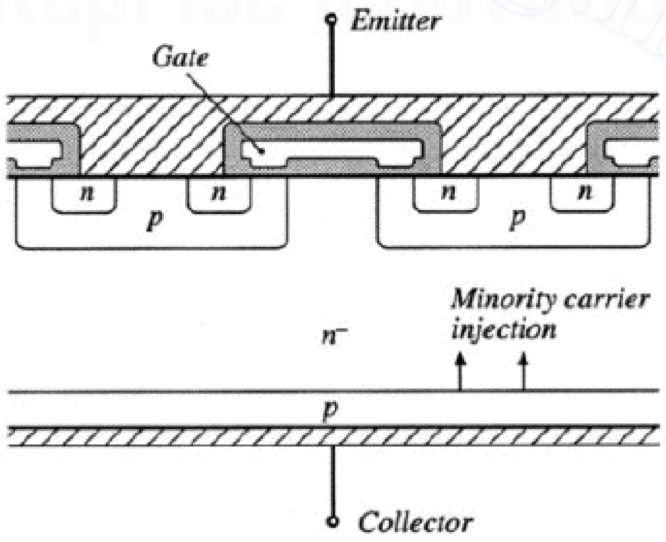
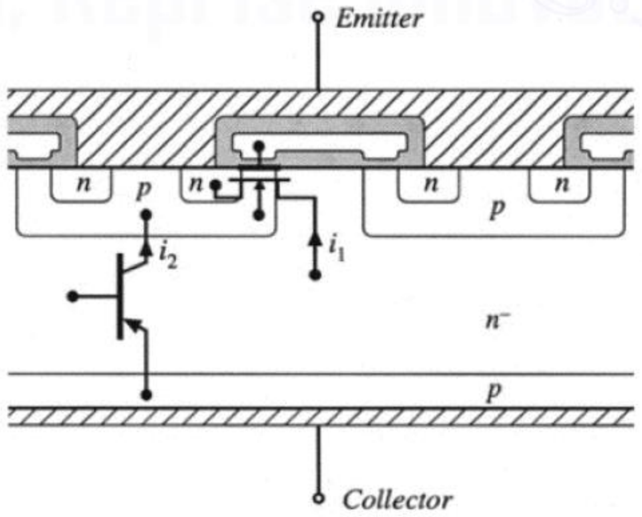
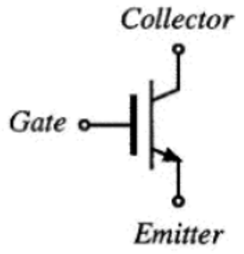
Power IGBT

- Combines the advantages of BJTs and MOSFETs
- high input impedance (MOSFET) and low on-state conduction losses (BJT)
- no second breakdown problem
- Similar to MOSFET construction
- Key difference: p region connected to the collector of IGBT
- Performance of an IGBT is closer to that of a BJT than MOSFET
- Added p region is responsible for minority carrier injection into the ***n***$^-$ region.
- IGBT is a voltage-controlled device with four alternate *PNPN* layers







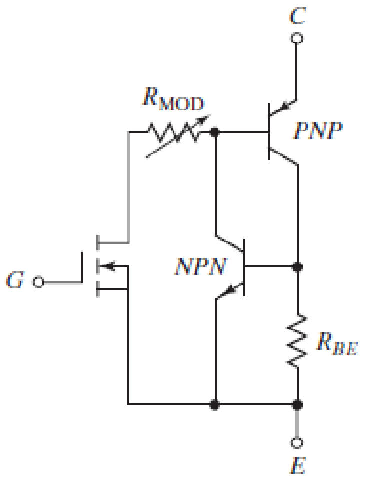
- When IGBT conducts, the **pn** $^{-}$ junction is forward-biased, and minority charges injected into the **n**$^{-}$ region cause conductivity modulation

- This reduces the on-resistance of the n- region, and allows high-voltage IGBTs to be constructed which have low forward voltage drops

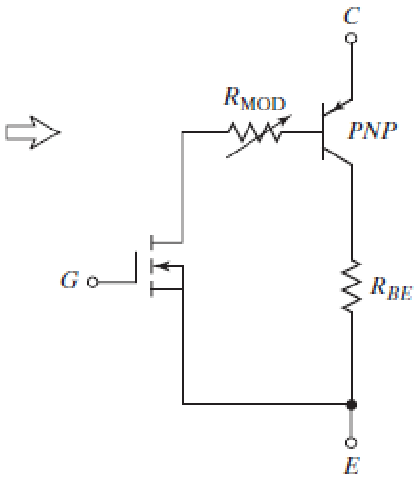
- The forward voltage drops of these devices are typically 2 to 4 V, much lower than would be obtained in equivalent MOSFETs of the same silicon area

- The IGBT functions effectively as an n-channel power MOSFET cascaded by a PNP emitter-follower BJT.

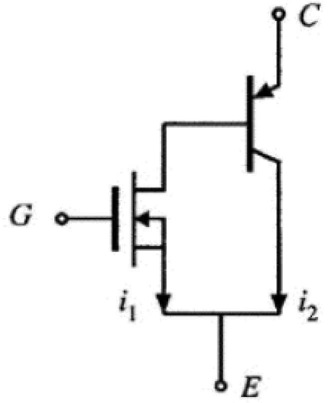
- Two effective currents: the effective MOSFET channel current i_1 and effective PNP collector current i_2



(b) Equivalent circuit



(c) Simplified circuit



- The price paid for the reduced voltage drop of the IGBT is its increased switching times, especially during turn-off transition

- IGBT turn-off transition exhibits a phenomenon known as current tailing

- The PNP collector current i_2 continues to flow as long as minority charge is present in the **n-** region

- Since there is no way to actively remove the stored minority charge, it slowly decays via recombination.

- So i_2 slowly decays in proportion to the minority charge, and a current tail is observed

- The length of the current tail can be reduced by introduction of recombination centers in the n- region, at expense of increased on-resistance

- The current gain of the effective PNP transistor can also be minimized, causing i_l to be greater than 4

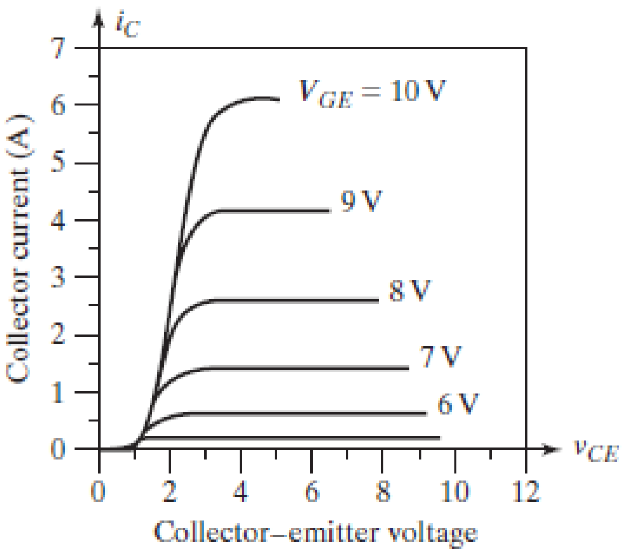
- Turn-off switching time of the IGBT is significantly longer than that of the MOSFET

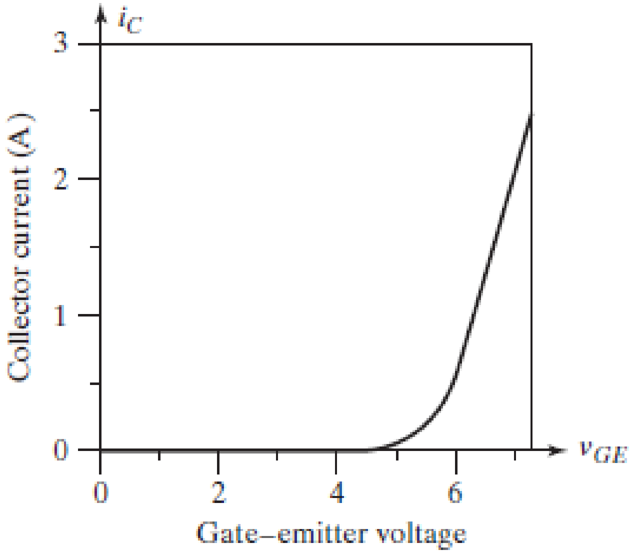
- The added **pn$^-$** diode junction of the IGBT is not normally designed to block significant voltage. Hence, the IGBT has negligible reverse voltage-blocking capability

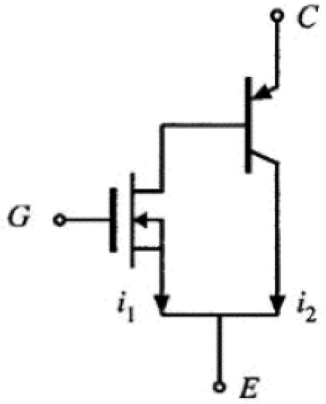
- These devices are quite robust, hot-spot and current crowding problems are nonexistent, and the need for external snubber circuits is minimal

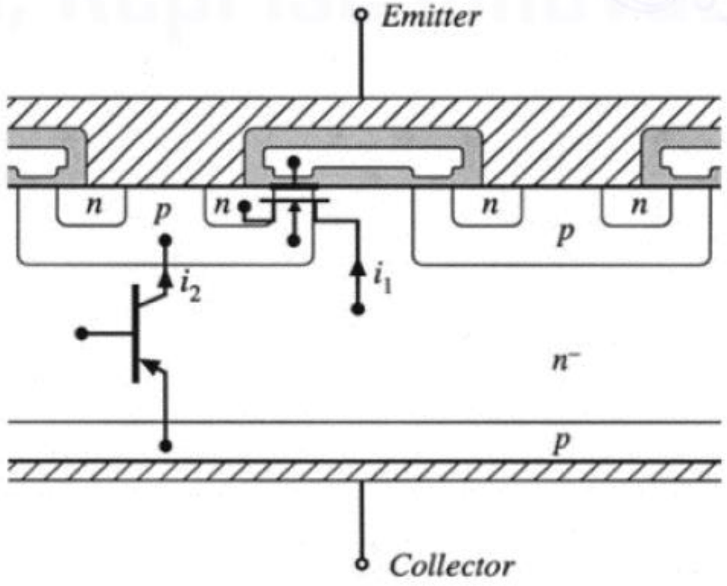
- IGBTs can be easily connected in parallel, with a modest current derating. Large modules are commercially available, containing multiple parallel-connected chips.

