# Power Supplies

## 10.1. INTRODUCTION

Power supply is an essential component of an equipment. Industries, research laboratories, computer systems, commercial establishments all need power supplies. However, the power supply requirements of different users are vastly different mainly as regards voltage, power level and quality of power supply (voltage regulation and ripple content).

Power supplies can be dc or ac. Both of these have their own fields of applications. DC power supplies are needed mainly for research laboratories etc. AC power supplies are generally needed as stand by source for critical loads (during the time when mains supply is not available). Such ac supplies are designated as uninterruptible power supply (UPS).

Power supply specifications are in general, different for different applications. However, the following specifications are common :

1. Isolation between source and load.
2. Compact size.
3. High efficiency.
4. Low harmonic distortion.
5. Good voltage regulation.

## 10.2. SHUNT AND SERIES REGULATORS

These regulators use zener diode and operational amplifier to keep the output voltage constant for different load conditions and also for different input voltage conditions. The input voltage is a dc voltage which in turn may be obtained from mains ac voltage through a rectifier. A regulated power supply may use either shunt regulator or series regulator.

### 10.2.1. Shunt Regulator

Figure 10.1 uses a shunt regulator. The rectifier converts mains ac voltage to dc voltage. The filter eliminates ripples from the output of the rectifier.

The zener diode holds the inverting input of op amp at a constant voltage. The voltage divider formed by $R_1$ and $R_2$ samples the load voltage and supplies a feedback voltage to the non-inverting input. The output of the op amp is the input to the base of the shunt transistor. The negative feedback helps in keeping the output voltage constant inspite of changes in input voltage and load conditions.

The action of shunt regulator is as under. If the output voltage increases, the feedback signal to the non-inverting input increases and the output voltage of op amp increases. Since the output of the op amp is driving the base of transistor $T$, the collector current of transistor increases. This collector current is flowing through resistance $R_s$, and, therefore, the voltage drop across $R_s$ increases. This increase in voltage drop across $R_s$ offsets the increase in output voltage. A reverse action occurs if the output voltage decreases. Thus, the negative feedback offsets any increase or decrease in output voltage. The relevant equations for finding various currents and output voltage are :



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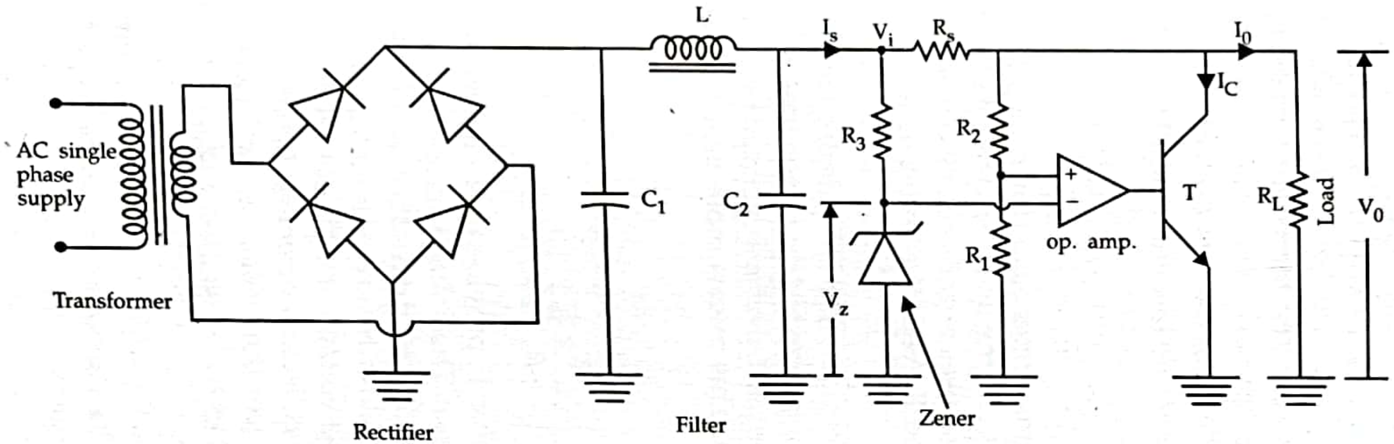


*Fig. 10.1. Shunt regulator*

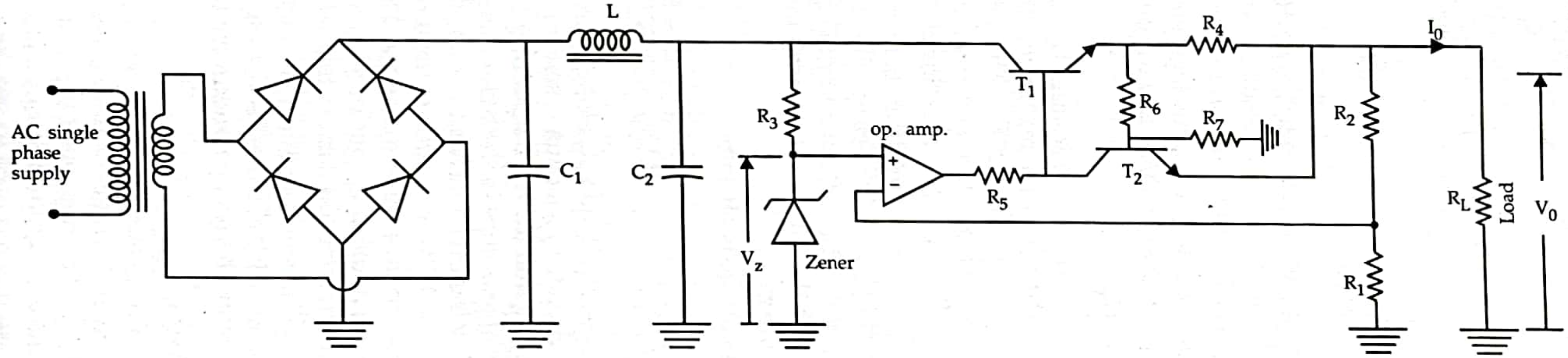


*Fig. 10.2. Series Regulator*

## 10.3. SWITCHING REGULATORS

A switching regulator converts an unregulated dc voltage into a constant dc voltage either lower or higher than the input voltage. These regulators use pulse width modulation to achieve voltage regulation. The output voltage is held constant under varying line voltage and load resistance conditions by adjusting the duty cycle. The switching device may be a power BJT or power FET. A switching regulator may be a buck regulator, a boost regulator or a buck-boost regulator.

### 10.3.1. Buck Regulator

Figure 10.11 shows the circuit of a buck regulator. It gives an output voltage which is less than input voltage, hence the name buck. In Fig. 10.11, a power BJT is used as the switching device. It is seen from Fig. 10.11 that this circuit is like a step down chopper. The pulse width modulator switches on

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the power BJT for a time interval $T_{on}$ and switches it off for a time interval $T_{off}$. The total time $(T_{on} + T_{off})$ is the switching period and $\frac{1}{T_{on}+T_{off}}$ is the switching frequency. The ratio $\frac{T_{on}}{(T_{on}+T_{off})}$ is the duty cycle $\alpha$.

