans. : Given data :

V_s = 15 V, Slope of gate - cathode characteristic = 130, P_g = 0.5 W

i) Triggering voltage and ii) Triggering current

$$\frac{V_g}{I_g} = 130, \text{ Hence } V_g = 130 I_g$$

$$P_g = 0.5 \text{ W, Hence } V_g I_g = 0.5 \qquad (\text{since } P_g = V_g I_g)$$

Hence $(130 I_g) I_g = 0.5$, Putting for V_g in above equation

$$\therefore \quad 130\, I_g^2 = 0.5 \Rightarrow I_g = \sqrt{\frac{0.5}{130}} = 62\ mA$$

And $$V_g = 130\, I_g = 130 \times 62 \times 10^{-3} = \mathbf{8.06\ V}$$

ii) Gate series resistance (R_s)

From Fig. 1 we can write,

$$V_s = R_s I_g + V_g$$

$$\therefore \quad R_s = \frac{V_s - V_g}{I_g} = \frac{15 - 8.06}{62 \times 10^{-3}} = 112\ \Omega$$

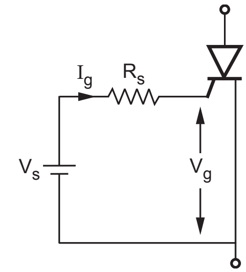


Fig. 1

OR

Q.2 a) *Draw construction diagram of n-channel enhancement type MOSFET and explain its steady state characteristics* **(Refer sections 1.5.1 and 1.5.2)** **[5]**

b) *Compare power MOSFET with SCR.* **(Refer section 1.6.7)** **[5]**

Q.3 a) *Draw and explain single phase fully controlled bridge converter for R-L load with various o/p voltage waveforms.* **(Refer section 2.3.2)** **[7]**

b) *A single phase semi converter is operated from 120 V, 50 Hz AC supply. The load is resistive having resistance of 15 Ω. If the average output voltage is 25 % of the maximum possible average output voltage, determine the firing angle* (α).
(Refer example 2.2.10) **[3]**

OR

Q.4 a) *Draw and explain three phase half controlled bridge converter for R load with o/p voltage waveforms.* **(Refer section 2.7)** **[7]**

b) *Explain the significance of free wheeling diode in controlled rectifiers.*
(Refer example 2.3.5 and section 2.2.3.1) **[3]**

Q.5 a) *Draw and explain single phase full bridge inverter for R-L load with o/p voltage and current waveforms.* **(Refer section 3.3.2)** **[6]**

b) *Single phase full bridge inverter is operated from 48 V dc supply, it has a resistive load of* $R = 2.4\,\Omega$. *Find its.* **[4]**

i) Output power (P_0)

ii) Total Harmonic Distortion (THD) **(Refer example 3.3.5)**

OR

Q.6 a) *Explain* 120^o *mode in three phase inverters for balanced star R load with circuit diagram in detail.* **(Refer section 3.4.2)** **[10]**

May - 2016
Power Electronics
T.E. (E&Tc) Semester - II (2012 Course)
[End Sem. Exam] [4958] - 1048A

SPPU
Solved Paper

Time : 2 $\frac{1}{2}$ Hours] **[Maximum Marks : 70**

Note :

1) All questions are compulsory.

2) Figures to the right indicate full marks.

Q.1 a) *What are power devices ? Explain with characteristics any one power device used for power control applications.* **[4]**

Ans. : Power devices : The device that is used as a switch in power converters is called a power device. The power device has anode-cathode and gate or collector-emitter and base. The gate or base is used to turn-on or off the device.

b) *What are phase controlled converters ? Explain with circuit diagram and waveforms working of 1ϕ full controlled converter with suitable load. Comment on rectification, inversion mode and power factor.*
(Refer Q.1(a) and Q.2(b) of Dec.-2015) **[10]**

c) *What is the need of triggering circuits ? Explain in brief UJT triggering circuit for SCR.* **(Refer section 1.10.5)** **[6]**

Ans. : Need of triggring circuit : The triggering circuit is required due to following reasons :

i) The power devices is turned on or off by triggering circuit.

ii) The triggering circuit provides enough amount of current and voltage to switch the power device.

iii) The triggering circuit isolates the low power control circuit and high power circuit.

OR

Q.2) a) *What are DC to AC converters ? Explain with circuit diagram and waveforms working 3ϕ voltage source Inverter operating in 180^o mode. Comment on duty cycle and power factor.* **(Refer Q.1(b) of Dec.-2015)** **[8]**

Ans. : Power factor : The power factor of DC to AC converter or inverter can be kept close to unity by sinusoidal PWM control.

b) *Explain in brief difference between converter grade SCRS and inverter grade SCRs.* **(Refer section 1.3.5)** **[4]**

c) *A single phase full controlled converter is fed from 230 V, 50 Hz supply. The load is highly inductive find the average load voltage and current if the load resistance is 10 Ω and firing angle α = 45°.* **(Refer example 2.3.6).** **[8]**

Q.3 a) *What are DC to DC converters explain with diagram working of 4 Quadrant chopper comment on power factor.*
(Refer Q.3(a) of Dec.-2015) **[8]**

b) *Explain with circuit diagram and waveforms working of SCR based 1 φ AC full wave power controller circuit.*
(Refer Q.3(b) of Dec.-2015) **[8]**

OR

Q.4 a) *What is Triac ? Explain with circuit diagram and waveform and how AC power is controlled with triac. Justify why some times SCR's are prefered over triacs for low power applications.* **(Refer Q.4(b) of Dec.-2015)** **[8]**

Ans. : Triac : The triac is bidirectional four layer device. It has two terminals MT1 and MT2 and its on-off is controlled by a gate. It conducts in both the directions.

b) *A DC chopper operates on 230 V DC and frequency of 400 Hz; feeds an RL load. Determine the on - time of chopper for output of 150 V.* **[8]**

Ans. :

$$V_s = 230 \text{ V} \quad f = 400 \text{ Hz hence } T = \frac{1}{f} = \frac{1}{400} \text{ sec.}$$

$$V_{o\,(av)} = 150 \text{ V.}$$

$$V_{o(av)} = \delta V_s = \frac{T_{on}}{T} V_s$$

$$\therefore \quad 150 = \frac{T_{on}}{1/400} 230$$

$$\therefore \quad V_s = 150 \times \frac{1}{400} \times \frac{1}{230} = 1.63 \text{ msec.}$$

Q.5 a) *What is need of uninterruptable power supplies in industries ? Explain with block diagram working of On-line UPS state its specifications.* **(Refer section 6.10.1) [8]**

Ans. : Need of UPS in industries : Many operations in industries need continuous power supply since their operation cannot be paused. For examples chemical reactors, textile mills, heat exchangers, lifts and hoists, medicine industries, paint workshops etc. require uninterrupted power supply.

Specifications of on-line UPS

Capacity	:	1 kVA
Technology	:	MOSFET-PWM
Input	:	160 V to 295 V, 40 Hz to 60 Hz.
Input-output	:	Single phase - single phase
Output voltage	:	230 V ± 1 % and 50 Hz ± 0.5%
Waveform	:	Pure sine wave
Efficiency	:	More than 90%
Bypass	:	Synchronized static bypass.
Battery	:	36 V.
Recharge time	:	8 to 10 Hours.

b) *What are DC drives ? Explain with circuit diagram working of 1 ϕ separately excited DC Motor with inductive load. Suggest power factor improvement techniques.* **(Refer section 6.6.2)** **[8]**

Ans. : DC drives : The speed of DC motor is controlled with the help of DC converters such as controlled rectifier or chopper. This setup is called a DC drive.