- IGBT is inherently faster than a BJT but inferior to that of MOSFETs
- The current rating of a single IGBT can be up to 6500 V, 2400 A and the switching frequency can be up to 20 kHz
- medium-power applications such as dc and ac motor drives, power supplies, solid-state relays, and contractors









- IGBT (similar to MOSFET), the gate-emitter voltage controls the state of the device.

- When $V_{GS} < V_{GS(th)}$ there is no inversion layer created to connect the drain to the source and, device OFF.

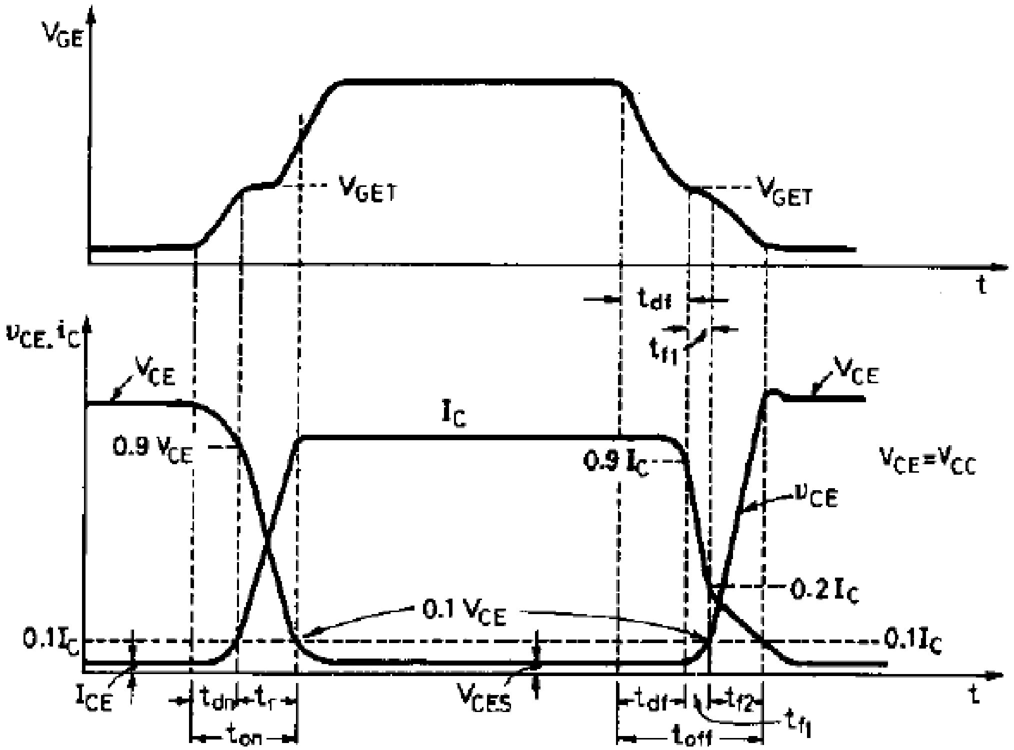
- The applied collector-emitter voltage is dropped across pn^- junction and only a very small leakage current flows.

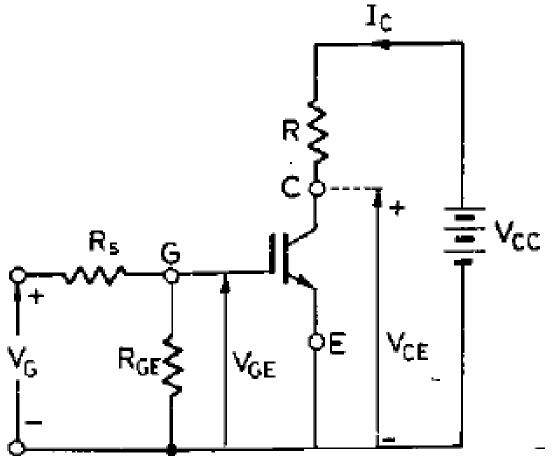
- When the gate-source voltage exceeds the threshold, an inversion layer formed beneath the gate of the IGBT

- This layer shorts the $\mathbf{n}^-$ drift region to the n^+ source region exactly as in the MOSFET

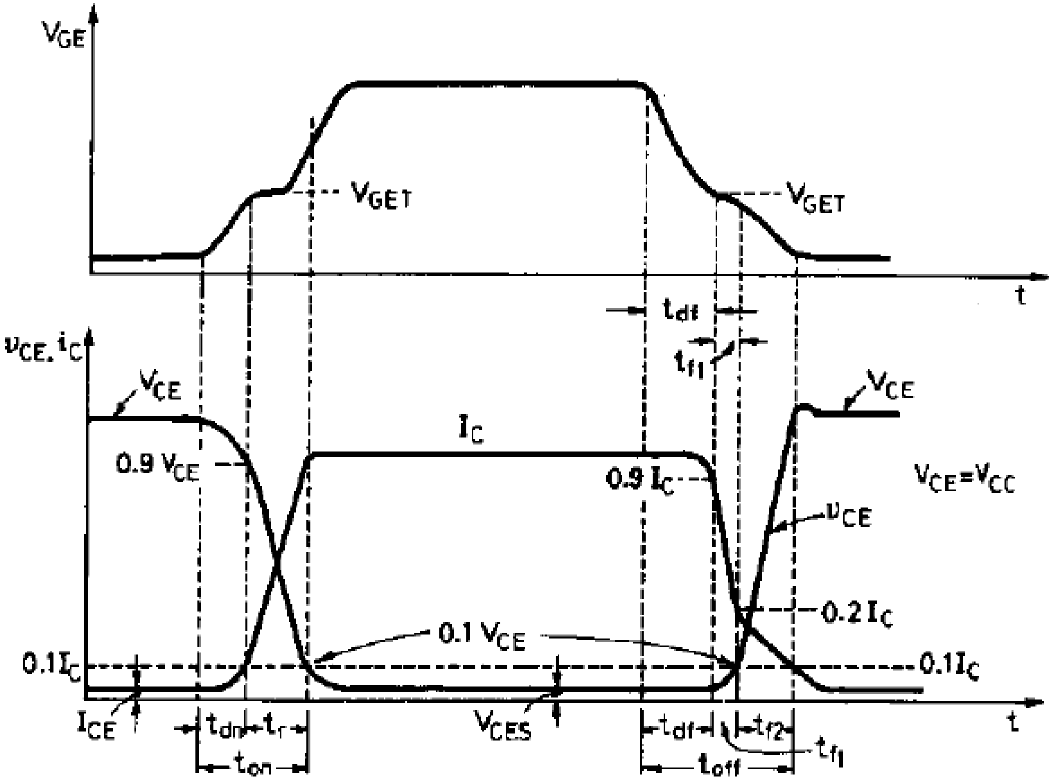
- substantial hole injection from the p drain contact layer into the n- drift region

Switching characteristics IGBT





- The tum-on time is defined as the time between the instants of forward blocking to forward on-state
- Turn-on time =delay time (t_{dn}) + rise time (t_r)
- Delay time - the time for the collector-emitter voltage to fall from V_{CE} to 0.9 V_{CE} **(or)** time for the collector current to rise from its initial leakage current I_{CE} to 0.1 I_C
- V_{CE} - initial collector-emitter voltage
- I_c - final value of collector current
- t_r is the time during which collector-emitter voltage falls from 0.9 V_{CE} -- 0.1 V_{CE} **(or)** time for the collector current to rise from 0.1 I_c to final value I_c
- After t_{on} , the collector current is Ic and the collector-emitter voltage falls to small value called conduction drop V_{CES} (S denotes saturated value)

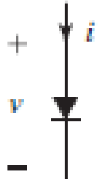
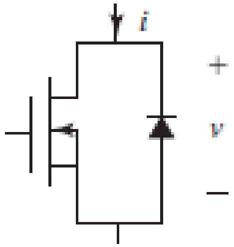
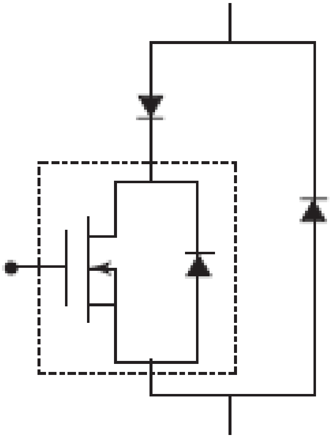


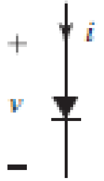
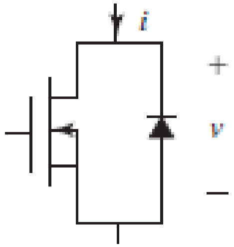
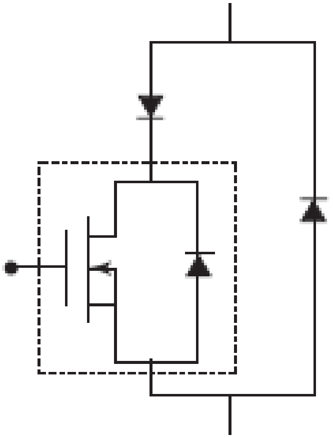
- The turn-off time consists of three intervals : delay time (t_{df}), initial fall time (t_{f1}), final fall time (t_{f2})
- Delay time is the time during which gate voltage falls from V_{GE} to threshold voltage V_{GET} (the collector current falls from I_c to 0.9 I_c
- At the end t_{df} collector-emitter voltage begins to rise.
- T_{f1} is defined as the time during which collector current falls from 90 to 20% of its initial value I_c
  (OR)
  time during which collector-emitter voltage rises from V_{CES} to 0.1 V_{CE}
- T_{f2} is the time during which collector current falls from 20 to 10% Ic
  (OR)
  the time during which collector-emitter voltage rises from 0.1 V_{CE} to final value V_{CE}