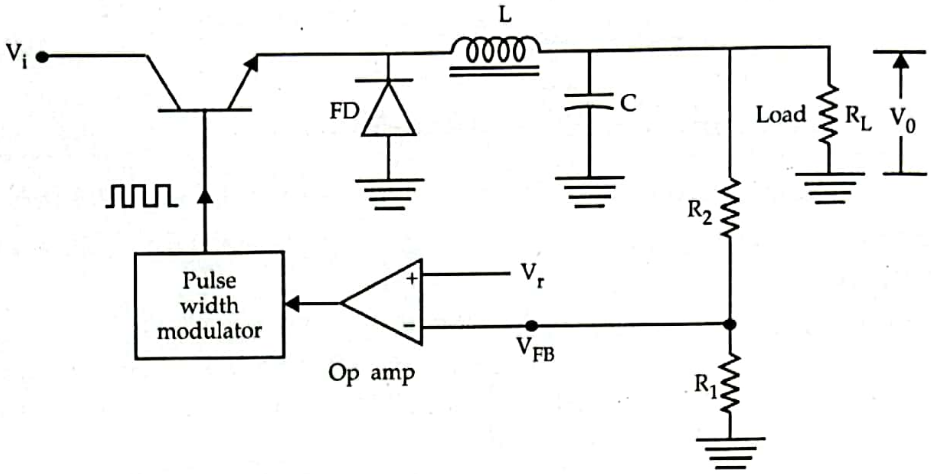


*Fig. 10.11. Buck regulator.*

The op amp is acting as a comparator. If the output voltage tends to increase, the feedback signal $V_{FB}$ increases and reduces the comparator output. The duty cycle $\alpha$ is reduced and $V_0$ is reduced. If $V_0$ tends to decrease, $V_{FB}$ decreases causing an increase in comparator output, an increase in duty cycle and an increase in $V_0$.

When the pulse from the PWM (pulse width modulator) is high, BJT turns on and the input $V_i$ feeds the load through inductor $L$. The freewheeling diode (FD) is reverse biased and hence cut off. Fig. 10.12 *(a)* shows the circuit during the mode which lasts for time $T_{on}$.

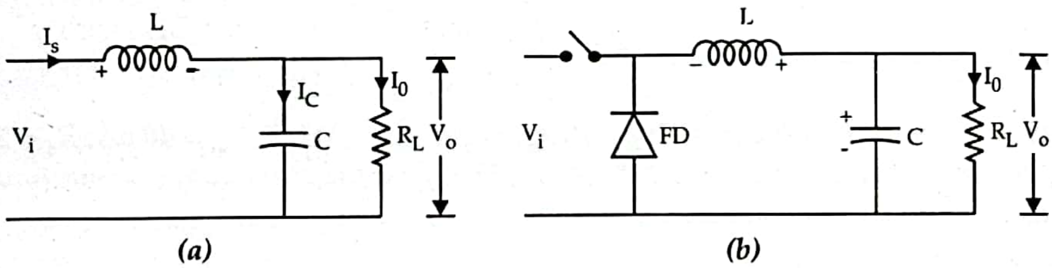


*Fig. 10.12. Modes of operation of buck regulator.*

When pulse from PWM is low, BJT is turned off. The magnetic field of inductance starts collapsing and a reverse voltage is induced across $L$. The freewheeling diode is forward biased and energy stored in inductance keeps the flow of current through the load. The capacitor also discharges and feeds current to the load. The circuit during this mode of operation is shown in Fig. 10.12 *(b)*. This mode lasts for time $T_{off}$.

Due to high gain of op amp, there is a virtual short-circuit at the input of op amp and reference voltage $V_r = V_{FB}$. The output voltage is

$$V_0 = \frac{R_1 + R_2}{R_1} V_r \qquad ...(10.6)$$

### 10.3.2. Boost Regulator

Figure 10.13 shows the circuit of a boost regulator. This circuit uses an op amp, a pulse width modulator to apply gate pulse of MOSFET M, a freewheeling diode FD, inductor $L$, capacitor $C$ and potential divider formed by $R_1$ and $R_2$. A boost regulator steps up the voltage.

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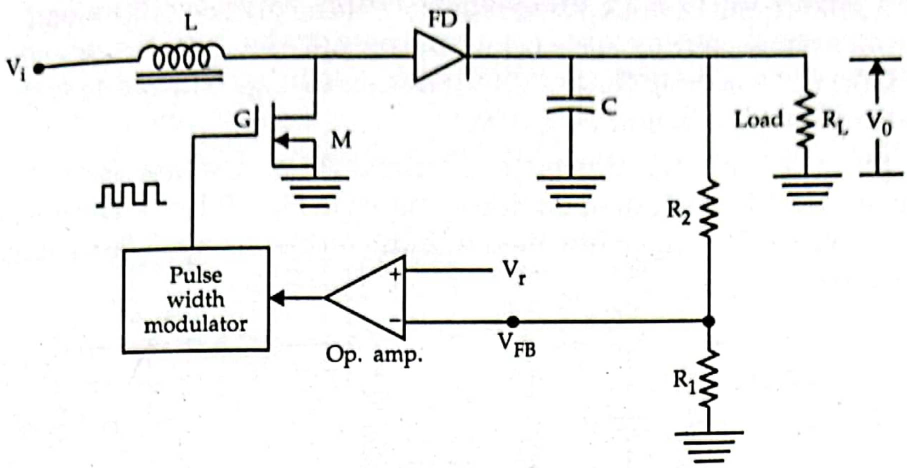


*Fig. 10.13. Boost regulator.*

When pulse is high, the MOSFET switch is closed and energy is stored in the magnetic field of inductance $L$. The capacitor supplies the load current for the period $T_{on}$. Figure 10.14 *(a)* shows the equivalent circuit during this mode of operation.

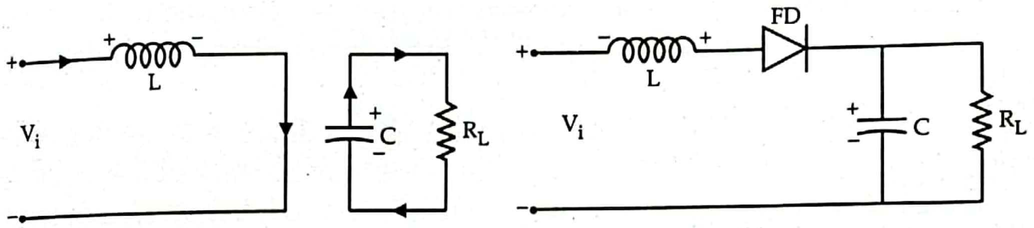


*Fig. 10.14. Modes of operation of boost regulator.*

When pulse is low, the MOSFET switch is open. The magnetic field of inductor collapses and induces a reverse voltage across the inductor. The equivalent circuit for this mode of operation is shown in Fig. 10.14 *(b)*. The inductor supplies current to the load. The output voltage is again given by Eqn. (10.6).