Power factor improvement techniques : These techniques are used to reduce the displacement factor and improve power factor of controlled rectifier input. The power factor improvement techniques are as follows :

i) Symmetric Angle Control (SAC)

ii) Extinction Angle Control (EAC)

iii) Pulse Width Modulation control (PWM)

OR

Q.6 a) *What are AC drives ? Explain with block diagram, speed control technique of 3 ϕ Inductor motor by using $\frac{V}{F}$ method.* **(Refer section 6.9)** **[8]**

Ans. : AC drives : The speed of induction motor is controlled with the help of inverters and AC voltage regulators. This set up is called AC drive.

b) *Write short notes on any two.*

i) HVDC **(Refer Q.8 (b) (i) of Dec.-2015)**

ii) Battery charger **(Refer Q.6 (b) (i) Dec.-2015)**

iii) PWM techniques **(Refer section 3.6)**

iv) Stepper Motors. **[8]**

Ans. : iv) Stepper Motors : Stepper motor is known by its important property to convert a train of input pulses i.e. a square wave pulses into a precisely defined increment in the shaft position. Each pulse moves the shaft through a fixed angle.

The stepper motor is an electromechanical device which actuates a train of step movements of shaft in response to train of input pulses. The step movement may be angular or linear. There is one-one relationship between an input pulse and step movement of the shaft. Each pulse input actuates one step movement of the shaft.

When a given number of drive pulses are supplied to the motor, the shaft gets turned through a known angle. The angle through which the motor turns or shaft moves for each pulse is known as the **step angle**, expressed in degrees.

As such angle is dependent on the number of input pulses, the motor is suitable for controlling position by controlling the number of input pulses. Such system, used to control the position is called **position control system**.

The average motor speed is proportional to the rate at which the input pulse command is delivered. When the rate is low, the motor rotates in steps but for high rate of pulses, due to inertia, it rotates smoothly like d.c. motors. Due to this property it is also used in speed control systems.

These motors are available in sub-fractional horse power ratings. As the input command is in pulses, the stepper motor is compatible with modern digital equipments.

Types of stepper motors

The stepper motors can be divided into three categories :

1. Variable reluctance stepper motors
2. Permanent magnet stepper motors
3. Hybrid stepper motors

Q.7 a) *What are resonant converters ? Explain with circuit diagram and waveforms working of ZVS resonant converters.* **(Refer Q.7(a) of Dec.-2015)** **[10]**

b) *Compare linear, switched mode and resonant based power supplies.* **(Refer Q.8(a) of Dec.-2015)** **[8]**

OR

Q.8 a) *What is SLR ? Explain with circuit diagram and waveforms above resonant converter comment on Pf.* **(Refer section 5.7.2)** **[9]**

b) *Explain dv/dt; di/dt with details and snubber circuit.* **(Refer sections 5.3.1 and 5.4)** **[9]**

December - 2016
Power Electronics
T.E. (E&Tc) Semester - II (2012 Course)
[End Sem. Exam] [5058]-368

SPPU
Solved Paper

Time : 2 $\frac{1}{2}$ Hours] **[Maximum Marks : 70**

Note :

1) ***Answer Q.1 or Q.2, Q.3 or Q.4, Q.5 or Q.6, Q.7 or Q.8***
2) ***Draw neat diagrams and waveforms wherever necessary.***
3) ***Figures to the right indicate full marks.***
4) ***Use of nonprogrammable calculators is allowed.***
5) ***Assume suitable data, if necessary.***

Q.1 a) *Draw and explain steady state characteristics of IGBT.* **(Refer section 1.6.3)** **[7]**

b) *Explain triggering circuit for SCR using IC 785.* **(Not in new syllabus)** **[6]**

c) *Draw neat circuit diagram and explain single phase full bridge inverter with R-L load. Explain the effect of FWD on the operation of it.* **(Refer section 3.3)** **[7]**

Q.2 a) *Explain with circuit diagram and waveforms three phase inverter with 180 degree conduction mode.* **(Refer section 3.4.1)** **[7]**

b) *Draw and explain the steady state characteristics of SCR.* **(Refer section 1.2)** **[6]**

c) *Draw the circuit diagram of three phase semi converter with R load. Explain its operation. Draw the output voltage waveform.* **(Refer section 2.7)** **[7]**

Q.3 a) *What is DC to DC converter? Explain 4 quadrant chopper with circuit diagram and waveforms.* **(Refer sections 4.1 and 4.4.5)** **[9]**

b) *Draw the circuit diagram of single phase AC voltage controller with R load. Explain its operation. Draw the waveform of output voltage.*
(Refer section 6.1) **[9]**

Q.4 a) *In a dc chopper, the average load current is 30 Amps, chopping frequency is 250 Hz, supply voltage 110 volts. Calculate the ON and OFF periods of the chopper if the load resistance is 2 ohms.* **(Refer section 4.1)** **[8]**

b) *Draw the block schematic of SMPS and explain its advantages over Linear Power Supply.* **(Refer section 4.6)** **[10]**

Q.5 a) *Explain OFF-line UPS with neat block-diagram. State its specifications and applications.* **(Refer section 6.10)** **[6]**

b) *Explain with circuit diagram working of single phase separately excited DC motor drive. Draw neat waveforms across load.* **(Refer section 4.5)** **[10]**

Q.6 a) *What are AC drives? Explain with block diagram, speed control technique of three phase induction motor by using V/F method.* **(Refer section 6.9)** **[8]**

b) *Write short notes on :* **[8]**

i) Electronic ballast and ii) Battery charger **(Refer section 6.3)**

Q.7 a) *Explain SLR half bridge DC/DC converter with neat circuit diagram and waveforms.* **(Refer section 5.7.2)** **[8]**

b) *What is EMI ? Explain different sources and minimizing techniques of EMI.* **(Refer section 5.8)** **[8]**

Q.8 a) *Explain with circuit diagram and neat waveforms ZCS resonant converters.* **(Refer section 5.7.3)** **[10]**

b) *Explain overvoltage and over current protection circuits.* **(Refer sections 5.1 and 5.2)**

April - 2017 Power Electronics T.E. (E&Tc) Semester - II (2012 course) [In Sem. Exam -23]	SPPU Solved Paper

Time : 1 Hour] **[Maximum Marks : 30**

Note :

1) Answer Q.1 or Q.2, Q.3 or Q.4, Q.5 or Q.6.

2) Neat diagrams and waveforms must be drawn wherever necessary.

3) Figures to the right indicate full marks.

4) Use of nonprogrammable calculator is allowed.

5) Assume suitable data, if necessary.

Q.1 a) *Explain construction and steady state characteristics of SCR.* **(Refer sections 1.1 and 1.2)** **[6]**

b) *For an SCR, the gate triggering circuit has a source voltage of 15 V and load line slope of – 120 V/A. The minimum gate current to turn on the SCR is 25 mA. If average gate power dissipation is 0.4 W, calculate triggering voltage and triggering current.* **(Refer section 1.9)** **[4]**

OR

Q.2 a) *Draw and explain synchronized UJT triggering circuit for SCR with waveforms.* **(Refer section 1.10.5)** **[6]**

b) *Compare power MOSFET with IGBT.* **(Refer section 1.6.7)** **[4]**

Q.3 a) *Draw and explain single phase fully controlled bridge converter for R-L load with various o/p voltage waveforms.* **(Refer section 2.3)** **[6]**

b) *A single phase semi converter is operated from 230 V, 50 Hz AC supply. The load is resistive having resistance of 10 Ω. If the firing angle (α) is 60°, calculate*
i) Average o/p voltage ii) Rms o/p voltage **(Refer example 2.2.9)** **[4]**

OR

Q.4 a) *Draw and explain three phase fully controlled bridge converter for R load with o/p voltage waveforms.* **(Refer section 2.8)** **[7]**

b) *What is commutation? Explain natural commutation with forced commutation for SCR.* **(Refer section 2.1)** **[3]**

Q.5 a) *Draw and explain single phase full bridge inverter for R-L load with o/p voltage and current waveforms.* **(Refer section 3.3.2)** **[5]**

b) *Single phase full bridge inverter is operated from 48V dc supply, it has a resistive load of R = 2.4 Ω. Find its rms o/p voltage at fundamental frequency.* **(Refer similar example 3.3.3)** **[2]**

c) *Compare free wheeling diode and feedback diode ?* **(Refer section 2.2)** **[3]**

OR

Q.6 a) *Compare 180° mode and 120° mode in three phase inverters for balanced star R load.* **(Refer section 3.4)** **[6]**

b) *Write a note on PWM inverters.* **(Refer section 3.5)** **[4]**

May - 2017
Power Electronics
T.E. (E&Tc) Semester - II (2012 course)
[End Sem. Exam] [5153]-560