Comparisons of Transistors

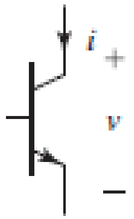
- A diode is one quadrant uncontrolled device
- BJT or an IGBT is one-quadrant controlled device
- A transistor with an antiparallel diode allows withstanding bidirectional current flows
- A transistor in series with a diode allows withstanding positive and negative voltages
- Due to internal diode, MOSFET is a two-quadrant device that allows bidirectional current flow
- Any transistor (MOSFETs, BJTs, IGBTs) in combination with diodes can be operated in four quadrants

Switch Type	Base/Gate Control Variable	Control Characteristic	Switching Frequency	On-State Voltage Drop	Max. Voltage Rating V_s	Max. Current Rating I_s	Advantages	Limitations
MOSFET	Voltage	Continuous	Very high	High	1 kV $S_s = V_s I_s$ $= 0.1$ MVA	150 A $S_s = V_s I_s$ $= 0.1$ MVA	Higher switching speed Low switching loss Simple gate-drive circuit Little gate power Negative temperature coefficient on drain current and facilitates parallel operation	High on-state drop, as high as 10 V Lower off-state voltage capability Unipolar voltage device
COOLMOS	Voltage	Continuous	Very high	Low	1 kV	100 A	Low gate-drive requirement and low on-state power drop	Low-power device Low voltage and current ratings
BJT	Current	Continuous	Medium 20 kHz	Low	1.5 kV $S_s = V_s I_s$ $= 1.5$ MVA	1 kA $S_s = V_s I_s$ $= 1.5$ MVA	Simple switch Low on-state drop Higher off-state voltage capability High switching loss	Current controlled device and requires a higher base current to turn-on and sustain on-state current Base drive power loss Charge recovery time and slower switching speed Secondary breakdown region High switching losses Unipolar voltage device
IGBT	Voltage	Continuous	High	Medium	3.5 kV $S_s = V_s I_s$ $= 1.5$ MVA	2 kA $S_s = V_s I_s$ $= 1.5$ MVA	Low on-state voltage Little gate power	Lower off-state voltage capability Unipolar voltage device
SIT	Voltage	Continuous	Very high	High			High-voltage rating	Higher on-state voltage drop Lower current ratings

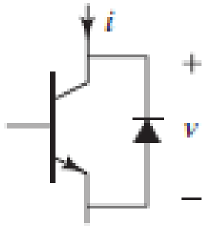
Devices	Positive Voltage Withstanding	Negative Voltage Withstanding	Positive Current Flow	Negative Current Flow	Symbol
Diode					
MOSFET					
MOSFET with two external diodes					

Devices	Positive Voltage Withstanding	Negative Voltage Withstanding	Positive Current Flow	Negative Current Flow	Symbol
Diode		x	x		
MOSFET	x		x	x	
MOSFET with two external diodes	x		x	x	

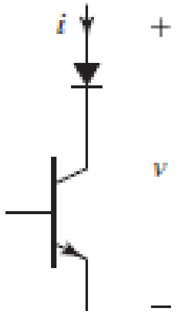
BJT/IGBT

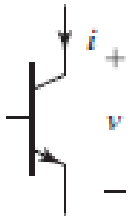
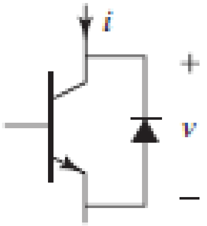
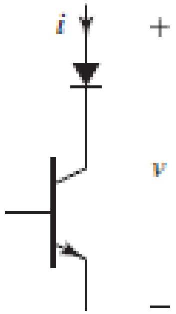


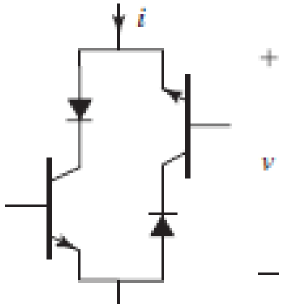
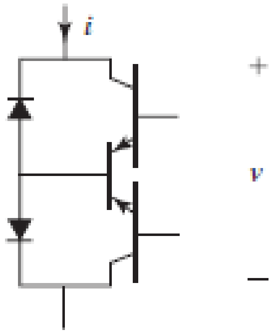
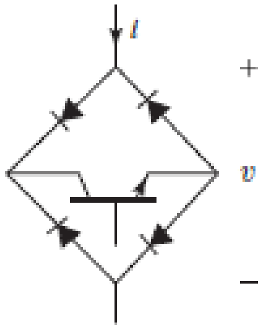
BJT/IGBT with
an antiparallel
diode

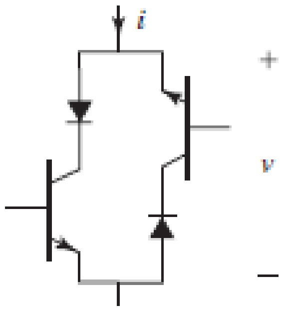
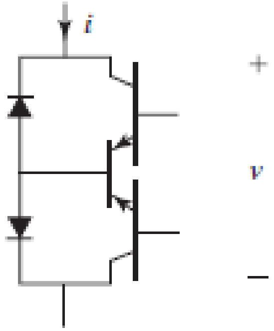
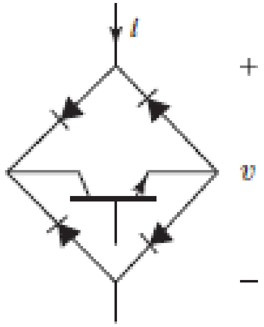


BJT/IGBT with
a series diode

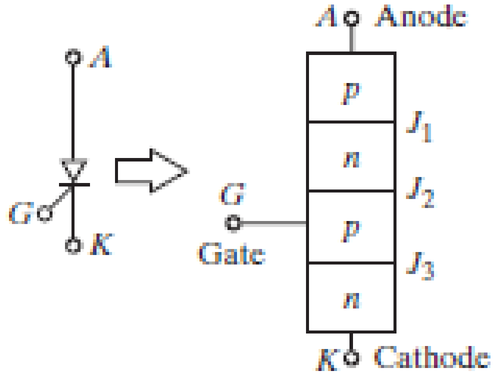


BJT/IGBT	x		x		
BJT/IGBT with an antiparallel diode	x		x	x	
BJT/IGBT with a series diode	x	x	x		

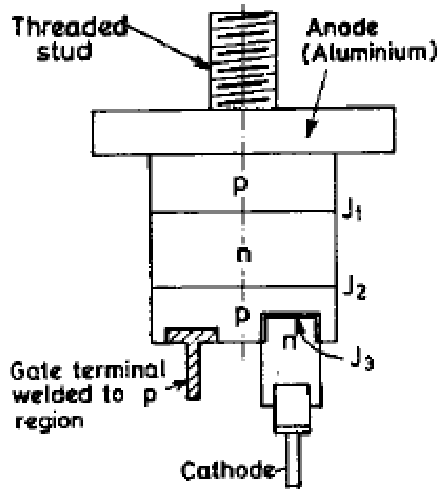
Devices	Positive Voltage Withstanding	Negative Voltage Withstanding	Positive Current Flow	Negative Current Flow	Symbol
Two BJTs/ IGBTs with two series diodes					
Two BJTs/ IGBTs with two antiparal-lel diodes					
BJT/IGBT with four bridge-connected diodes					

Devices	Positive Voltage Withstanding	Negative Voltage Withstanding	Positive Current Flow	Negative Current Flow	Symbol
Two BJTs/ IGBTs with two series diodes	x	x	x	x	
Two BJTs/ IGBTs with two antiparal-lel diodes	x	x	x	x	
BJT/IGBT with four bridge-connected diodes	x	x	x	x	

Thyristors



- Thyristors are a family of power semiconductor devices
- They are operated as bistable switches, operating from nonconducting state to conducting state
- Conventional thyristors are designed without gate-controlled turn-off capability
- However, Gate turn-off thyristors (GTOs) are designed to have both controlled turn-on and turn-off capability
- Compared to transistors, thyristors have lower on-state conduction losses and higher power handling capability
- But transistors generally have superior switching performances in terms of faster switching speed and lower switching losses.



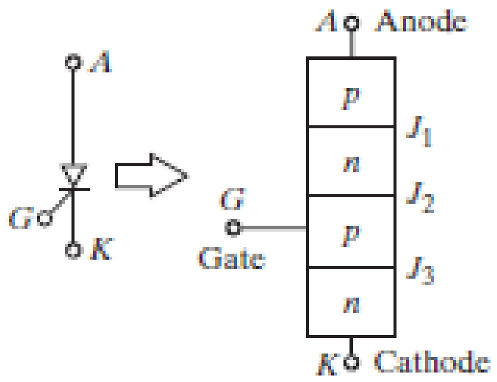
- Silicon carbide (SiC)-based double-junction injecting devices like thyristors have the potential to alleviate many of these limitations:

a) lower on-state voltage, b) multikilohertz switching c) ease of paralleling d) higher device blocking voltage

- Example- high-voltage (10–25 kV) SiC thyristors

- SiC thyristor is one of the most promising devices for high-voltage switching applications

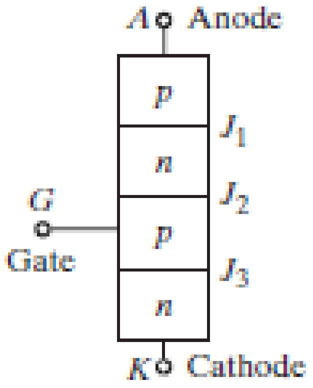
- Four-layer semiconductor device of *PNPN* structure with three *pn* junctions.