If voltage $V_0$ increases, the comparator output decreases and the duty cycle $\alpha$ decreases. Thus, the increase in $V_0$ is offset. If the voltage $V_0$ decreases, feedback voltage $V$ decreases and the comparator output increases. This increases the duty cycle $\alpha$ and a consequent increase in $V_0$.

### 10.3.3. Buck-Boost Regulator

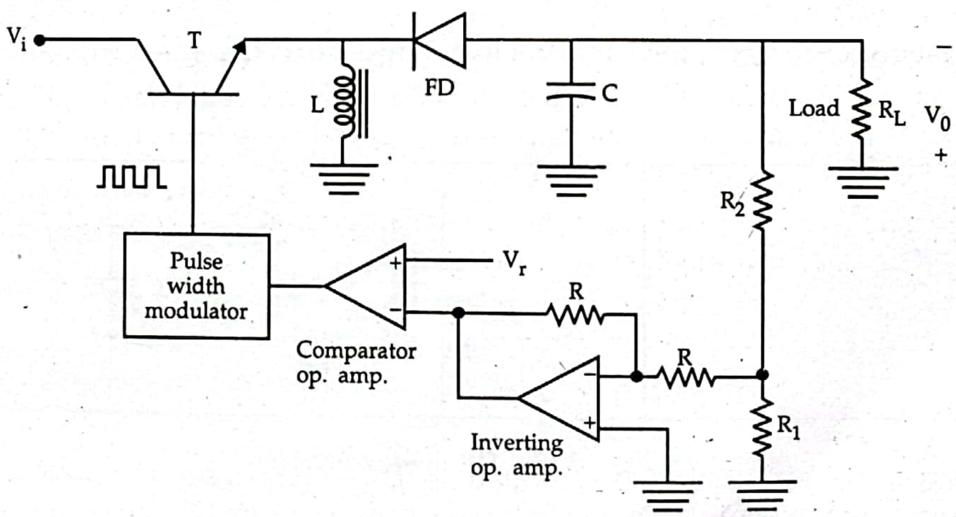


*Fig. 10.15. Buck-boost regulator.*

Figure 10.15 shows the circuit of buck-boost regulator. It can give an output voltage which is higher or lower than input voltage. If duty cycle is low, the output voltage is lower than $V_i$. If duty cycle is high, $V_0$ is more than $V_i$. Moreover, the polarity of output voltage is opposite to that of input voltage. Therefore, it is also known as *inverting regulator.*

When the pulse is high, the transistor is turned on and source feeds the inductance. The equivalent circuit under this mode of operation is shown in Fig. 10.16 *(a)*. The voltage across inductor is equal to source voltage. The magnetic field of inductor builds up. The capacitor discharges and supplies load current.

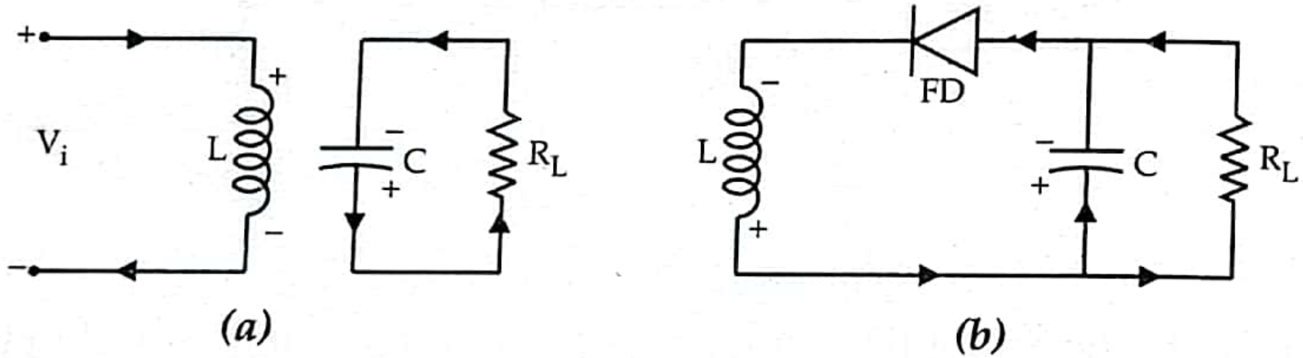


*Fig. 10.16. Modes of operation of buck-books regulator.*

When the pulse is low, the transistor is turned off. The magnetic field of inductance collapses. The polarity of voltage induced across inductance reverses. The equivalent circuit for this mode is shown in Fig. 10.16 *(b)*. The inductance supplies the load current. The capacitor charges during this mode of operation.

This circuit uses an inverting op amp to invert the feedback voltage before it is fed to the inverting input of the comparator. If output voltage tends to increase, the duty cycle is reduced and if the output voltage tends to decrease, the duty cycle is increased. In both these situations negative feedback helps in keeping the output voltage constant.

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supplies are necessary.

## 10.4. SWITCHED MODE POWER SUPPLY (SMPS)

A switched mode power supply is a multistage ac power supply. Its principle is similar to that of chopper. The duty cycle of chopper controls the dc output voltage. Since the frequency of switching is high, the ripple frequency is also high and ripples can be filtered out easily. It can have many configurations viz., flyback, push pull, half bridge and full bridge.

### 10.4.1. Flyback Converter

Figure 10.23 shows the circuit of flyback converter. The ac mains voltage is converted to dc by an ac-dc converter and fed to the SMPS. When transistor $T$ is on, voltage is fed to transformer primary winding and a voltage is induced in secondary due to mutual induction. When transistor is off, the secondary induces a voltage in primary. The diode $D_2$ prevents the flow of current in the primary winding due to this induced voltage. When transistor is off, the capacitor discharges through resistance $R$.