SPPU
Solved Paper

Time : 2 $\frac{1}{2}$ Hours] **[Maximum Marks : 70**

Q.1 a) *Draw steady state characteristics of SCR. Explain IL, $I_H V_{BO}, V_{BR}$, and show them on the characteristics.* **[Refer section 1.2]** **[7]**

b) *Explain two transistor analogy of an SCR. Drive anode current equation of SCR.* **[Refer section 1.2.5]** **[7]**

c) *Draw the circuit diagram of gate drive circuit for IGBT. Explain its operation.* **[Refer section 1.12]** **[6]**

OR

Q.2 a) *Draw the construction of power MOSFET and explain steady state characteristics of power MOSFET. Compare it with SCR and IGBT.*
[Refer sections 1.5.1, 1.5.2, 1.6.7] **[7]**

b) *Explain 180 degree conduction method of three phase voltage source inverter for balanced star connected resistive load.* **[Refer section 3.5.1]** **[6]**

c) *Draw the circuit diagram of single phase full controller bridge rectifier with R-L load. Explain its operation. Draw the waveform of output voltage and current.* **[Refer section 2.3.2]** **[7]**

Q.3 a) *What is DC to DC converter? Explain different methods for controlling the output voltage of chopper.* **[Refer section 4.1.1]** **[9]**

b) *Draw the circuit diagram of single phase AC voltage controller with R load. Explain its operation. Draw the waveform of output voltage.* **[Refer section 6.1]** **[9]**

OR

Q.4 a) *In a dc chopper, the average load current is 30 Amps, chopping frequency is 250 Hz, supply voltage is 110 volts. Calculate the ON and OFF periods of the chopper if the load resistance is 2 ohms.* **[Refer section 4.1]** **[9]**

b) *Draw the block schematic of SMPS and explain its advantages over Linear Power Supply.* **[Refer section 4.6]** **[9]**

Q.5 a) *Explain On-line UPS with neat block-diagram. State its specifications and applications.* **[Refer section 6.10.1]** **[6]**

b) *Explain with circuit diagram working of single phase seperately excited DC motor drive. Draw neat waveforms across load.* **[Refer sections 6.5 and 6.6.2]** **[10]**

OR

Q.6 a) *Compare ON-Line and OFF-Line UPS. Justify why ON-Line UPS is better.* **[Refer section 6.10.5]** **[8]**

b) *Explain electronic ballast. What are the advantages of fluorescent lamp over conventional lamp ?* **[Refer section 6.3]** **[8]**

Q.7 a) *Explain SLR half bridge DC/DC converter with neat circuit diagram and waveforms.* **[Refer section 5.7.2]** **[8]**

b) *Explain dv/dt, di/dt and snubber circuit in detail.* **[Refer sections 5.3 and 5.4]** **[8]**

OR

Q.8 a) *Explain with circuit diagram and neat waveforms ZCS resonant converters.* **[Refer section 5.7.3]** **[10]**

b) *Explain overvoltage and over current protection circuits.* **[Refer sections 5.1 and 5.2]** **[6]**

May - 2018 **Power Electronics** T.E. (E&Tc) Semester - II (2015 Course) [End Sem. Exam] [5353] - 556	SPPU **Solved Paper**

Time : 2 $\frac{1}{2}$ Hours] **[Maximum Marks : 70**

Note :

1) ***Answer Q.1 or Q.2, Q.3 or Q.4, Q.5 or Q.6, Q.7 or Q.8***
2) ***Neat diagrams must be drawn wherever necessary.***
3) ***Use of logarithmic tables slide rule, Mollier charts, electronic pocket calculator and steam tables in allowed.***
4) ***Assume suitable data if necessary.***
5) ***Figures to the right indicate full marks.***

Q.1 a) *Draw the construction of SCR and explain the operation using two transistor analogy with expression of anode current.* **(Refer sections 1.1.1 and 1.2.5)** **[7]**

b) *Discuss the needs of series operation of SCR and explain the static and dynamic equalizing circuit. State its advantages and limitations.* **(Refer section 1.14)** **[7]**

c) *What are voltage control methods of inverter ? Explain any one technique.* **(Refer section 3.5)** **[6]**

OR

Q.2 a) *Draw steady state I-V characteristics of SCR. Explain the parameters I_L, I_H, V_{BO}, V_{BR} and show them on the characteristics.* **(Refer section 1.2)** **[7]**

b) *Draw the construction of power MOSFET and explain I-V steady state characteristics of power MOSFET. Compare and contrast with SCR.* **(Refer sections 1.5.1, 1.5.2 and Table 1.6.1)** **[7]**

c) *Draw and explain single phase full converter with highly inductive load with input and output waveforms at 60 °C and 120 °C.* **(Refer section 2.3.2)** **[6]**

Q.3 a) *In DC chopper, average load current is 25 A, chopping frequency is 1 kHz, V_s = 220 V, calculate ON and OFF period of chopper and duty cycle, if load resistance is 2 ohms, draw waveforms with values of voltage current and time ?* **[8]**

Ans. :

$$I_{o(av)} = 25 \text{ A}, V_s = 220 \text{ V}, R = 2\ \Omega, f = 1 \text{ kHz}$$

$$T = \frac{1}{f} = \frac{1}{1 \text{ kHz}} = \frac{1}{1000} = 1 \text{ msec}$$

$$V_{o(av)} = I_{o(av)} \cdot R = 25 \times 2 = 50 \text{ V}$$

$$\therefore \quad \text{Duty cycle } \delta = \frac{V_{o(av)}}{V_S} = \frac{50}{220} = 0.2273$$

And $$T_{on} = \delta \cdot T = 0.2273 \times 1 \text{ msec} = 0.2273 \text{ msec}$$

$$\therefore \quad T_{off} = T - T_{on} = (1 - 0.2273) \text{ msec} = 0.7727 \text{ msec}$$

Waveforms will be similar to those shown in Fig. 4.1.2.

b) *Draw and explain step up chopper with circuit diagram and waveforms ? Derive the expression of its output voltage ?* **(Refer section 4.3 and example 4.3.1)** **[8]**

OR

Q.4 a) *Draw the circuit diagram and explain working of single phase full waves ac voltage controller using IGBT with R load, derive equation for rms output voltage ?* **(Refer section 6.1 and example 6.1.1)** **[8]**

b) *Draw the diagram and explain the operation of step down SMPS ? Draw the diagram showing implementation of this SMPS using PWM IC LM 3524 ?* **(Refer sections 4.6 and 4.9)** **[8]**

Q.5 a) *What are resonant converters ? Explain necessity of resonant converters. State its advantages.* **(Refer sections 5.7 and 5.7.1)** **[8]**

b) *With the help of circuit diagram, explain how overvoltage protection is achieved using selenium diode and metal oxide varistor ?* **[10]**

Ans. :

- Fig. 1 shows the circuit diagram of overvoltage protection using selenium diode and metal oxide varistor.

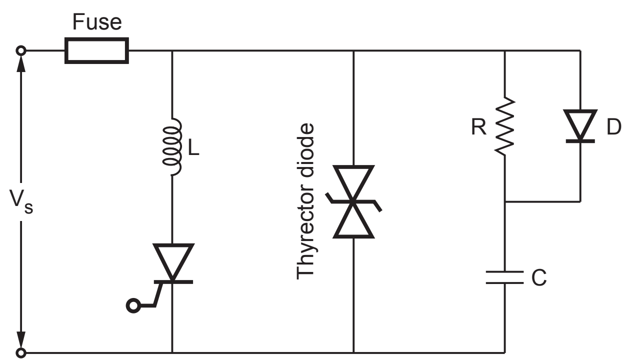


Fig. 1 Overvoltage protection using selenium diode or MOV

- The voltage control device has falling resistance characteristic with increasing voltage.
- It has high resistance under normal voltage. It draws very small leakage current.
- When high voltage surge appears, the voltage control device offers low resistance and produces a virtual short circuit across the SCR. Hence SCR current is diverted and it is protected.
- Selenium thyractor diodes, metal oxide varistor (MOV) or avalanche diodes are commonly used voltage control devices.