- Three terminals: anode, cathode, and gate

- Thyristors are manufactured by diffusion

- When the anode voltage is made positive w.r.t the cathode, the junctions *J*1 and *J*3 are forward biased



- J_2 is reverse biased, and only a small leakage current flows from anode to cathode

- *forward blocking* or *off-state* condition and the leakage current is known as *off-state current* I_D

- If anode-to-cathode voltage V_{AK} is increased to a sufficiently large value, the reverse-biased junction J_2 breaks

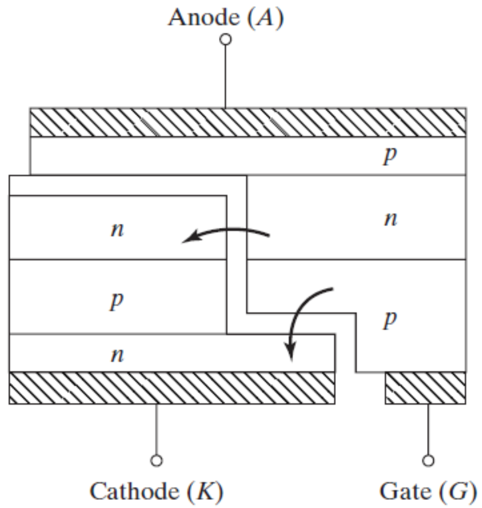
- *avalanche breakdown* and the corresponding voltage is called *forward breakdown voltage* V_{BO}

- *J*1 and *J*3 are already forward biased, there is free movement of carriers across all three junctions, resulting in a large forward anode current.

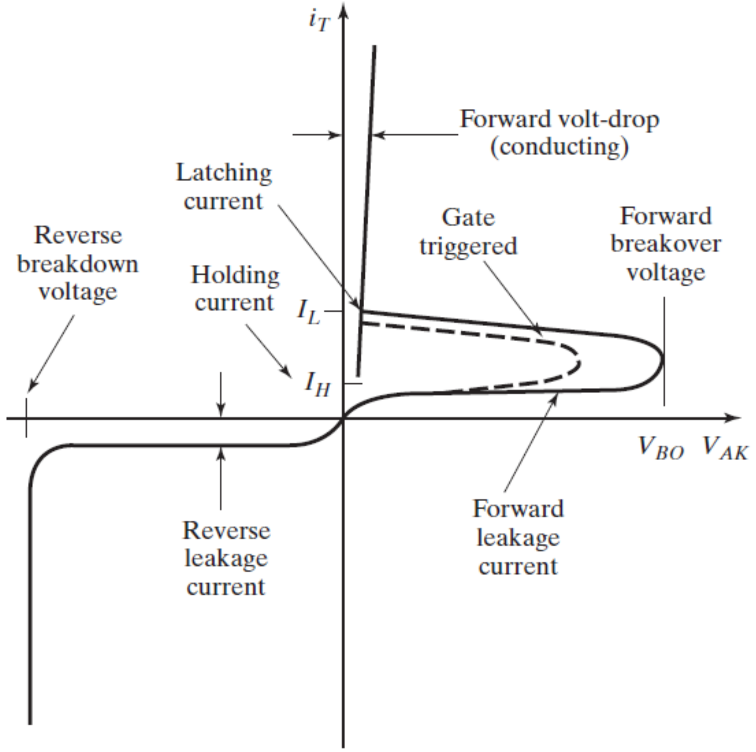
- The device is in a *conducting state*, or *on-state*

- The voltage drop during on-state is the ohmic drop in the four layers and it is small (1 V)

- *Latching current* I_L is the minimum anode current required to maintain the thyristor in on-state immediately after a thyristor has been turned on and the gate signal has been removed



- anode current must be more than I_L to maintain the required amount of carrier flow across the junction
- *Holding current* (I_H) is the minimum anode current to maintain the thyristor in the on-state
- $I_L > I_H$
- if the forward anode current is reduced below I_H, a depletion region develops around junction *J2*
- The cross section of a thyristor can be split into two sections of *NPN* and *PNP*



(b) v–i Characteristics

- When the cathode voltage is positive with respect to the anode, the junction $\boldsymbol{J_2}$ is forward biased but junctions $\boldsymbol{J_1}$ and $\boldsymbol{J_3}$ are reverse biased

- Similar to two series-connected diodes with reverse voltage across them

- **reverse blocking state** and a reverse leakage current, known as *reverse current* I_R flows through the device

- A thyristor can be turned on by increasing the forward voltage V_{AK} beyond V_{BO}, (destructive method)

- Forward voltage is maintained below V_{BO} and the thyristor is turned on by applying a positive voltage between its gate and cathode

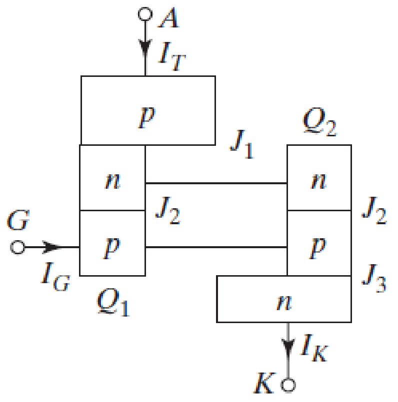
- Once a thyristor is turned on by a gating signal and its anode current is greater than the holding current, the device continues to conduct even if the gating signal is removed

- Once a thyristor conducts, it behaves like a conducting diode and there is no control over the device.

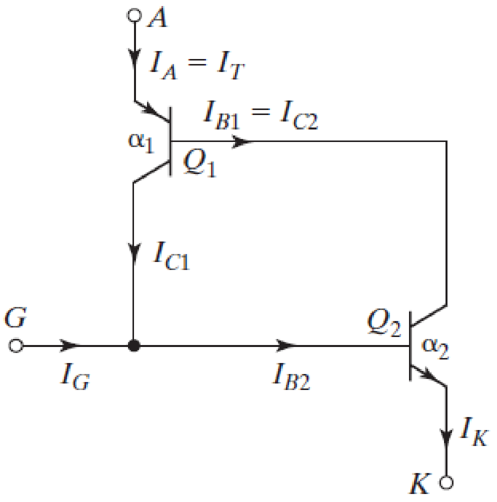
- The device cannot be turned off by another positive or negative gate pulse

Two-Transistor Model of Thyristor

- Thyristor can be considered as two complementary transistors, a *PNP*-transistor (*Q*1) and a *NPN*-transistor (*Q*2)



(a) Basic structure



(b) Equivalent circuit

- The collector current $\boldsymbol{I_C}$ of a thyristor is related to the emitter current $\boldsymbol{I_E}$ and the leakage current of the collector–base junction, $\boldsymbol{I_{CBO}}$

$$I_C = \alpha I_E + I_{CBO}$$

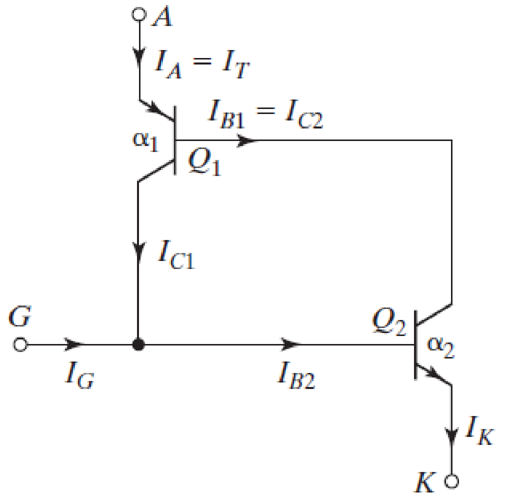
- common-base current gain is defined as $\alpha \approx I_C/I_E$

- For transistor $Q1$, the emitter current is the anode current I_A, and the collector current $I_{C1} = \alpha_1 I_A + I_{CBO1}$

- α_1 is the current gain and I_{CBO1} is the leakage current for $Q1$

- Similarly, for transistor Q_2, the collector current I_{C2} is $I_{C2} = \alpha_2 I_K + I_{CBO2}$

- α_2 is the current gain and I_{CBO2} is the leakage current for Q_2

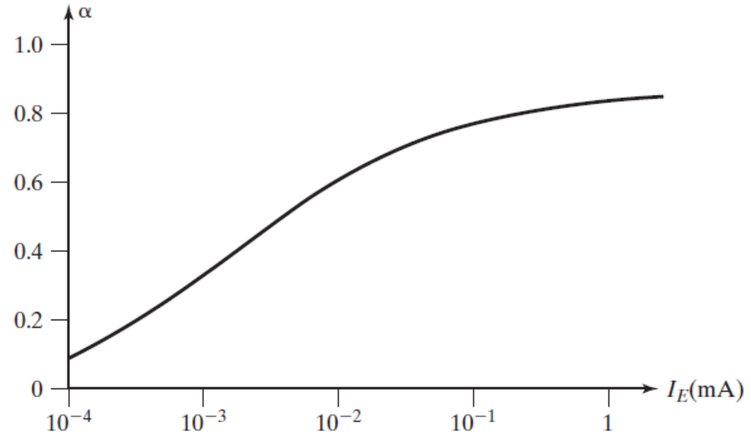


$$I_A = I_{C1} + I_{C2} = \alpha_1 I_A + I_{CBO1} + \alpha_2 I_K + I_{CBO2}$$

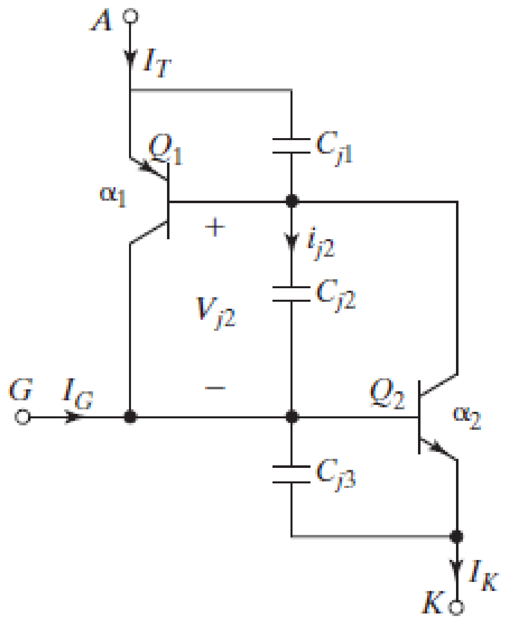
- For a gating current of I_G, $I_K = I_A + I_G$

$$I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)}$$

- The current gain α_1 varies with the emitter current $I_A = I_E$, α_2 varies with I_K $(= I_A + I_G)$
- If the gate current I_G is suddenly increased (0 to 1 mA) this immediately increases anode current I_A, which would further increase α_1 and α_2
- Current gain α_2 depends on I_A and I_G
- The increase in the values of α_1 and α_2 further increases I_A. Therefore, there is a regenerative or positive feedback effect.
- If $\alpha_1 + \alpha_2$ tends to be unity, large value of anode current I_A flows and the thyristor turns on with a small gate current
- Under transient conditions, the capacitances of the *pn*-junctions influence the characteristics of the thyristor.
- If a thyristor is in a blocking state, a rapidly rising voltage applied across the device would cause high current flow through the junction capacitors.