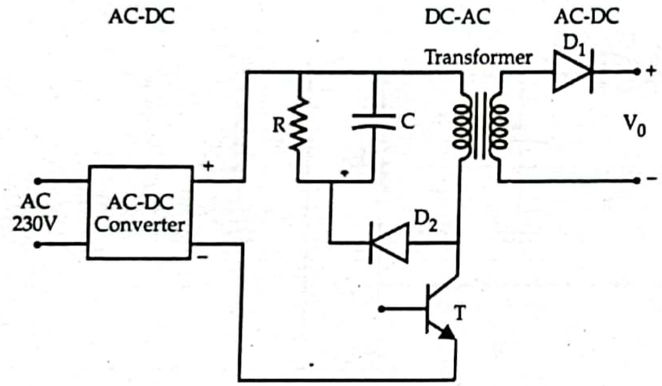


*Fig. 10.23. Flyback converter SMPS.*

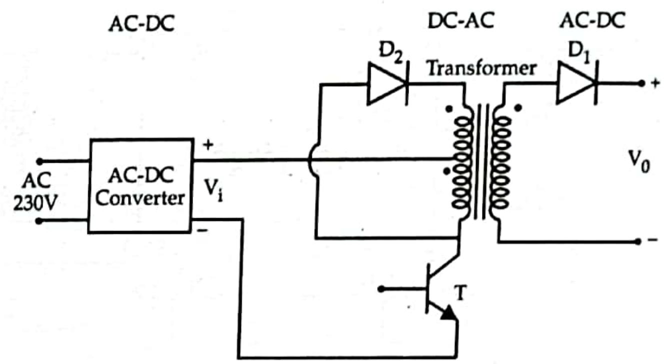


*Fig. 10.24. Flyback converter SMPS with reset winding.*

The diode $D_1$ acts as a half wave rectifier. To keep the voltage $V_0$ constant, a feedback signal from the output can be fed to the base of transistor $T$.

Figure 10.24 shows the flyback converter with reset winding. With this connection the energy stored in the transformer core is returned to the supply and the efficiency of the circuit is improved.

### 10.4.2. Push Pull Converter

Figure 10.25 shows the circuit of push pull converter. When transistor $T_1$ is turned on, the input voltage is fed to lower half of primary winding. When $T_2$ is turned on, input voltage is fed to upper half of primary winding. Thus the voltage across primary swings from $+V_i$ to $-V_i$. Each of the

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transistors $T_1$ and $T_2$ operates with 50% duty cycle. The average output voltage is given by $V_o = \alpha V_i$, where $\alpha$ is the duty cycle.

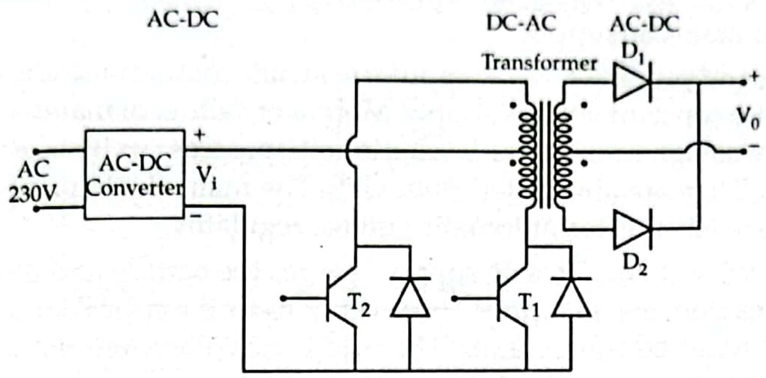


*Fig. 10.25. Pust-pull converter SMPS.*

### 10.4.3. Half Bridge Converter

Figure 10.26 shows a circuit known as *half bridge converter*. When transistor $T_1$ is on, the voltage impressed across primary is $V_i/2$. When $T_2$ is on, the voltage impressed across primary is $-V_i/2$. Thus the primary voltage swings from $+V_i/2$ to $-V_i/2$. The average output voltage is $0.5\,V_i (N_2/N_1)$.

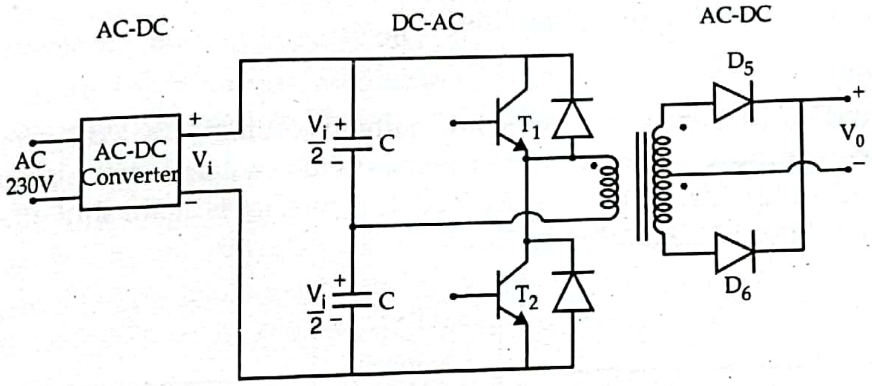


*Fig. 10.26. Half bridge converter SMPS.*

### 10.4.4. Full Bridge Converter

Figure 10.27 shows this circuit. It uses 4 transistors $T_1, T_2, T_3, T_4$ When $T_1$, $T_2$ are turned on voltage $V_i$ is applied to primary. When $T_3$, $T_4$ are turned on, voltage $-V_i$ is applied to primary. The average output voltage $V_o = (N_2/N_1)V_i$.

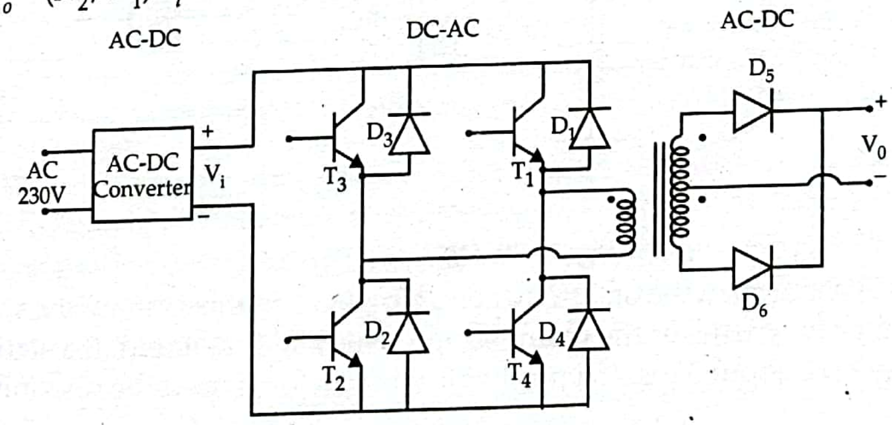


*Fig. 10.27. Full bridge converter SMPS.*

It has been found that full bridge circuit causes minimum voltage and current stresses across transistors. Therefore, this circuit is very popular for high power applications above 750 W or so.

## 10.5. UPS

UPS means uninterrupted power supply, *i.e.*, a power supply which continues to feed devices even in the event of failure of mains ac supply.

Many equipments and processes, *e.g.*, computer systems, communication systems, continuous process industries require constant voltage supply. Moreover, failure of mains supply can cause loss of data in computers, wastage of material in continuous process industries etc. Such loads are known as critical loads. They are always fed from UPS. The main elements of a UPS are : rectifier, battery, inverter, static switches, filter, automatic voltage regulator.