OR

Q.6 a) *Explain with the neat diagram and waveforms L-type ZCS resonant converters ?* **(Refer Section 5.7.3)** **[10]**

b) *Explain need of heat sink and its design considerations to protect the power devices. A power device has a thermal resistance of 200 °C/W. Calculate the maximum permissible power dissipation, when the* $T_{j\max} = 90\ °C$ *and* $T_A = 25\ °C$. **[8]**

Ans. : Refer section 5.5 for theory part.

Maximum permissible power dissipation of given as,

$$P = \frac{T_j - T_a}{R_{\theta_{ja}}} = \frac{90-25}{200} = 0.325 \text{ W}$$

Q.7 a) *With the help of block diagram, explain the working of LED lamp driver circuit used for domestic lightening applications.* **(Refer section 6.4)** **[8]**

b) *What are the various types of UPS systems ? With the help of block diagram, explain function of each block of on line UPS system ?* **(Refer section 6.10)** **[8]**

OR

Q.8 a) *Calculate the back-up time in hour for a UPS with battery rating of 12 V, 15 AH capacity, maximum input power rating is 800 VA, actual power consumed by intercom system load is 300 watts at lagging power factor of 0.9. Assume efficiency of UPS is 85 %.* **[8]**

Ans. : Load power in VA to be supplied by the battery at the input of inverter will be,

$$\text{Low power} = \frac{\text{Load power (watts)}}{\text{PF} \times \text{UPS efficiency}}$$

$$= \frac{300}{0.9 \times 0.85} = 392.15 \text{ VA}$$

$$\therefore \quad \text{Backup time} = \frac{\text{Battery voltage} \times \text{AH rating}}{\text{Load power}}$$

$$= \frac{12 \times 150}{392.15} \approx 5 \text{ Hours}$$

b) *Draw and explain the operation fan regulator circuit using triac with neat waveforms at various points ?* **(Refer section 6.2)** **[8]**

December - 2018
Power Electronics
T.E. (E&Tc) Semester - II (2015 course)
[End Sem Exam.] [5460]-556

SPPU
Solved Paper

Time : 2 $\frac{1}{2}$ Hours] **[Maximum Marks : 70**

Instructions to the candidates :

1) ***Neat diagrams must be drawn wherever necessary.***
2) ***Use of logarithmic tables slide rule, Mollier charts, electronic pocket calculator and steam tables is allowed.***
3) ***Assume suitable data, if necessary.***

Q.1 a) *Explain the gate drive circuit requirements for MOSFET and draw the sample drive circuit.* **(Refer sections 1.11)** **[6]**

b) *Explain effect of source impedance on the performance of 1Φ full converter. Derive the expression for average output voltage.* **(Refer section 2.4)** **[6]**

c) *In a single phase full converter with highly inductive load is fed from 120V RMS ac mains and fired at α = 45°, Calculate.*
i) Average load voltage ii) RMS load voltage iii) Power factor. **[8]**

Ans. : Given data : $V_s = 120$ V, $\alpha = \frac{\pi}{4}$ or 45°

i) Average output voltage

$$V_{o(av)} = \frac{2V_m}{\pi}\cos\alpha = \frac{2\times 120\sqrt{2}}{\pi}\cos\ 45° = 76.4 \text{ Volts}$$

ii) RMS load voltage

$$V_{o(rms)} = V_s = 120 \text{ V}$$

iii) Power factor

$$\text{PF} = \frac{2\sqrt{2}}{\pi}\cos\alpha = \frac{2\sqrt{2}}{\pi}\cos\ 45° = 0.637$$

OR

Q.2 a) *In a full AC to DC converter, explain the rectification mode and line commutated inverter mode of operation with relevant waveforms.*
(Refer sections 2.3.2.1 and 2.3.3) **[7]**

b) *Explain single pulse PWM and sinusoidal PWM control technique for 1ϕ inverter.* **(Refer sections 3.5.2 and 3.5.4)** **[7]**

c) *Explain the following parameters in relation to ac to dc converters,*
i) Displacement factor ii) Harmonic factor iii) Power factor.
(Refer example 2.3.8) **[6]**

Q.3 a) *Explain the principle of step up chopper feeding R-L load, with neat diagrams and waveforms of load voltage, load current, voltage across switch and current through switch. Derive the expression of output voltage.*
(Refer section 4.3 and example 4.3.1) **[8]**

b) *Explain the operation of Flyback type SMPS and discuss advantages and limitations.* **(Refer sections 4.8.1)** **[8]**

OR

Q.4 a) *Explain 4 quadrant operation of chopper for DC motor as a load.*
(Refer sections 4.4.5) **[8]**

b) *Draw and explain the operation of single phase AC voltage controller using SCR or IGBT with necessary waveforms. Derive the expression of RMS voltage of output.* **(Refer section 6.1 and example 6.1.1)** **[8]**

Q.5 a) *Draw the neat diagram of ZCS resonant converter. Explain the operation through waveforms.* **(Refer section 5.7.3)** **[8]**

b) *In a MOSFET operating in a circuit with V_{DS} = 25V and I_D = 1A, the thermal resistance $\theta_{jc} = 1°C / W$. Maximum Junction temperature is 125°C and ambient temperature is 25°C, the thermal grease is used between heat sink and device case reduces the θ_{cs} = 0.3° C/W, find the appropriate heat sink.* **[8]**

OR

Q.6 a) *Draw the neat diagram of ZVS resonant converter. Explain the operation through waveforms.* **(Refer section 5.7.4)** **[8]**

b) *Explain dv/dt, di/dt and snubber circuit protection.* **(Refer sections 5.3 and 5.4)**

[8]

Q.7 a) *A UPS is driving a load of 200 W with lagging pf of 0.82. The efficiency of the inverter is 85 % and the battery is 12 V.*
Find : i) kVA rating of inverter ii) AH rating of battery **[6]**

Ans. :

$$P_{o(UPS)} = 200 \text{ W}, \quad \text{PF} = 0.82$$

$$\eta_{(inverter)} = 0.85, \qquad V_{dc} = 12 \text{ V}$$

$$\text{PF} = \frac{\text{Active power output}}{\text{Total RMS power (kVA)}}$$

$$\therefore \quad \text{kVA rating} = \frac{\text{Active power}}{\text{PF}} = \frac{200}{0.82} = 244 \text{ VA} = 0.244 \text{ kVA}$$

$$\text{Rectifier wattage} = \frac{P_{o(UPS)}}{\eta_{(inverter)}} = \frac{200}{0.85} = 235.3 \text{ W}$$

$$\text{Battery wattage} = \text{Battery voltage} \times \text{Battery current}$$

$$235.3 = 12 \times I_{dc} \Rightarrow I_{dc} = 19.6 \text{ A}$$

$$\therefore \quad \text{AH rating} = I_{dc} \times \text{Backup time}$$

$$= 19.6 \times \frac{1}{2} = 9.8 \approx 10 \text{ AH for half an hour backup.}$$

b) *Draw and explain the fan regulator using Triac and Diac with waveform at various circuit points.* **(Refer sections 6.2)** **[6]**

c) *What are the methods of speed control of DC motor ? Explain how the speed of the separately excited dc motor can be controlled by DC drive system ?*
(Refer sections 6.5.2 and 6.6.2) **[6]**

OR

Q.8 a) *What is stepper motor drive ? Explain with necessary sequence generation how it works.* **(Not in new syllabus)** **[8]**

b) *Draw and explain torque speed characteristics of DC drive and explain the constant power and constant speed operation of DC motor.* **(Refer section 6.5.3)**

[10]

April - 2019
Power Electronics
T.E. (E&Tc) Semester - II (2015 course)
[In Sem Exam.] [119]

SPPU
Solved Paper

Time : 1 Hour] **[Maximum Marks : 30**

Instructions to the candidates :