Typical variation of current gain with emitter current



- The current through capacitor C_{j2} can be expressed as $$i_{j2} = \frac{d(q_{j2})}{dt} = \frac{d}{dt}(C_{j2} V_{j2}) = V_{j2}\frac{dC_{j2}}{dt} + C_{j2}\frac{dV_{j2}}{dt}$$

- C_{j2} and V_{j2} are the capacitance and voltage of junction J_2, q_{j2} is the charge in the junction

- If the rate of rise of voltage dv/dt is large, then i_{j2} would be large and would result in increased leakage currents I_{CBO1} and I_{CBO2}

- High enough values of I_{CBO1} and I_{CBO2} may cause $\alpha_1 + \alpha_2$ tending to unity and result in undesirable turn-on of the thyristor

Thyristor Turn-On Methods

Thermal

- If the temperature of a thyristor is high, there is an increase in the number of electron–hole pairs, which increases the leakage currents.

- This increase in currents causes α_1 and α_2 to increase.

- Due to the regenerative action, $\alpha_1 + \alpha_2$ may tend to unity and the thyristor may be turned on

- Turn-on may cause thermal runaway and is normally avoided

Light

- If light is allowed to strike junctions of a thyristor, the electron–hole pairs increase --- thyristor may be turned on.

- The light-activated thyristors are turned on by allowing light to strike the silicon wafers.

- The pulse of light of appropriate wavelength is guided by optical fibres for irradiation.
- If the intensity of this light thrown on SCR exceeds a certain value, forward-biased SCR is turned on.
- Such a thyristor is known as light-activated SCR (LASCR)
- LASCR may be triggered with a light source or with a gate signal.
- Sometimes a combination of both light source and gate signal is used to trigger an SCR
- Light-triggered thyristors have been used in high-voltage direct current (HVDC) transmission systems

Forward voltage triggering

- When anode to cathode forward voltage is increased with gate circuit open, the reverse biased junction $\mathbf{J_2}$ will break (forward breakover voltage V_{BO})
- JI, J3 are already forward biased, breakdown of junction J2 allows free movement of carriers
- If forward V_{AK} > forward breakdown voltage V_{BO}, sufficient leakage current flows to initiate regenerative turn-on
- large forward anode-current flows and is limited by the load impedance
- This type of turn-on may be destructive and should be avoided
- V_{BR} is slightly more than V_{BO}
- After the avalanche breakdown, junction J2 looses its reverse blocking capability.

dv/dt

- If the rate of rise of the V_{AK} is high, the charging current of the capacitive junctions may be sufficient enough to turn on the thyristor.

- High value of charging current may damage the thyristor and the device must be protected against high *dv/dt*.

- Reverse biased junction behaves like a capacitor because of the space charge present

- This charging or displacement current across junction J2 is collector currents of Q2 and Q1

- Currents I_{c1}, I_{c2} will induce emitter current in Q2, Q1.

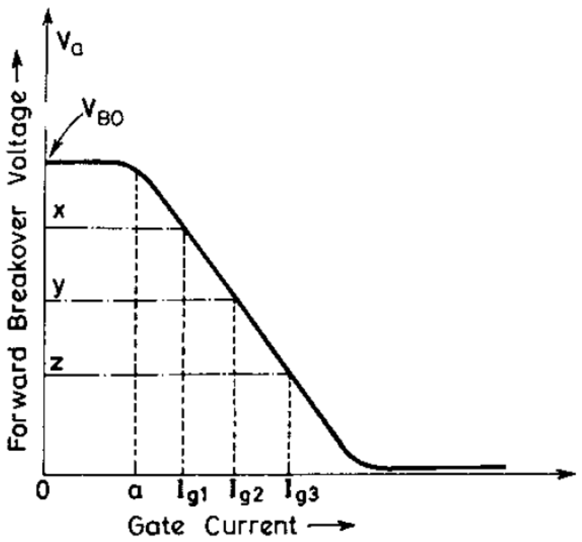
- When, $\alpha_1 + \alpha_2$ approach unity it leads to eventual switching action of the thyristor.

Gate current

- If a thyristor is F.B, the injection of gate current by applying positive gate voltage between the gate and cathode terminals turns on the thyristor

- As the gate current is increased, the forward blocking voltage is decreased

- simple, reliable and efficient, most usual method of firing the forward biased SCRs.
- Thyristor will remain in forward blocking state with normal working voltage across anode and cathode and with gate open.
- When turn-on of a thyristor is required, a positive gate voltage between gate and cathode is applied
- Charges are injected into the inner p layer and voltage at which forward breakover occurs is reduced.
- Higher the gate current lower is the forward breakdown voltage
- When positive gate current is applied, gate P layer is flooded with electrons from the cathode.
- cathode N layer is heavily doped as compared to gate P layer
- some of electrons reach junction J2 ----width of depletion layer around junction reduced.---junction J2 breaks down at applied voltage lower than V_{BO}



- No gate current required to remain in on state

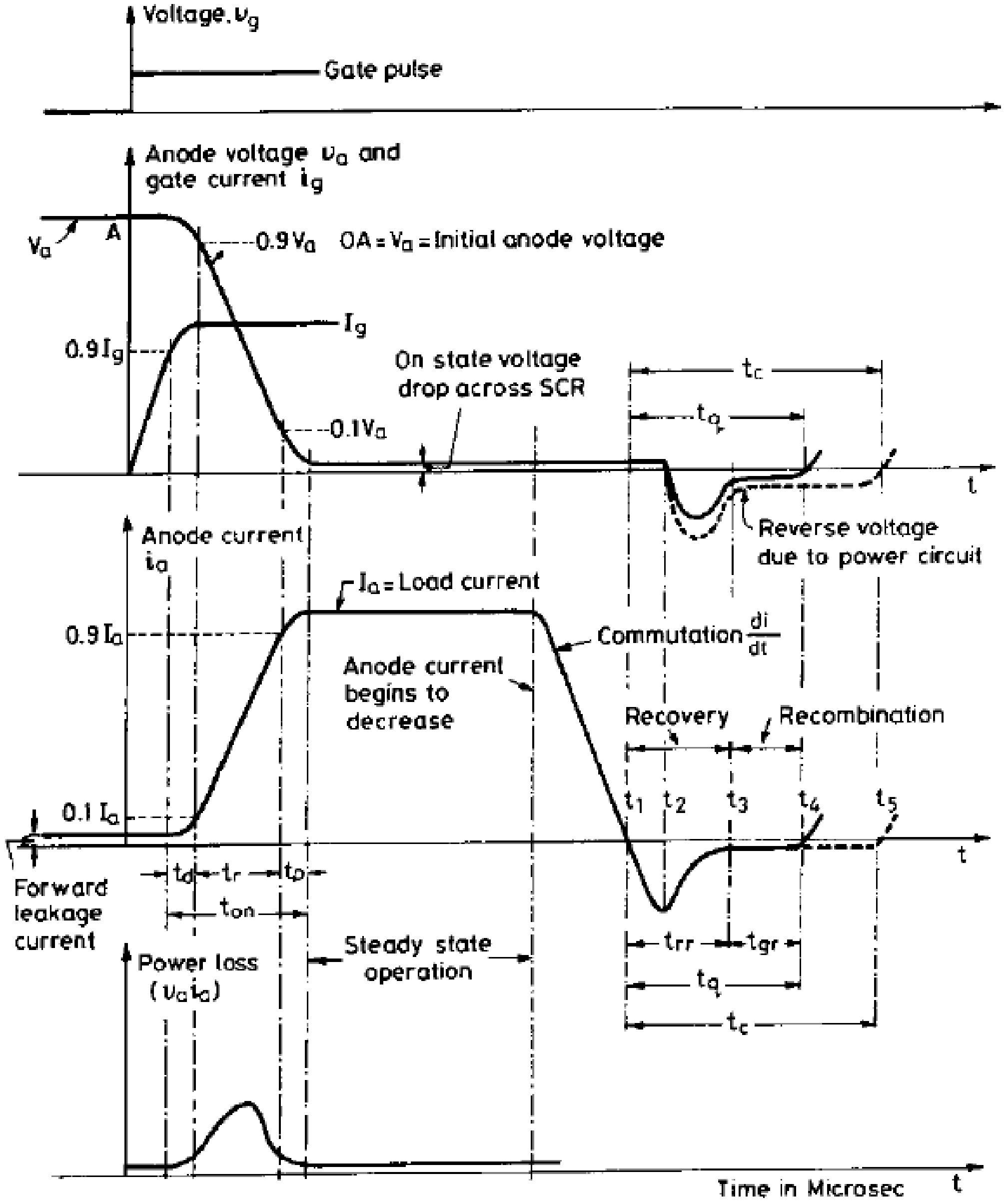
Switching characteristics of thyristors

- Switching, dynamic or transient characteristics of thyristors
- Static and switching characteristics of thyristors are required for economical and reliable design of converter equipment
- The time variations of the voltage across a thyristor and the current through it during turn-on and turn-off processes give the switching characteristics of a thyristor

Turn ON characteristics

- A forward-biased thyristor is usually turned on by applying a positive gate voltage between gate and cathode
- Transition time from forward off-state (blocking) to forward on-state -----> turn on time
- Total turn-on time divided into three intervals ; (i) delay time $\mathbf{t_d}$, (ii) rise time $\mathbf{t_r}$ and (iii) spread time $\mathbf{t_p}$

Switching characteristics



(i) Delay time td :

- The delay time td is measured from the instant at which gate current reaches 0.9 I_g to the instant at which anode current reaches 0.1 I_a.
- I_g and I_a are the final values of gate and anode currents.
- time during which anode voltage falls from V_a to 0.9 V_a where V_a initial value of anode voltage.
- time during which anode current rises from forward leakage current to 0.1 I_a , Ia- final value of anode current.
- With the thyristor initially in the forward blocking state, the anode voltage is OA and anode current is small leakage current
- As gate current begins to flow, it has non-uniform distribution of current density over the cathode surface due to the p layer.
- Its value is much higher near the gate but decreases rapidly as the distance from gate increases

- During delay time t_d, anode current flows in a narrow region near the gate where gate current density is highest

- Delay time (fraction of a microsecond) can be decreased by applying high gate current and more forward voltage between anode and cathode

<u>(ii) Rise time tr :</u>

- time taken by the anode current to rise from 0.1 I_a to 0.9 I_a.