The rectifier converts ac to dc. This dc supply charges the battery and also feeds the inverter. The filter removes ripples from the dc supply. The inverter feeds the critical loads. The static switches connect/disconnect the required components. The automatic voltage regulator keeps the output ac voltage constant. It uses negative feedback to maintain constant output voltage. Present day UPS (especially those for computer systems) use pulse width modulated inverter because the output of such an inverter is perfect sine wave.

The battery works as a standby source of supply. It can be either lead acid battery or nickle cadmium battery. The electrolyte in the nickle cadmium battery is non-corrosive and does not emit bad fumes. Its life is also longer. As such a nickle cadmium battery is better. However, a nickle cadmium battery is more costly as compared to lead acid battery.

UPS can be classified as off line and on line.

### 10.5.1. Off Line UPS

In this configuration (Fig. 10.28) the inverter is normally in off state. The load is fed from the mains supply. When the mains supply is not available, a static switch switches on the inverter and connects it to the load automatically. When supply is restored, the inverter is again shut off. In such a system automatic voltage regulator is, generally, not used.

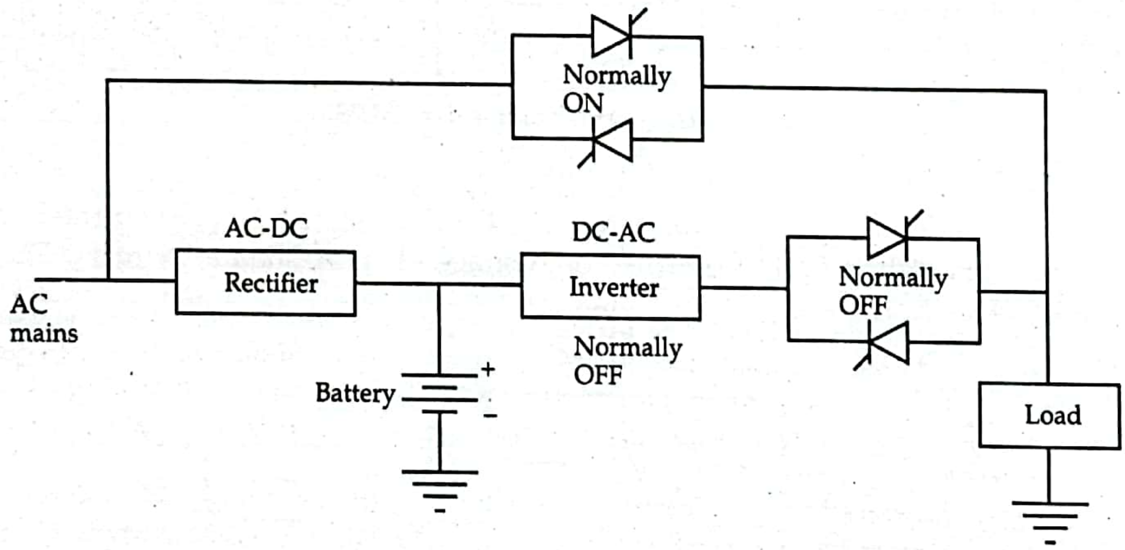


*Fig. 10.28. Off line UPS.*

This system is cheaper than the on line system. However, in this system, the supply to the load is disrupted momentarily whenever the mains supply fails and is restored. If a static switch is used each disruption may take about 5 ms. If a mechanical contactor is used the disruption time may be about 50 ms.

### 10.5.2. On Line UPS

In this configuration (Fig. 10.29) the load is always fed by the inverter. Thus, the rectifier and inverter are always on. The rectifier also keeps the battery in charged condition. The output from inverter is

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always conditioned, *i.e.*, constant voltage, constant frequency. (However, if necessary an automatic voltage regulator can also be used). If the inverter becomes faulty the load is fed directly from the mains supply (by closing the normally open switch).

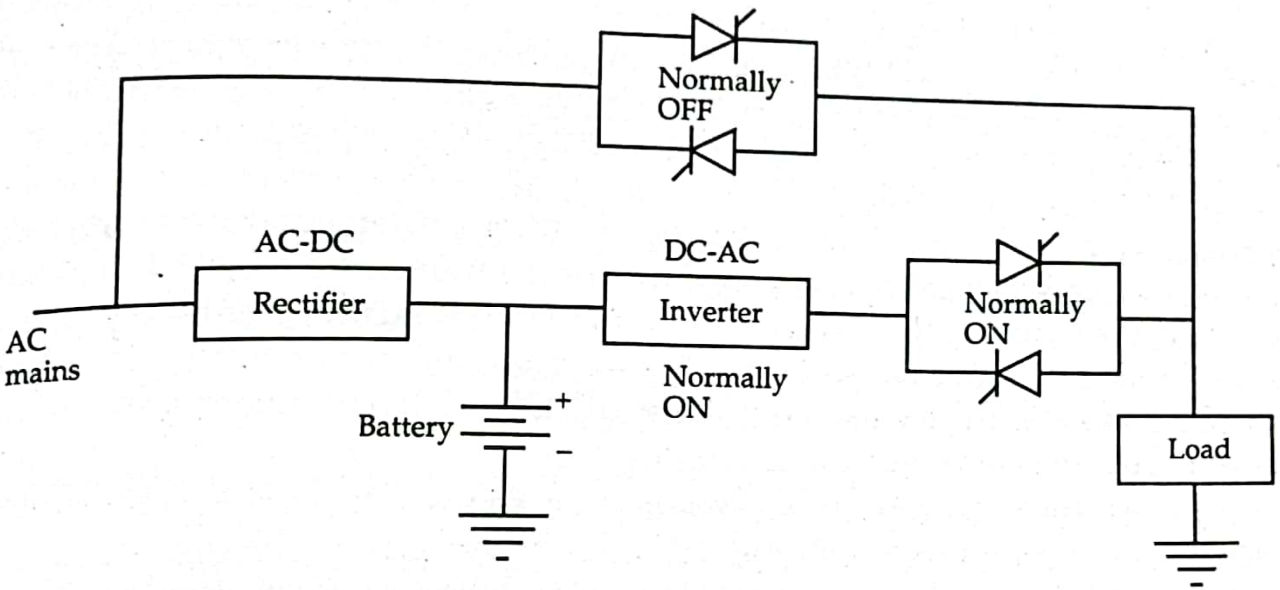


*Fig. 10.29. On line UPS.*

On line UPS has three modes of operation :

1. **Normal mode, input supply available :** The mains supply feeds the load through the rectifier-inverter combination. The output of rectifier keeps the battery in charged condition.
2. **Outage mode, input supply not available :** The battery feeds the load through the inverter. However, every UPS has a maximum time limit for which this mode can last. If the outage time exceeds this maximum time limit, the UPS shuts down.
3. **By pass mode :** This mode exists during overload conditions or when a fault develops in UPS. The normally off by pass switch is turned on and the load is fed directly from the mains supply.