1) ***Answer Q.1 or Q.2, Q.3 or Q.4, Q.5 or Q.6.***

2) ***Figures to the right indicate full marks.***

Q.1 a) *Explain following rating of SCR,* **[6]**

i) Holding current **(Refer section 1.2.4.2)**

ii) Latching current **(Refer section 1.2.4.1)**

iii) V_{BO} **(Refer section 1.2.1)**

iv) V_{RRM} **(Refer section 1.8.1)**

b) *Draw the V-I characteristics of IGBT. Mark and explain various operating regions and SOA of the IGBT.* **(Refer sections 1.6.2 and 1.6.3)** **[4]**

OR

Q.2 a) *Explain how the following devices can be operated as switch with necessary driving conditions.*
i) SCR ii) IGBT **(Refer sections 1.2 and 1.6)** **[6]**

b) *Draw and explain switching characteristics of SCR.* **(Refer section 1.3)** **[4]**

Q.3 a) *With the help of neat circuit diagram and waveforms, explain the operation of 1*ϕ *Full-converter for* $\alpha = 30°$ *and* $\alpha = 60°$ *with R load.* **(Refer section 2.3)** **[5]**

b) *Draw and explain the single phase dual converter. Explain the 4 quadrant operation of dual converter.* **(Refer section 2.6)** **[5]**

OR

Q.4 a) *Explain effect of source Inductance on the performance of 1* Φ *full converter. Derive the expression for average output voltage.* **(Refer section 2.4.2)** **[4]**

b) *In a single phase semi converter with highly inductive load is fed from 120 V RMS as mains and fired at $\alpha = 90°$, Calculate*
i) Average load voltage ii) RMS load voltage iii) Displacement factor **[6]**

Ans. : Given : $V_s = 120$ V, $\alpha = 90°$ or $\frac{\pi}{2}$

Hence, $V_m = \sqrt{2}V_s = 120 \times \sqrt{2}$

i) Average load voltage :

$$V_{o(av)} = \frac{V_m}{\pi}(1+\cos\alpha) = \frac{120\sqrt{2}}{\pi}\left(1+\cos\frac{\pi}{2}\right) = 54 \text{ Volts}$$

ii) RMS load voltage :

$$V_{o(rms)} = \left\{\frac{V_m^2}{2\pi}\left[\pi-\alpha+\frac{1}{2}\sin 2\alpha\right]\right\}^{\frac{1}{2}}$$

$$= \left\{\frac{(120\sqrt{2})^2}{2\pi}\left[\pi-\frac{\pi}{2}+\frac{1}{2}\sin\left(2\times\frac{\pi}{2}\right)\right]\right\}^{\frac{1}{2}} = 84.85 \text{ Volts}$$

iii) Displacement factor :

$$DF = \cos\phi_1 = \cos\left(-\frac{\alpha}{2}\right) = \cos\left(\frac{\alpha}{2}\right)$$

$$= \cos\left(\frac{90}{2}\right) = 0.707$$

Q.5 a) *With the help of neat circuit diagram and waveforms, explain the working of single phase bridge inverter for R load. Derive the expression for RMS output voltage.* **(Refer section 3.3 and example 3.3.1)** **[6]**

b) *Explain Single pulse PWM and Sinusoidal PWM control technique for 1ϕ inverter.* **(Refer sections 3.5.2 and 3.5.4)** **[4]**

OR

Q.6 a) *With the help of neat circuit diagram and waveform explain the working of 3ϕ voltage source inverter R load with 120° conduction mode.* **(Refer section 3.4.2)** **[6]**

b) *With the Fourier expression, explain what are the harmonics presents in the output of single phase 50 Hz square wave inverter with R-L Load ? Calculate RMS value 1^{st}, 3^{rd} and 5^{th} harmonic if the dc supply is 48 Volts ?* **[4]**

Ans. : Consider that the square waver inverter is 1 ϕ full bridge inverter. Refer example 3.3.1 for Fourier series of output voltage. It shows that *"odd"* harmonics are present in the output.

RMS value of 1^{st}, 3^{rd} and 5^{th} harmonic :

From example 3.3.1, the rms value of n^{th} harmonic is given as,

$$V_{n(rms)} = \frac{0.9V_s}{n}$$

Fundamental or 1^{st} harmonic, $V_{1(rms)} = \frac{0.9V_s}{1} = 0.9\ V_s$

3^{rd} harmonic, $V_{3(rms)} = \frac{0.9V_s}{3} = 0.3\ V_s$

5^{th} harmonic, $V_{5(rms)} = \frac{0.9V_s}{5} = 0.18\ V_s$

May - 2019 **Power Electronics** T.E. (E&Tc) Semester - II (2015 course) [End Sem Exam.] [5560]-556	SPPU **Solved Paper**

Time : 2 $\frac{1}{2}$ Hours] **[Maximum Marks : 70**

Q.1 a) *Explain the nature of gate characteristics and analyze the gate circuit requirements.* **(Refer section 1.9)** **[7]**

b) *Draw and explain working of single phase fully controlled rectifier for R load. Draw input output Voltage waveforms. State equation for average output voltage.* **(Refer section 2.3.1 and example 2.3.1)** **[7]**

c) *Explain 120° conduction mode of three phase inverter for balanced star R load with circuit diagram.* **(Refer section 3.4.2)** **[6]**

OR

Q.2 a) *Describe the concept of Safe operating areas of MOSFET and IGBT.* **(Refer sections 1.5.4 and 1.6.2)** **[7]**

b) *Draw and explain three phase semi converter for R load with input and output voltage waveforms.* **(Refer section 2.7)** **[7]**

c) *Explain 180° conduction mode of three phase inverter for balanced star R load with circuit diagram.* **(Refer section 3.4.1)** **[6]**

Q.3 a) *Explain the operation of step down chopper with circuit diagram and derive an expression for its output voltage in terms of chopping frequency.*
(Refer section 4.1 and example 4.1.1) **[8]**

b) *Classify SMPS, draw a generalized block diagram of SMPS. State its advantages and limitations.* **(Refer section 4.6)** **[8]**

OR

Q.4 a) *In DC chopper, average load current is 30 A, Chopping frequency is 500 Hz, V_s = 110 V. Calculate on and off period of chopper, if RL is 2 Ohms. Illustrate your answer with suitable waveforms.* **[8]**

Ans. : Given : $I_{o(av)} = 30$ A, $f = 500$ Hz, $V_s = 110$ V, $R = 2\ \Omega$

Find T_{ON} and T_{OFF}

$$T = \frac{1}{f} = 0.002 \text{ sec}$$

$$I_{o(av)} = \frac{\delta V_s}{R}$$

$$\delta = \frac{I_{o\,(av)}R}{V_s} = \frac{30 \times 2}{110} = 0.5454$$

$$T_{ON} = \delta \cdot T = 0.54 \times 0.002 = 1.091 \text{ msec}$$

$$T_{OFF} = T - T_{ON} = 0.909 \text{ msec}$$

b) *Explain working of single phase full wave bidirectional controller using SCR with R load. Draw waveform and state equation of RMS output voltage.*
(Refer section 6.1) **[8]**

Q.5 a) *What is resonant converter ? State necessity of the resonant converter ?*
(Refer sections 5.7 and 5.7.1) **[8]**

b) *Explain design considerations of heat sink to reduce switching losses in the power circuits. Name four protection devices.* **[8]**

Ans. : Design considerations to reduce switching losses :

i) Type of switching should be considered. This means on/off times of power devices.

ii) The power dissipation should be derated properly to design the heat sink.

iii) The type of load must be considered while designing the heat sink.

iv) Switching environment or air flow must be taken into consideration while designing the heat sink.

v) The type of switching device also affects the design of heat sink.