- time required for the forward blocking off-state voltage to fall from 0.9 to 0.1 of its initial value OA.

- The rise time is inversely proportional to the magnitude of gate current and its build up rate (high and steep current pulses)

- the main factor determining tr is the nature of anode circuit (series RL circuit, the rate of rise of anode current is slow)

- As the t_r is small, the anode current is not able to spread over the entire cross-section of cathode

- anode current conducts over a conducting channel during **tr**

- During rise time, turn-on losses in the thyristor are the highest due to high anode voltage and large anode current occurring together.

- As these losses occur only over a small conducting region, local hot spots may be formed and the device may be damaged.

(iii) **Spread time t_s** :

- time taken by the anode current to rise from 0.9 I_a to I_a.

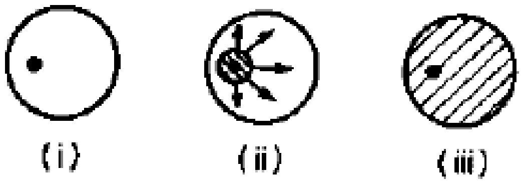
- time for the forward blocking voltage to fall from 0.1 of its initial value to the on-state voltage drop (1 to 1.5 V)

- During this time, conduction spreads over the entire cross-section of the cathode of SCR

- After the spread time, anode current attains steady state value and the voltage drop across SCR is equal to the on-state voltage drop (order of 1 to 1.5 V)

- Total turn-on time of an SCR is equal to the sum of delay time, rise time and spread time. (order of 1 to 4 μsec)

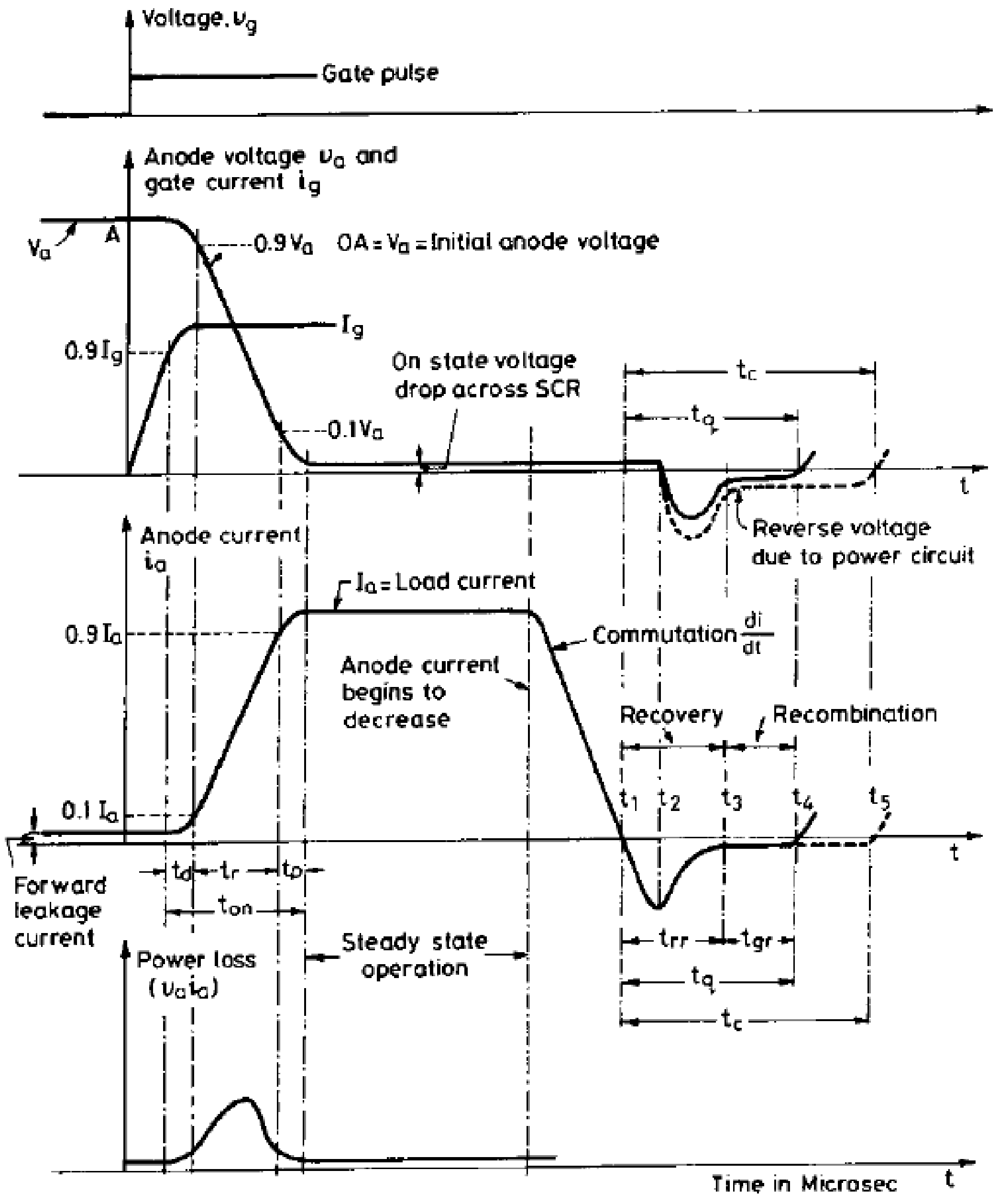
- During turn-on, SCR is similar to a charge controlled device



Turn OFF characteristics

- Turn off means on to off state and is capable of blocking the forward voltage
- Dynamic process of the SCR from conduction state to forward blocking state is called **commutation process or turn-off** process.
- SCR can be turned off by reducing the anode current below holding current.
- If forward voltage is applied to the SCR at the moment its anode current falls to zero, the device will not be able to block this forward voltage as the carriers in the four layers are still favourable for conduction.
- It is essential that the thyristor is reverse biased for a finite period after the anode current has reached zero
- The turn-off time (tq) is defined as the time between the instant anode current becomes zero and the instant SCR regains forward blocking capability

- all the excess carriers from the four layers of SCR must be removed
- This removal of excess carriers consists of sweeping out of holes from outer p-layer and electrons from outer n-layer.
- carriers around junction J_2 can be removed only by recombination
- turn-off time = reverse recovery time $\mathbf{t_{rr}}$ + gate recovery time $\mathbf{t_{gr}}$



- At instant t_1, anode current becomes zero.
- After t_1, anode current builds up in the reverse direction with the same di/dt slope as before
- The reason for the reversal of anode current after t_1 is due to the presence of carriers stored in the four layers.
- Reverse recovery current removes excess carriers from the end junctions J_1 and J_3 between the instants t_1 and t_3.
- At instant t_2, about 60% of the stored charges are removed from the outer two layers
- carrier density across J_l and J_3 begins to decrease and with this reverse recovery current also starts decaying.
- The reverse current decay is fast in the beginning but gradual thereafter.
- The fast decay of recovery current causes a reverse voltage across the device due to the circuit inductance.

- At instant t_3, when reverse recovery current nearly zero value, end junctions JI and J3 recover and SCR is able to block the reverse voltage. (similar to that of a diode)
- At the end of reverse recovery period ($t_1 – t_3$), the middle junction J_2 still has trapped charges
- Thyristor is not able to block the forward voltage at t_3.
- The trapped charges around J_2, i.e. in the inner two layers, cannot flow to the external circuit
- These trapped charges must decay only by recombination.
- Recombination is possible if a reverse voltage is maintained across SCR.
- The rate of recombination of charges is independent of the external circuit parameters.
- The time for the recombination of charges between t_3 and t_4 is called gate recovery time t_{gr}.
- At instant t_4, junction J2 recovers and the forward voltage can be reapplied between anode and cathode.

- The thyristor turn-off time t_q is in the range of 3 to 100 μsec.
- The turn-off time is influenced by the magnitude of forward current, di/dt at the time of commutation and junction temperature.
- The turn-off time provided to the thyristor by the practical circuit is called circuit turn-off time t_c.
- It is defined as the time between the instant anode current becomes zero and the instant reverse voltage due to practical circuit reaches zero
- $T_c > T_q$ (desired)
- Thyristors with slow turn-off time (50 — 100 μsec) are called converter grade SCRs
- Application: phase-controlled rectifiers, ac voltage controllers, cycloconverters etc
- fast turn-off time (3 — 50 μsec) are called inverter-grade SCRs.
- Application: inverters, choppers and force-commutated converters.