## 2.13. HEAT SINKS AND MOUNTINGS

We have discussed the losses in thyristors in section 2.8.3. The heat generated due to these losses has to be dissipated to the environment. If heat dissipation is not proper, the junction temperature may rise beyond limit and damage the thyristor. The maximum junction temperature should not exceed 125°C. To ensure adequate heat dissipation, heat sinks are attached to the case of the thyristor. The heat is transferred from junction to the case, then to the sink and from sink to the atmosphere.

### 2.13.1. Thermal Ohm's Law

The heat dissipation is governed by thermal ohm's law. As per analogy with electric circuit theory, temperature difference is analogous to voltage difference, heat is analogous to charge and thermal resistance is analogous to electrical resistance.

As per thermal ohm's law, the heat dissipation is given by the equation

$$\theta_{21} = \frac{T_2 - T_1}{P_{21}} \qquad \text{...(2.13)}$$

where $\theta$ = Thermal resistance between points 2 and 1

$P_{21}$ = Power loss to be dissipated from point 2 to point 1, W

$T_2$ = Temperature of point 2, °C

$T_1$ = Temperature of point 1, °C

A thermal ohm is that thermal resistance which needs a temperature difference of 1°C across it to cause a heat flow of 1 W. Thus the thermal resistance has the units of °C/watt. The thermal resistivity (symbol $g$) is analogous to electrical resistivity and has the units of °C-m/watt.

### 2.13.2. Thermal Equivalent Circuit

Figure 2.31 shows the thermal equivalent circuit of SCR and Triac. $P_{av}$ is the average power loss in the device which has to be dissipated. $T_j$, $T_c$ and $T_s$ denote temperatures of junction, case and sink. $T_A$ is ambient temperature, $\theta_{jc}$, $\theta_{cs}$ and $\theta_{sA}$ are thermal resistances from junction to case, case to sink and sink to atmosphere respectively. The values of $\theta_{jc}$ and $\theta_{cs}$ are generally specified by the manufacturers. The power loss $P_{av}$ is also specified. Therefore, $\theta_{sA}$ can be calculated for the ambient temperature $T_A$. From the value of $\theta_{sA}$, the dimensions of heat sink can be calculated.

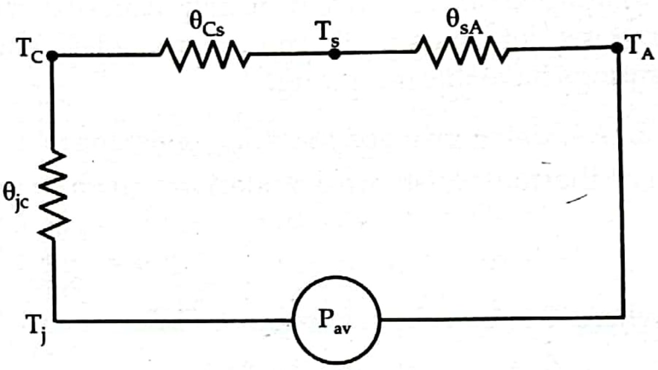


*Fig. 2.31. Thermal equivalent circuit of thyristor.*

Typical values of $\theta_{cs}$ vary from 0.05°C/W to 0.5°C/W depending on the type of case of the thyristor. Many types of extruded aluminium heat sinks are manufactured. Cooling fins are used to increase the surface area. Heat dissipation from the sink is mainly through convection. As such a large surface area helps in proper heat dissipation. In some cases natural air cooling may not be sufficient and it may be necessary to use forced air or forced fluid (generally water) cooling. Oil cooling is also used. Oil cooling provides necessary electrical insulation and eliminates the problem of corrosion. Most thyristor applications require operation at 400 Hz or so. Therefore, the actual loss may be more than average power loss. A suitable derating factor is used in calculations.

### 2.13.3. Mountings

Many types of mountings are used for thyristors depending on the power rating.

*(a)* **Lead mounting :** For very low power devices (current rating less than 1A) lead mounting is used as shown in Fig. 2.32 *(a)*. No additional heat sink is required.

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(*b*) **Stud mounting :** Figure 2.32 (*b*) shows the stud mounting. It is the most commonly used mounting. It uses a copper or aluminium stud which also acts as anode terminal. The stud is also used for thermal contact with heat exchanger. Thus the anode and heat sink are in electrical contact. It is suitable for small and medium size devices.

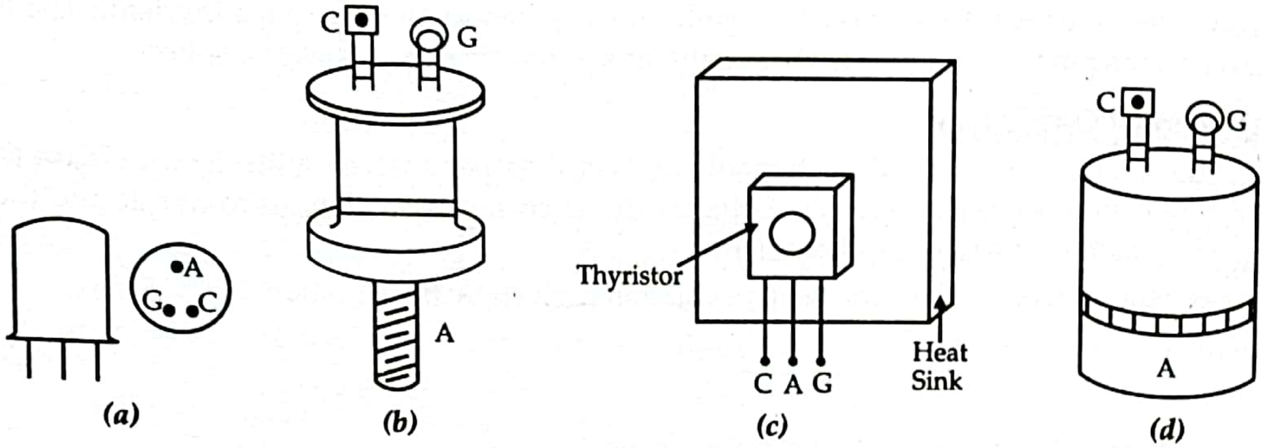


*Fig. 2.32. SCR mountings.*

(*c*) **Bolted mounting :** Figure 2.32 (*c*) shows the bolted mounting (also known as bolt down mounting). The device is attached to the heat sink by bolts. An insulation sheet can also be placed between the device and heat sink to electrically insulate the device from the heat sink.

(*d*) **Press-fit mounting :** Figure 2.32 (*d*) shows this mounting. The device is pressed into a hole in the heat sink. It is frequently used for devices of large ratings.

(*e*) **Pressure mounting :** It is also known as disc type mounting because of its shape. The device is clamped between two heat sinks using external force. It is necessary to ensure that the device does not get deformed while being mounted. Cooling can be by air or water. Thyristors of high current ratings have this mounting.

### 2.13.4. Calculation of Thermal Resistance

The thermal resistance of material is given by :

$$\theta = \frac{l}{\lambda A}$$

where $\theta$ = thermal resistance °C/W.