OR

Q.6 a) *Compare zero current and zero voltage switching resonant converters ?* **[8]**

Ans. :

Sr. No.	ZCS	ZVC
1.	Switches change their positions at zero current.	Switches change their positions at zero voltage.
2.	Switch is required to handle peak current.	Switch is required to handle peak voltage.
3.	Not preferred at high frequencies due to internal capacitances.	Preferred over ZCS at high frequencies.
4.	Switch voltage is limited to DC supply voltage, V_s.	Switch current is limited to load current, I_o.

b) *A power device has a thermal resistance of 200 °C/Watt. Calculate the maximum permissible power dissipation when maximum junction temperature is 75 °C and ambient temperature is 37°C.* **[8]**

Ans. : $R_\theta = 200°C/W$

$$T_j = 75 \text{ °C}$$

$$T_a = 37 \text{ °C}$$

$$R_\theta = \frac{T_j - T_a}{P}$$

$$P = \frac{75-37}{200}$$

$$P = 0.19 \text{ W}$$

Q.7 a) *With a circuit diagram, explain an application of Triac to control the domestic fan speed.* **(Refer section 6.2)** **[8]**

b) *Explain working of LED lamp Driver Circuit used as a domestic tube light.* **(Refer section 6.4)** **[10]**

OR

Q.8 a) *What are Drives ? Explain the working of Variable frequency three phase induction motor drive.*
(Refer section 6.9) **[8]**

b) *Explain working of on Line UPS. State four important commercial specifications.* **(Refer section 6.10.1)** **[10]**

December - 2019 Power Electronics T.E. (E&Tc) Semester - II (2015 course) [End Sem Exam.] [5669] - 546	SPPU Solved Paper

Time : $2\frac{1}{2}$ Hours] **[Maximum Marks : 70**

Q.1 a) *Draw the dynamic characteristics of SCR and explain the turn on and turn off process of SCR in detail ?* **(Refer section 1.3)** **[7]**

b) *With the help of neat circuit diagram and waveforms explain the operation of 3-ϕ semi converter for R-load with $\alpha = 60°$.* **(Refer section 2.7)** **[7]**

c) *List out the different voltage control techniques used in inverters ? Explain any one in detail ?* **(Refer section 3.5)** **[6]**

OR

Q.2 a) *Draw and explain steady state characteristics of power MOSFET ?*
(Refer section 1.5.2) **[6]**

b) *Explain the operation of symmetric 1ϕ semi converter with continuous load current. Draw the waveforms and state the equation for average output voltage.* **(Refer section 2.8)** **[7]**

c) *Explain 1-ϕ full bridge inverter for RL load using MOSFET draw necessary circuit diagram and waveforms.* **(Refer section 3.3)** **[7]**

Q.3 a) *Draw and explain step down chopper for R-load with circuit diagram and wave forms. Derive expression for avg output voltage ?*
(Refer section 4.1) **[8]**

b) *Derive the expression for average o/p voltage of step up chopper. A step up chopper has i/p voltage of 220 V and o/p voltage of 660 V. If the non conducting time is 100 μ sec. Calculate pulse width of o/p voltage. Also find the new o/p voltage if pulse width is half for constant frequency operation.* **[8]**

Ans. : Part A : Solution to numerical example

Let the average voltage across the inductance be V_L. The value of this voltage over one cycle (0 to T) will be,

$$V_L = \frac{1}{T}\int_0^T v_L(t)\, dt$$

The inductance voltage is $v_L(t) = L\frac{di_L}{dt}$. Hence above equation will be,

$$V_L = \frac{1}{T}\int_0^T L\frac{di_L(t)}{dt}\, dt = \frac{L}{T}\int_0^T di_L(t) \qquad \text{... (1)}$$

The above integration is with respect to inductance current $di_L(t)$, hence we should change the limits appropriately.

At $t = 0$ (lower limit), $i_L(t) = I_{min}$

and at $t = T$ (upper limit), $i_L(t) = I_{min}$

Hence equation (1) will be,

$$V_L = \frac{L}{T}\int_{I_{min}}^{I_{min}} d\, i_L(t) = \frac{L}{T}\left[i_L(t)\right]_{I_{min}}^{I_{min}}$$

$$= \frac{L}{T}\left[I_{min} - I_{min}\right] = 0 \qquad \text{... (2)}$$

Thus the average voltage across the inductance is zero. The inductance stores the energy when the switch is 'ON' and supplies the energy to the load when the switch is 'OFF'.

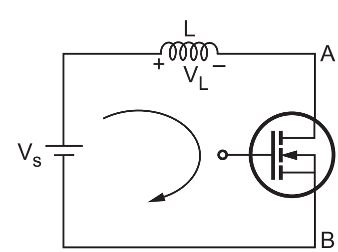


Fig. 1 Loop formed by supply, inductance and switch in step-up chopper

Now let us consider the loop formed by supply voltage V_s, inductance and switch. This loop is shown in Fig. 1. The voltage across the switch is v_{AB}. The waveform of v_{AB} is shown in Fig.1. The average value of v_{AB} can be obtained as follows :

$$V_{AB} = \frac{1}{T}\int_0^T v_{AB}(t)\, dt$$

In Fig. 1. observe that $v_{AB} = V_{o\,(av)}$ from δT to T and rest of the period it is zero. Hence above equation becomes,

$$V_{AB} = \frac{1}{T}\int_{\delta T}^{T} V_{o(av)}\, dt = \frac{V_{o\,(av)}}{T}(T - \delta T)$$

$$= V_{o\,(av)}(1-\delta) \qquad \text{... (3)}$$

By KVL to the loop shown in Fig. 1,

$$V_s = V_L + V_{AB}$$

The above equation holds for steady state. Putting values from equations (2) and (3) in above equation,

$$V_s = 0 + V_{o\,(av)}(1-\delta)$$

$$\therefore \quad V_{o\,(av)} = \frac{V_s}{1-\delta} \qquad \text{... (4)}$$

This equation gives the value of average output voltage. When $\delta = 0$, $V_{o\,(av)} = V_s$ and $V_{o(av)} \to \infty$ as δ approaches to unity. The value of duty cycle 'δ' lies between 0 and 1.

Part - B : Solution to numerical example

Supply voltage, $V_s = 220$ V, output voltage, $V_{o(av)} = 660$ V, $T_{off} = 100\ \mu$sec

i) To calculate T_{on}

We know that,

$$V_{o(av)} = \frac{V_s}{1-\delta}$$

$$\therefore \quad 660 = \frac{220}{1-\delta}$$

$$\therefore \quad \delta = 0.6666 \text{ or } \frac{2}{3}$$

Duty cycle is given as,

$$\delta = \frac{T_{on}}{T_{on} + T_{off}}$$

$$\frac{2}{3} = \frac{T_{on}}{T_{on} + 100 \times 10^{-6}}$$

$$\therefore \quad T_{on} = 200\ \mu\text{sec}$$

ii) To obtain output voltage if T_{on} is halved

Chopper frequency is,

$$f = \frac{1}{T} = \frac{1}{T_{on} + T_{off}} = \frac{1}{200\mu s + 100\mu s} = \frac{1}{300 \times 10^{-6}}$$

Hence chopper period is,

$$T = \frac{1}{f} = 300 \times 10^{-6} \text{ sec}$$

Since T_{on} is halved, it will be,

$$T_{on} = \frac{200\mu s}{2} = 100\ \mu\text{sec}$$

$\therefore$ Duty cycle, $$\delta = \frac{T_{on}}{T} = \frac{100\mu\text{ sec}}{300\mu\text{ sec}} = \frac{1}{3}$$

Therefore new output voltage will be,

$$V_{o(av)} = \frac{V_s}{1-\delta} = \frac{220}{1-\frac{1}{3}} = 330\text{ V}$$

Thus the output voltage is also reduced by half.