Firing circuits of thyristors

- Light triggering is used in some applications, particularly in a series-connected string
- Gate triggering is the most common method of turning on the SCRs
- This method accurately turns on the SCR at the desired instant of time
- In addition, gate triggering is an efficient and reliable method.

Main Features of Firing Circuits

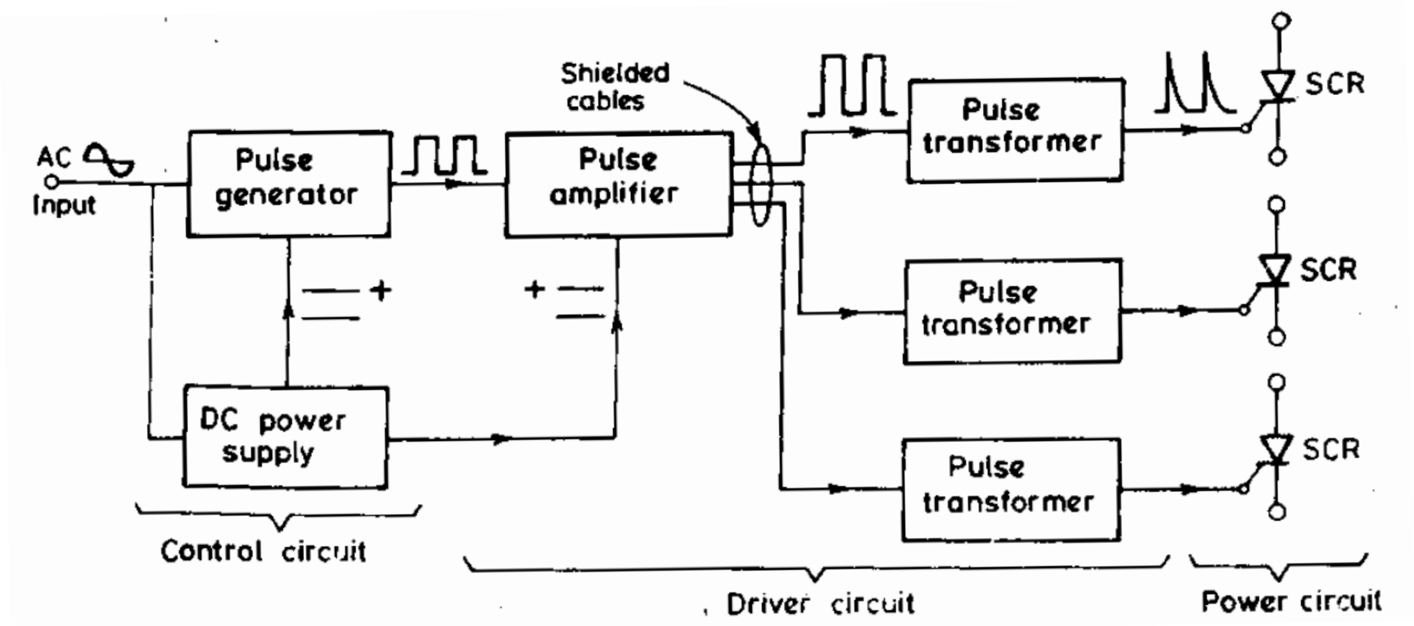
- Controlling the onset of conduction in an SCR is by means of gate control
- The gate control circuit is also called firing, or triggering, circuit.
- These gating circuits are usually low-power electronic circuits.

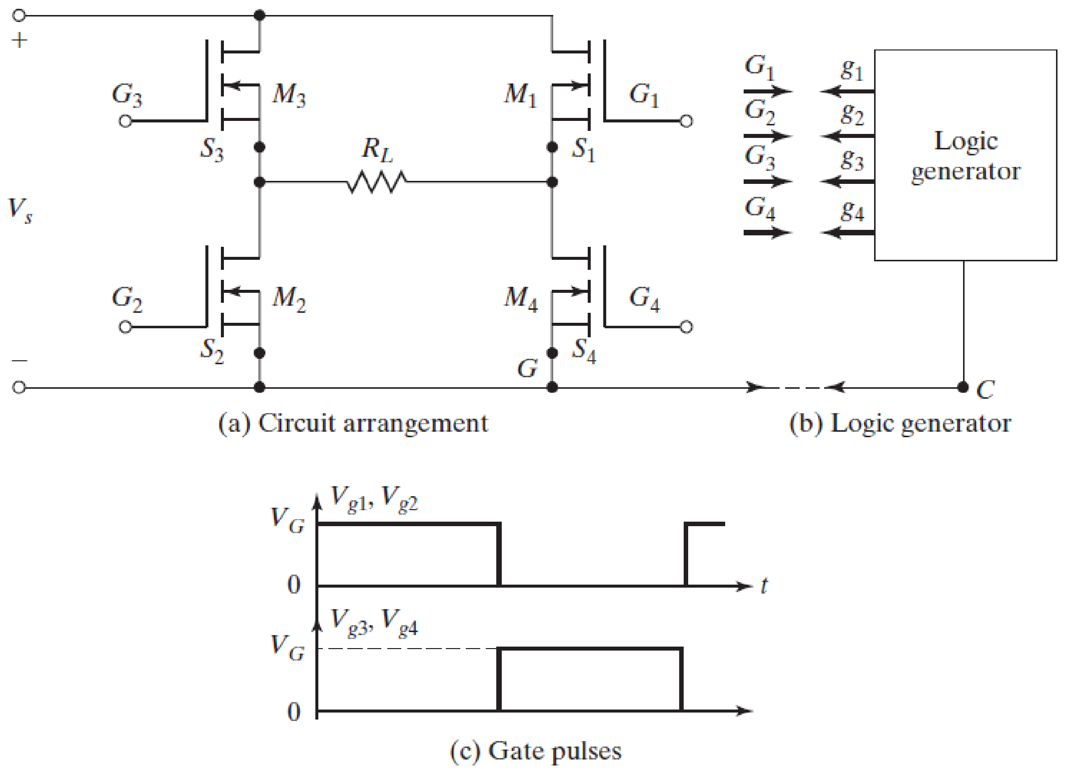
A firing circuit should fulfil two functions :

- Firing circuit should produce gating pulses for each SCR at the desired instant for proper operation of the power circuit.
- These pulses must be periodic in nature and the sequence of firing must correspond with the type of power controller.
- For example, in a 3-phase full converter using six SCRs, gating circuit must produce one trigger pulse after every 60^0 interval
- The control signal generated by firing circuit is fed to a driver circuit and then to gate-cathode
- A driver circuit consists of a pulse amplifier and a pulse transformer.

A firing circuit scheme consists of the following:

- regulated dc power supply (obtained from an alternating voltage source)
- Pulse generator, supplied from both ac and dc sources, gives out voltage pulses
- Fed to pulse amplifier for their amplification
- Shielded cables transmit the amplified pulses to pulse transformers.
- pulse transformer isolates the low-voltage gate-cathode circuit from the high-voltage anode-cathode circuit.





Single-phase bridge inverter and gating signals

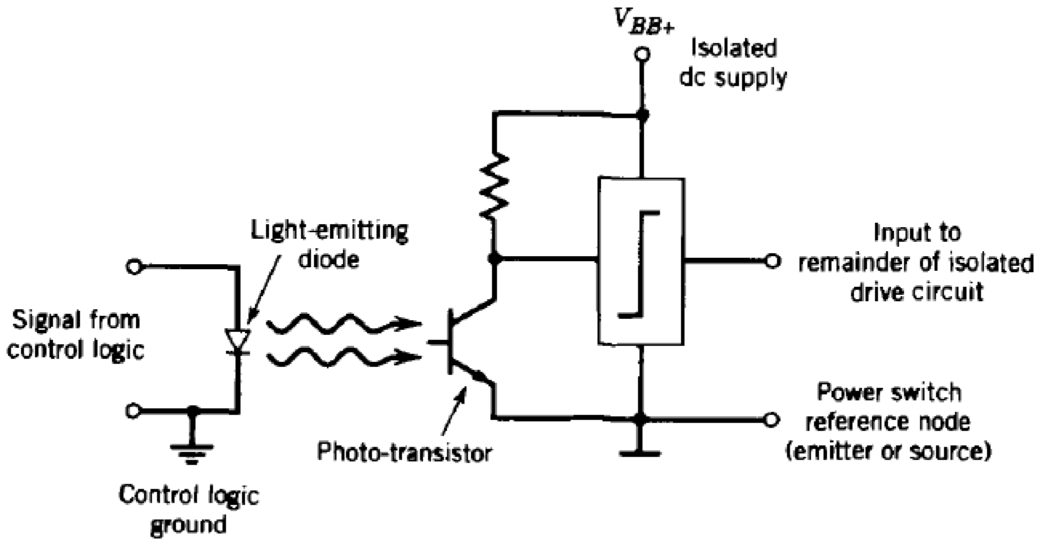
- For operating power transistors as switches, an appropriate gate voltage or base current must be applied

- The logic circuit generates four pulses which are shifted in time to perform the required logic sequence for power conversion from dc to ac (properly synchronized)

- The terminal g_1 which has a voltage of V_{g1} w.r.t terminal C should be applied between the gate terminal G_1 and source terminal S_1 of transistor M_1

- There is a need for isolation and interfacing circuits between the logic circuit and power transistors

- The basic ways to provide electrical isolation are either by optocouplers, fiber optics, or by transformers.
- The optocoupler consists of a light-emitting diode (LED), the output transistor, and built-in Schmitt trigger.
- A positive signal from the control logic causes the LED to emit light that is focused on the optically sensitive base region of a photo transistor