$A$ = cross-sectional area, m$^2$

$l$ = length, m

$\lambda$ = thermal conductivity W- m$^{-1}$ °C$^{-1}$

A material used commonly for heat sinks is 90% aluminium having thermal conductivity of 220 W-m$^{-1}$ °C$^{-1}$.

It is evident from Eqn. (2.13) that thermal resistance should be as low as possible so that for the same amount of power $P$, the temperature difference $(T_2 - T_1)$ is small. Therefore length $l$ for all heat flow paths should be small (consistent with the requirement of mechanical strength) and $A$ should be as large as possible. The thermal conductivity of material should also be as high as possible.

### 2.13.5. Heat Sinks

A number of heat sinks of extruded aluminium are manufactured for use with power electronic devices. The heat sinks are cooled by natural convection. If the surface of heat sink is coated with black oxide the thermal resistance decreases by about 25% (but the cost of heat sink also increases). If a fan is used for cooling, the thermal resistance decreases. For natural air cooled heat sinks the thermal time constant is in the range of 4-15 minutes. In forced air cooling, the time constant is less than one minute. In high power devices water or oil cooling is also used.

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The selection of a heat sink depends on allowable junction temperature, the ambient temperature and the power losses to be dissipated. Generally a worst case design is used by using maximum junction temperature, maximum ambient temperature and maximum possible losses. The losses should include on state losses and switching losses. Proper mounting of the SCR on the heat sink is also very important. Improper mounting may result in thermal resistance being much higher resulting higher junction temperature. Manufacturer's instructions should be followed in this regard.

### 2.13.6. Transient Thermal Response

It is important to remember that power losses during overloads and other transient conditions may be much higher than those during steady state conditions. The magnitude and duration of transient conditions determine the thermal behaviour. During these conditions the heat capacity of the device should also be considered. Heat capacity per unit volume is the rate of change of heat energy density $Q$ with repect to temperature $T$, *i.e.*,

$$c_v = \frac{dQ}{dT}$$

where $c_v$ is the heat capacity per unit volume J/m$^3$/K

If a material has length (in the direction of heat flow) $l$ and area of cross-section $A$, The heat capacity of the material is

$$C_s = A\,l\,c_v$$

where $C_s$ is that heat capacity.

Figure 2.33 shows some commonly used heat sinks

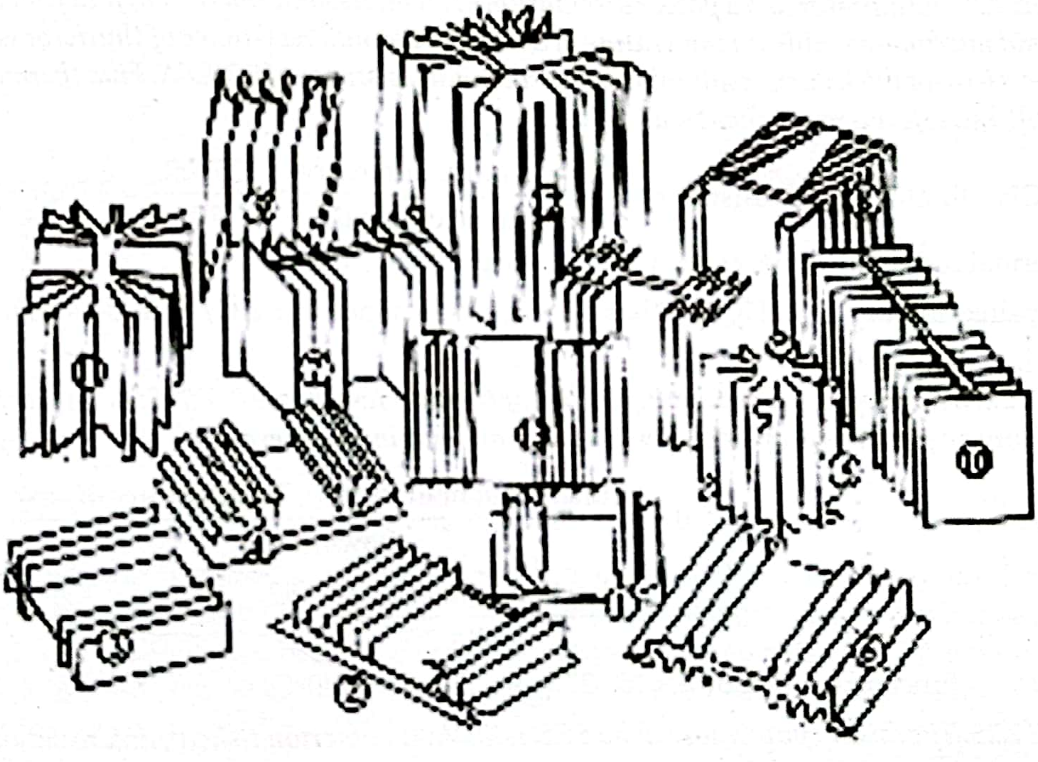

*Fig. 2.33. Some commonly used heat sinks for thyristors.*

Their thermal resistances and volumes are as under

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Heat sink number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Thermal resistance °C/W | 3.2 | 2.3 | 2.2 | 2.2 | 2.1 | 1.7 | 1.4 | 1.3 | 1.25 | 1.2 | 0.85 | 0.7 |
| Volume (cm$^3$) | 75 | 100 | 180 | 188 | 200 | 295 | 430 | 670 | 605 | 630 | 690 | 1300 |

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## 2.19. PROTECTION OF THYRISTORS

Every electrical device has maximum current and voltage ratings and thyristor is no exception. When these ratings are exceeded, the junction temperature of thyristor will increase. This may cause a deterioration in the performance and its breakdown. The different ratings have been discussed in section 2.8. It is essential that these ratings are not exceeded. In addition to the current, voltage and power ratings, a thyristor has maximum $di/dt$ and $dv/dt$ ratings. If the rate of rise of anode current is high, the current density in the region of the reverse biased junction may be high and may cause a hot spot and destroy the thyristor. A high $dv/dt$ may initiate conduction even without a gate signal. The $dv/dt$ rating of thyristor lies in the range of 20-500 V/μ second.

### 2.19.1. *di/dt* Protection

It is necessary that the current spreads uniformly over the surface of junctions. However, if the rate of rise of anode current is very high, the current may not spread uniformly and local hot spot areas may be formed.

Figure 2.56 shows a simple chopper circuit in which a fixed dc voltage $V$ is converted into a variable dc voltage by controlling the on and off periods of thyristor. The $di/dt$ in the circuit can be controlled by including an inductance $L$ in the circuit. The maximum $di/dt$ in this circuit is

$$\frac{di}{dt} = \frac{V}{L} \qquad ...(2.43)$$

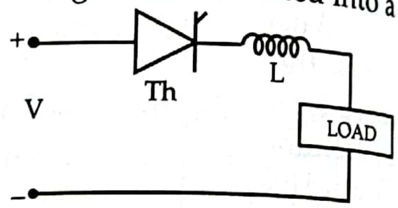


*Fig. 2.56.*

### 2.19.2. Over-voltage Protection

***(a)* Causes of Over-voltages**

A thyristor may be subjected to over-voltages due to following cases : (1) Thyristor commutation, (2) Current chopping, (3) Lightning and (4) Transformer in-rush current.