OR

Q.4 a) *With the help of circuit diagram and waveforms. Explain the operation of 1-ϕ full wave AC voltage controller with R-load ? Derive the expression for rms output voltage ?* **(Refer section 6.1)** **[8]**

b) *Derive the expression for average output voltage of step down chopper. If DC chopper has resistive load of R = 10 Ω and the input DC voltage is 300 V. When the chopper switch remains on its voltage drop is 2 V and the chopping frequency is 1 kHz. If duty cycle is 40 % determine.*
i) Average output voltage ii) rms output voltage
iii) Form factor iv) Ripple factor **[8]**

Ans. : Given $R = 10\ \Omega,\ V_s = 300\text{ V},\ V_{ch} = 2\text{ V}$

$f = 1\text{ kHz},\ \delta = 0.4$

i) Average output voltage :

$$V_{o(av)} = \delta(V_s - V_{ch})$$

$$\therefore \quad V_{o(av)} = 0.4(3.0 - 2) = \mathbf{119.2\ V}$$

ii) RMS output voltage :

$$V_{o(rms)} = \sqrt{\delta}(V_s - V_{ch})$$

$$\therefore \quad V_{o(rms)} = \sqrt{0.4}(300-2) = \mathbf{188.47\ V}$$

iii) Form factor (FF) :

$$FF = \frac{V_{o(rms)}}{V_{o(av)}} = \frac{188.47}{119.2} = \mathbf{1.58}$$

iv) Ripple factor (RF) :

$$RF = \sqrt{FF^2 - 1} = \sqrt{1.58^2 - 1} = \mathbf{1.22}$$

Q.5 a) *What is meant by electromagnetic interferance ? Explain it's sources and different minimization techniques in detail ?* **(Refer section 5.8)** **[10]**

b) *Explain the over voltage protection circuit using selenium diode and MOV to protect the power devices in detail ?* **[8]**

Ans. : i) Over voltage protection using MOV : Refer Q.5 (b) of May-2018.

ii) Overvoltage protection using selenium diodes

- Selenium diode has the characteristics similar to that of MOV and symbol is shown below : There are two types of selenium diodes -
  (i) Polarized and (ii) Non polarized
- The metal to selenium junction has very small forward breakover voltage, but high reverse breakdown voltage. The operating point lies before the knee (V_z) of the curve and draws very small negative current.
- When the overvoltage appears (more than V_z), the selenium diode starts conducting and protects the device.
- The polarized diode handles surges in only one direction and nonpolarized diode handles surges in both directions.
  Fig. 4 (a) shows typical over voltage protection circuits for DC and AC circuits.
- The advantage of selenium diodes is that it absorbs surge energy without much heating.

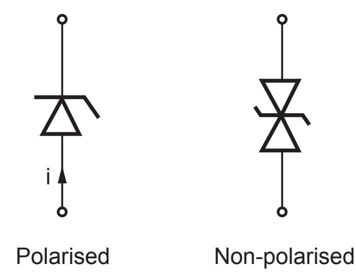


Fig. 2 Symbols of selenium diodes

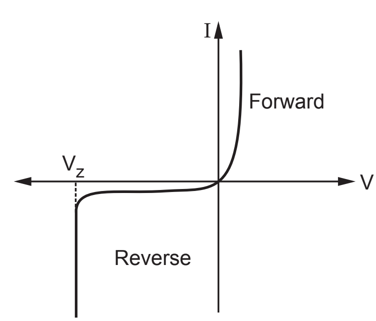


Fig. 3 Characteristics of selenium diode

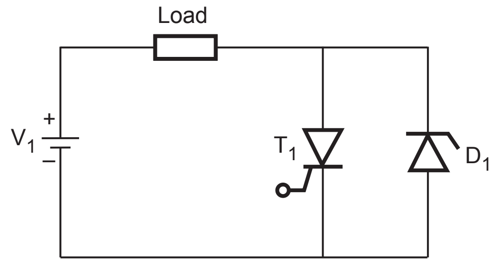


Fig. 4 (a) Selenium diode for DC circuit

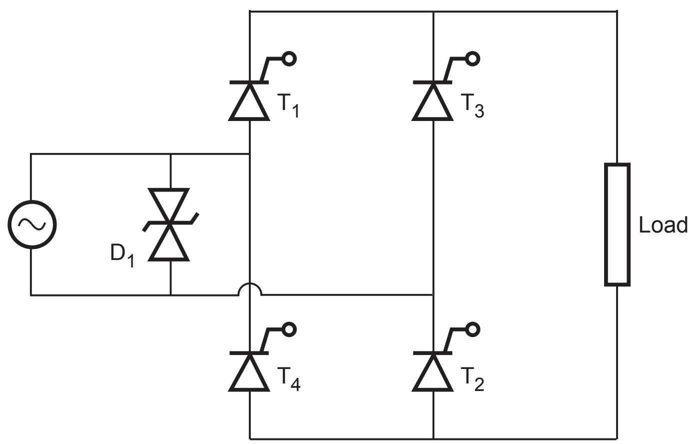


Fig. 4 (b) Selenium diode for AC circuits

OR

Q.6 a) *What is resonant converters ? Explain the concept of ZCS and ZVS. using circuit diagram and waveforms.* **(Refer section 5.7)** **[10]**

b) *What are the different cooling methods used for protection of power devices ? Explain in detail.* **[8]**

Ans. : The heat can be dissipated into ambience from the surface of the heat sink by following ways :

i) Natural convection ii) Forced air cooling

iii) Liquid cooling iv) Vapour phase cooling

Let us now study these techniques in detail.

1. Natural Convection : The heat sink surfaces have some treatment to support heat transfer by radiation and natural convection. Copper fins are plated or painted. Aluminium fins are normally painted or anodized. Presently most of the heat sinks used are black anodized. The surface of heat sink under the device is free of paint or anodization. This gives minimum contact thermal resistance. The heat can move from heat sink to ambience naturally due to temperature difference. The equation of heat transfer is given as,

$$Q = hA(T_1 - T_2)$$

Here Q is the heat rate

h is the convection heat transfer coefficient

A is the area available for convection

$T_1 - T_2$ is the temperature difference.

Natural convection is used when there is not much heat dissipation from the device. Normally the devices are mounted in the open air. The heat exchange takes place due to natural flow of the air. Natural convection is more effective when area of the heat sink is more.

2. Forced Air Cooling : The circulation of air over the fins of heat sink can be increased with the help of fans or compressors. The hot air is taken away from the heat sink fins with the help of cooling fan. Therefore heat convection is fast and cooling of power device is more effective. The heat rate is similar to that of natural convection. But the heat transfer coefficient now depends upon,

$$h = 11.2\sqrt{\frac{v}{l}} \times 10^{-4} W / in^2 \,°C$$

Here v is free steam linear cooling air velocity across fin surface.

l is length of the fin parallel to air flow.

Above equation shows that heating is more effective if air flow is more. Presently almost all the equipments right from computers to power supplies use forced air cooling. The exhaust fans are mounted on the equipments, then remove hot air. Forced air cooling is always better than natural convection.

3. Liquid Cooling : The power devices can also be cooled with the help of liquids. Normally oil or water is used as a coolent in liquid cooling. Liquid cooling can be of two types :

i) Oil-immersed natural cooling and ii) Forced liquid cooling.

i) **Oil-immersed natural cooling :** In the oil-immersed natural cooling the heat sink assembly is immersed in oil tank. The heat is transferred from the device to the heat sink fins and then to the oil. The heat is the transferred from the oil to tank surface and then to the atmosphere. The tanks also have fins on their surface. Hence the heat transfer from tank to atmosphere is also increased.

ii) Forced liquid cooling : The liquid flows at some velocity around the heat sinks assembly. The liquid normally flows in a closed loop system. After passing over the heated device and heat sink, the liquid gets hot. Then it is passed through the narrow fins of the tank. These fins are open to the air. Therefore liquid gets cooled through the fins.

4. **Vapour Phase Cooling :** Vapour phase cooling is normally used for high power devices. The heat produced by the device evaporates the liquid. This vapour then flows to the condenser. The condenser again converts the vapour to liquid and sents it to the device.
The hermetically sealed copper tubing is used to transport liquid to and vapour from the device. Freon 113 is used as the coolant because it boils at 47 °C. It is chemically inert and nontoxic. It has good dielectric constant.

Q.7 a) *With the help of block diagram explain the operation of electronic ballast in detail ?* **(Refer section 6.3)** **[8]**

b) *What is online ? Offline ups ? Explain block diagram and applications ?* **(Refer sections 6.10.1 and 6.10.2)** **[8]**

OR

Q.8 a) *With the help of neat circuit diagram explain the operation of fan regulator circuit using TRIAC.* **(Refer section 6.2)** **[8]**

b) *A UPS is driving a 600 W load which has a lagging p.f. of 0.8. The efficiency of the inverter is 80 %. The battery voltage is 24 V DC. Assume that there is a seperate charger for the battery. Determine*
i) KVA rating of the inverter ii) Wattage of rectifier
iii) A.H. rating of battery for backup time of 30 min **[8]**

Ans. : **Given data :**

$$P_{o(ups)} = 600 \text{ W}, pf = 0.8, \eta_{(inverter)} = 0.8, V_{dc} = 24 \text{ V}$$

i) kVA rating of inverter $= \dfrac{P_{o(ups)}}{pf} = \dfrac{600}{0.8} = 750 \text{ VA} = 0.75 \text{ kVA}$

ii) Rectifier wattage $= \dfrac{P_{o(ups)}}{\eta_{(inverter)}} = \dfrac{600}{0.8} = 750 \text{ W}$

iii) AH rating of battery $= I_{dc} \times \text{Back up time (Hrs)}$ …(1)

$$\text{Battery wattage} = \text{Battery voltage} \times \text{Battery current} (I_{dc})$$

$$750 = 24 \times I_{dc} \text{ (Here rectifier wattage = Battery wattage)}$$

$$\therefore \quad I_{dc} = 31.25 \text{ A}$$

Putting values in equation (1),

$$\text{AH rating} = 31.25 \times \frac{1}{2} = 15.625 \text{ AH} \approx 16 \text{ AH}$$

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SOLVED MODEL QUESTION PAPER (In Sem)

Power Devices & Circuits

T.E. (E&Tc) Semester - VI (As Per 2019 Pattern)

Time : 1 Hour] **[Maximum Marks : 30**

N. B. :

i) Attempt Q.1 or Q.2, Q.3 or Q.4.

ii) Neat diagrams must be drawn wherever necessary.

iii) Figures to the right side indicate full marks.

iv) Assume suitable data, if necessary.

Q.1 a) *Explain static charcteristics of SCR.* **(Refer section 1.2)** **[8]**

b) *Explain series and parallel operation of SCRs.* **(Refer section 1.14)** **[7]**

OR

Q.2 a) *Explain the two transistor mode of SCR.* **(Refer section 1.2.5)** **[8]**

b) *Explain steady state characteristics of IGBT.* **(Refer section 1.6.4)** **[7]**

Q.3 a) *Explain the effect of source inductance in full convertor.* **(Refer section 2.4.2)** **[8]**

b) *For a 1ϕ half bridge converter having highly inductive load, derive the following :*
i) Fourier series for supply current. ii) n^{th} harmonic of supply current.
iii) Fundamental component of supply current. iv) RMS value of supply current.
(Refer example 2.2.5) **[7]**

OR

Q.4 a) *Explain PWM technique for power factor improvement in converters.*
(Refer section 2.5.4) **[8]**

b) *For the 1 ϕ fully controlled bridge converter having load of 'R' determine the following : i) Average output voltage $V_{o(av)}$ ii) RMS output voltage $V_{o(rms)}$*
If supply voltage is 230 V, 50 Hz and firing angle is 60°, determine average output voltage. **(Refer example 2.3.1)** **[7]**

SOLVED MODEL QUESTION PAPER (End Sem)

Power Devices & Circuits

T.E. (E&Tc) Semester - VI (As Per 2019 Pattern)

Time : 2 $\frac{1}{2}$ Hours] **[Maximum Marks : 70**

N. B. :

i) ***Attempt Q.1 or Q.2, Q.3 or Q.4, Q.5 or Q.6, Q.7 or Q.8.***

ii) ***Neat diagrams must be drawn wherever necessary.***

iii) ***Figures to the right side indicate full marks.***

iv) ***Assume suitable data, if necessary.***

Q.1 a) *Obtain Fourier series for the output voltage waveform of half bridge inverter. Determine the rms value of the fundamental component of output voltage.* **(Refer example 3.1.2)** **[8]**

b) *Explain 180° mode of conduction in 3ϕ bridge inverters.* **(Refer section 3.4.1)** **[6]**

c) *Explain single pulse modulation technique to reduce harmonics in inverters.* **(Refer section 3.5.2)** **[4]**

OR

Q.2 a) *State the performance parameters for inverters.* **(Refer section 3.2)** **[6]**

b) *Compare 180° and 120° modes of conduction in 3ϕ inverters.* **(Refer section 3.4.3)** **[6]**

c) *Explain the operation of diode clamped multilevel inverter.* **(Refer section 3.7.5)** **[6]**

Q.3 a) *State and explain various chopper control techniques.* **(Refer section 4.1.1)** **[8]**

b) *Derive an expression for average output voltage of the step-up chopper.* **(Refer example 4.3.1)** **[6]**

c) *Write a note on SMPS.* **(Refer section 4.6)** **[4]**

OR

Q.4 a) *For a chopper shown below, DC source voltage is 230 V, load resistance is 10 Ω. Consider the voltage drop of 2 V across chopper when it is on. For a duty cycle of 0.4 calculate, i) Average and rms value of output voltage ii) Chopper efficiency*
(Refer example 4.1.3) **[8]**

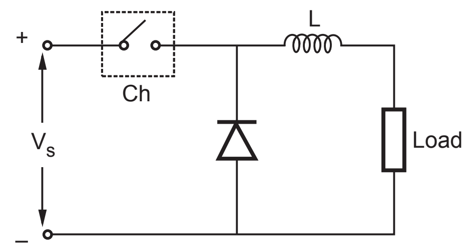

Fig. 1 Chopper circuit

b) *Explain the operation of four quadrant chopper.* **(Refer section 4.4.5)** **[6]**

c) *Explain the concept of MPPT.* **(Refer section 4.10)** **[4]**

Q.5 a) *What is concept of resonants converter ? Explain SLR converter.*
(Refer sections 5.7 and 5.7.2) **[8]**

b) *Determine the junction temperature for the thyristor which is dissipating the average power of 120 watts and* $R_{\theta_{jc}}$ *= 0.15 °C/W,* $R_{\theta_{cs}}$ *= 0.075 °C/W and* $R_{\theta_{sa}}$ *= 0.45 °C/W.* **(Refer example 5.5.1)** **[4]**

c) *Explain over voltage protection circuit for SCR.* **(Refer section 5.1.2)** **[5]**

OR

Q.6 a) *State advantages, disadvantages and applications of resonant converters.*
(Refer section 5.7.5) **[5]**

b) *What are different types of cooling methods for SCR.* **(Refer section 5.6)** **[4]**

c) *Calculate the values of snubber components R and C in Fig. 2 to protect SCR from reapplied dv/dt, if dv/dt rating of SCR is 100 V/μsec.* **(Refer example 5.3.1)** **[4]**

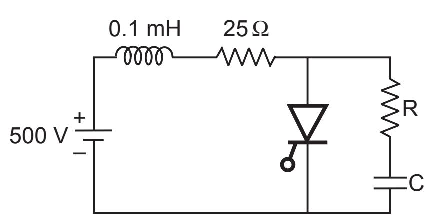

Fig. 2

d) *What are sources of EMI ? How it can be minimized ?*
(Refer sections 5.8.2 and 5.8.3) **[4]**

Q.7 a) *A single phase bidirectional regulator is feeding resistive load of* $10\ \Omega$. *The supply voltage is 230 V-50 Hz. If the firing angle is 45 degrees, calculate the power absorbed by the load. Derive necessary equations.* **(Refer example 6.1.2)** **[6]**

b) *Explain armature voltage control of DC motor with* 1ϕ *half bridge converter.*
(Refer section 6.6.2) **[6]**

c) *An online UPS is driving 800 W, 0.8 lagging PF load, an inverter efficiency is 80 % and dc link voltage and battery voltage is 48 V dc. Assuming batteries are ideal, Find i) VA rating of an inverter ii) Wattage or peak power requirement of rectifier. iii) AH capacity of batteries required for backup time of 30 minutes.*
(Refer example 6.10.1) **[5]**

OR

Q.8 a) *Draw the block diagram of electronic ballast and state its advantages and disadvantages.* **(Refer sections 6.3.2 and 6.3.3)** **[6]**

b) *How v/f control is achieved in inductor motor ? State its advantages.*
(Refer section 6.9) **[5]**

c) *Explain full bridge converter with interleaved boost PFC to charge battery in EVs.*
(Refer section 6.15) **[6]**

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