**1. Thyristor commutation :** When a thyristor turns off, a reverse current flows to sweep away the stored charge. This reverse current increases to its maximum value and then decays at a high rate. This high $di/dt$ induces a high over-voltage $L\,di/dt$ due to the circuit inductance $L$. It has been found that this over-voltage may be much higher than the rated value and may damage the thyristor.

**2. Current chopping :** When a small current is interrupted by a circuit breaker, the current may be brought to zero abruptly and ahead of the normal current zero. This is known as current chopping and is often observed when the no load current of a transformer is switched off. Current chopping often leads to dangerous over-voltages.

**3. Lightning :** HVDC systems are fed by high voltage transmission lines. Atmospheric lightning causes high magnitude over-voltages which travel on the lines as travelling waves. When these waves reach the converter station of HVDC system, the thyristors in the converter station may be subjected to these over-voltages.

**4. Transformer in-rush current :** When a transformer is switched on the initial magnetising current may be higher than the steady state value of magnetising current*. If a thyristor circuit is connected on the secondary side of transformer, the thyristor may be subjected to over-voltage because the transformer secondary voltage, because of the in-rush magnetising current, may be upto about twice the rated secondary voltage.

***(b)* Over-voltage Protection**

A simple over-voltage protection consists of a non-linear resistance connected across the thyristor. This non-linear resistance has a high resistance at low voltage and a low resistance at high voltage. Its $v$-$i$ characteristic can be written as

* The initial magnetising current is known as in-rush current.

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$$i = kv^{\alpha} \qquad ...(2.44)$$

where $i$ is the peak current, $v$ is the peak voltage, $k$ is a geometrical constant which depends on the design, rating and dimensions of the non-linear element and exponent $\alpha$ defines the degree of non-linear relationship between voltage and current. If the non-linear element is made of thyrite the value of $\alpha$ lies in the range of 4 to 6. For zinc oxide non-linear element, the value of $\alpha$ is about 25. It is seen in Eqn. (2.44), that if $\alpha = 4$, an increase of current by 100 times increases the voltage by 3.16 times only. By virtue of this characteristic the non-linear resistance limits the voltage across the thyristor.

### 2.19.3. Snubber Circuit

A special circuit known as snubber circuit is used for limiting $dv/dt$ across the thyristor. This circuit consists of a series $R$-$C$ circuit connected across the thyristor as shown in Fig. 2.57. The values of $R$ and $C$ can be determined as under :

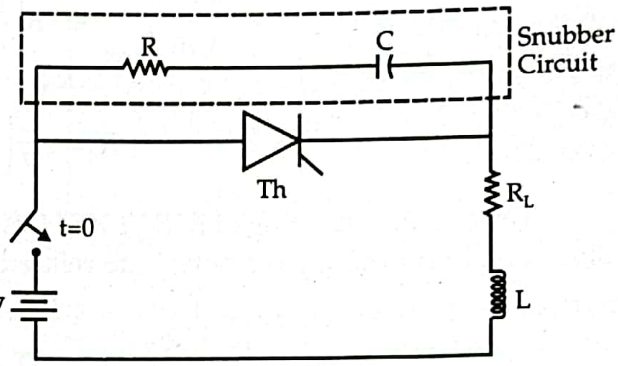


*Fig. 2.57. Subber circuit.*

When the circuit of Fig. 2.57 is switched on at $t = 0$, the capacitor behaves as a short-circuit (because voltage across a capacitor cannot change instantaneously). Moreover, the thyristor is in forward blocking state and has therefore, a very high resistance. Therefore, only resistances $R$ and $R_L$ and inductance $L$ are in the circuit. Hence KVL equation is

$$V = (R + R_L)\, i + L\,\frac{di}{dt} \qquad ...(2.45)$$

Taking Laplace transform

$$\frac{V}{s} = [R + R_L]I(s) + sL\,I(s)$$

or

$$I(s) = \frac{V/s}{(R+R_L)+sL} = \frac{V/L}{s\left(s+\dfrac{R+R_L}{L}\right)} \qquad ...(2.46)$$

Taking inverse Laplace transform

$$i = \frac{V}{R+R_L}\left[1-e^{-(R+R_L)t/L}\right] \qquad ...(2.47)$$

$$\frac{di}{dt} = \frac{V}{R+R_L}\left(\frac{R+R_L}{L}\right)e^{-(R+R_L)t/L}$$

or

$$\frac{di}{dt} = \frac{V}{L}e^{-(R+R_L)t/L} \qquad ...(2.48)$$

$\frac{di}{dt}$ is maximum when $t = 0$

$$\left(\frac{di}{dt}\right)_{max} = \frac{V}{L}$$

$$L = \frac{V}{(di/dt)_{max}} \qquad ...(2.49)$$

or

The voltage across the thyristor is $Ri$

i.e.,

$$v = Ri$$

or

$$\frac{dv}{dt} = R\frac{di}{dt}$$

$$\left(\frac{dv}{dt}\right)_{max} = R\left(\frac{di}{dt}\right)_{max} = R\frac{V}{L}$$

or

$$R = \frac{L}{V}\left(\frac{dv}{dt}\right)_{max} \qquad ...(2.50)$$

The circuit consisting of $R$, $R_L$, $L$ and $C$ is always designed to be critically damped. For a critically damped circuit these parameters are related as

$$R + R_L = 2\sqrt{\frac{L}{C}} \qquad ...(2.51)$$

The values of $R$ and C can be found from the Eqns. (2.50 and 2.51).

In an ac circuit the parameters $R$ and C can be found from Eqns. (2.50 and 2.51) by substituting maximum value of voltage in place of $V$.

A useful formula to find C in ac circuit is

$$C = 10\frac{VA}{V_s^2}\left(\frac{60}{f}\right) \qquad ...(2.52)$$

where $C$ = minimum value of C in μF

$VA$ = full load $VA$ rating of circuit

$V_s$ = applied voltage, $V$

$f$ = frequency, Hz

Resistance $R$ of snubber circuit can then be found from the equation

$$R = 2\varsigma\sqrt{\frac{L}{C}} \qquad ...(2.53)$$

where $\varsigma$ = damping factor, generally taken as 0.65

$L$ = effective inductance

When maximum value of $dv/dt$ is specified, C is given by

$$C = \frac{1}{2L}\left[\frac{0.564V_m}{dv/dt}\right]^2 \qquad ...(2.54)$$

where $V_m$ = peak value of applied ac voltage.

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