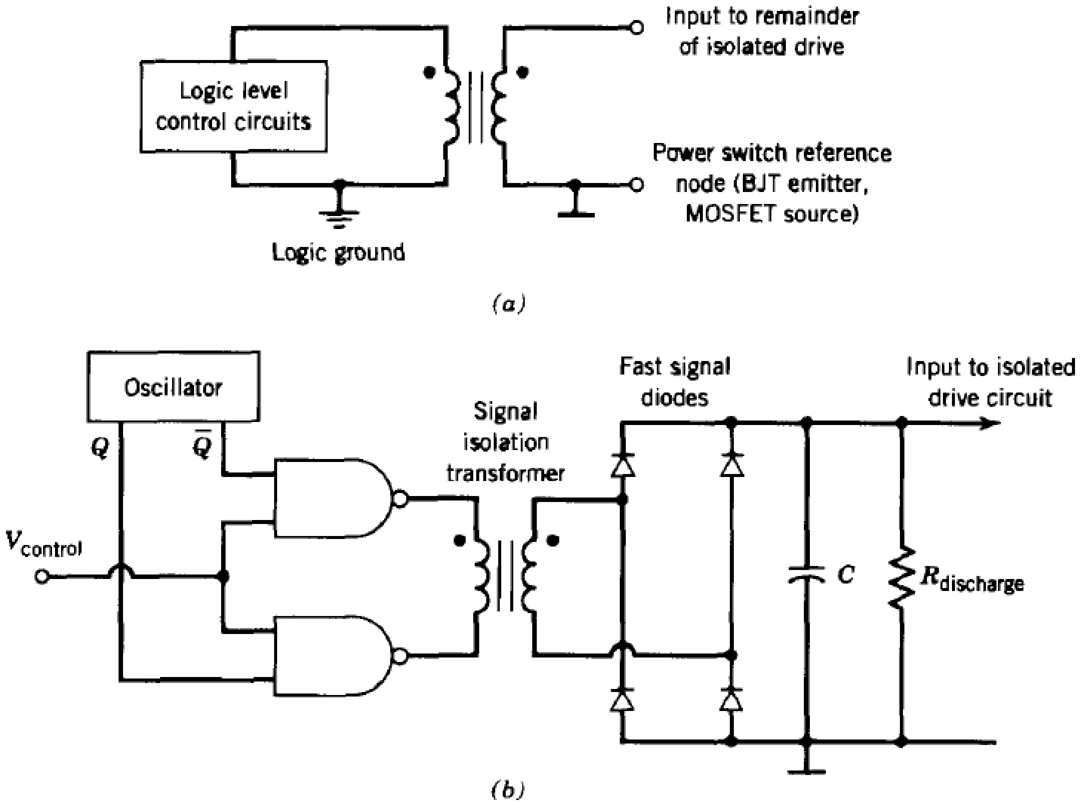
- The light falling on the base region generates a significant number of electron-hole pairs that causes the photo transistor to turn on

.

- The resulting drop in voltage at the photo transistor collector causes the Schmitt trigger to change state.
- The output of the Schmitt trigger is the optocoupler output and can be used as the control input to the isolated drive circuit.
- The capacitance between LED and the base of the receiving transistor within the optocoupler should be as small as possible to avoid retriggering
- To reduce this problem optocouplers with electrical shield between the LED and the receiver transistor should be used
- fiber optic cables can be used to completely eliminate this retriggering problem and to provide very high electrical isolation

Pulse transformer

- Instead of using optocouplers or fiber optic cables, the control signal can be coupled to the electrically isolated drive circuit by means of a transformer
- If the switching frequency is high and the duty ratio D varies only slightly around 0.5, a baseband control signal of appropriate magnitude can be applied directly to the primary of a relatively small and light weight pulse transformer
- The secondary output can be used to either directly drive the power switch or used as the input to an isolated drive circuit
- As the switching frequency is decreased below the tens of kilohertz range, a baseband control signal directly applied to
- the transformer primary becomes impractical because the size and weight of the transformer becomes increasingly larger



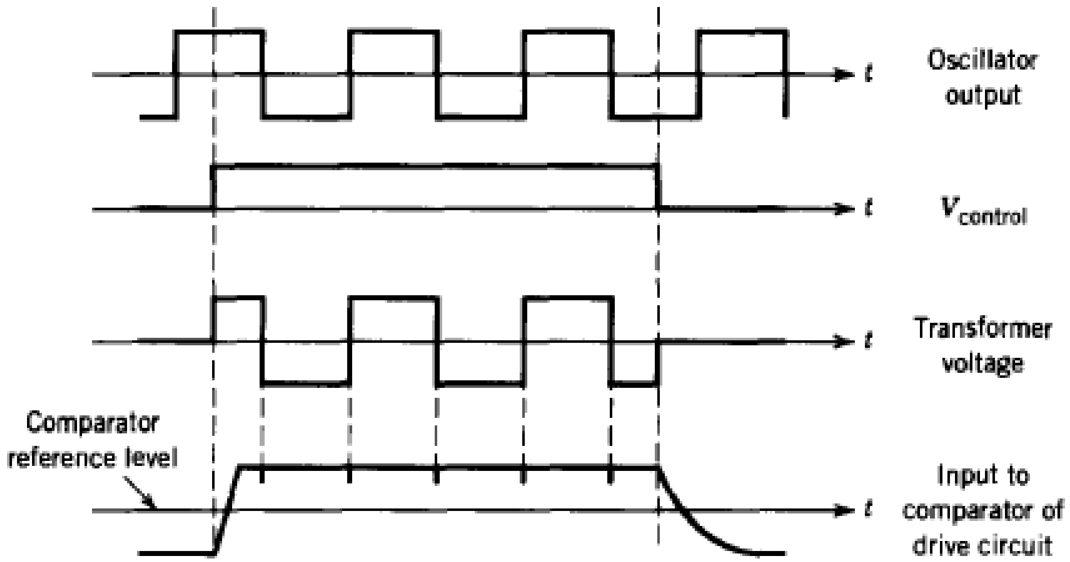
- Modulation of a high frequency carrier by a low frequency control signal enables a small high frequency pulse transformer to be used for even low frequency control signal

- the control signal modulates a high frequency oscillator output before being applied to the primary of a high frequency signal transformer

- Since a high frequency transformer can be made quite small, it is easy to avoid stray capacitance between the input and

- output winding and the transformer will be inexpensive

- The transformer secondary output is rectified and filtered and then applied to the comparator and the rest of the isolated drive circuit



Transformer coupling of control signals from control circuits to electrically isolated drive circuits.
In (a) the baseband control signal is directly connected to the transforrner primary.

In (b) the control signal modulates a high-frequency carrier that is then applied to the primary of n small high-frequency signal transformer.

The waveforms associated with (b) are shown in (c).

Thyristor protection

- Reliable operation demands that its specified ratings are not exceeded.
- thyristor may be subjected to overvoltages or overcurrents.
- During SCR turn-on, di/dt may be prohibitively large
- false triggering of SCR by high value of dv/dt.
- A spurious signal across gate-cathode terminals may lead to unwanted turn-on.
- A thyristor must be protected against all such abnormal conditions for satisfactory and reliable operation of SCR circuit and the equipment

di/dt protection

- When a thyristor is forward biased and turned on by a gate pulse, conduction of anode current begins in the immediate neighborhood of the gate-cathode junction.

- Thereafter, the current spreads across the whole area of junction.

- The thyristor design permits the spread of conduction to the whole junction area as rapidly as possible.

- If the rate of rise of anode current >spread velocity of carriers, local hotspots will be formed near the gate connection

- This localized heating may destroy the thyristor.

- Therefore, the rate of rise of anode current at the time of turn-on must be kept below specified limiting value

- The value of di/dt can be maintained below acceptable limit by using a small inductor (di/dt inductor) (Typical di/dt limit values of SCRs are 20-500 A/μsec)

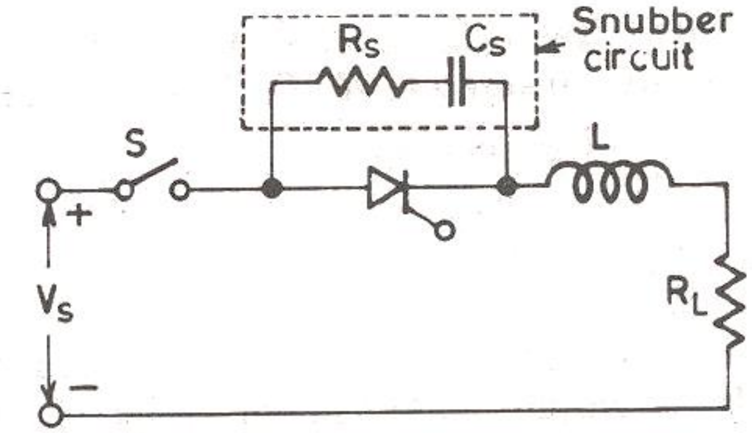
dv/dt protection

- With forward voltage across the AK of a thyristor, the two outer junctions are forward biased but the inner junction is reverse biased.
- This reverse biased junction J2, has the characteristics of a capacitor due to charges existing across the junction.
- space-charges exist in the depletion region around junction J2 and therefore junction J2 behaves like a capacitance.
- If the entire anode-cathode forward voltage Va appears across J2 junction and the charge is denoted by Q
- charging current given by Eq :

$$i = \frac{dQ}{dt} = \frac{d}{dt}(C_j \cdot V_a) = C_j \frac{dV_a}{dt} + V_a \frac{dC_j}{dt}$$

- The capacitance of junction J2, is almost constant

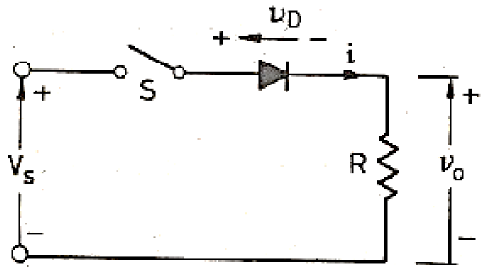
- If the rate of rise of forward voltage dV_a/dt is high, the charging current will be more.
- Charging current plays the role of gate current and turns on the SCR
- Such phenomena of turning-on a thyristor, called dv/dt turn-on (must be avoided)
- The rate of rise of forward anode to cathode voltage dVa/dt must be kept below the specified rated limit
- Typical value 20 — 500 V/μsec
- Large dv/dt can be limited by using snubber circuit in parallel to the device
- R_s is added inorder to limit the magnitude of discharge current



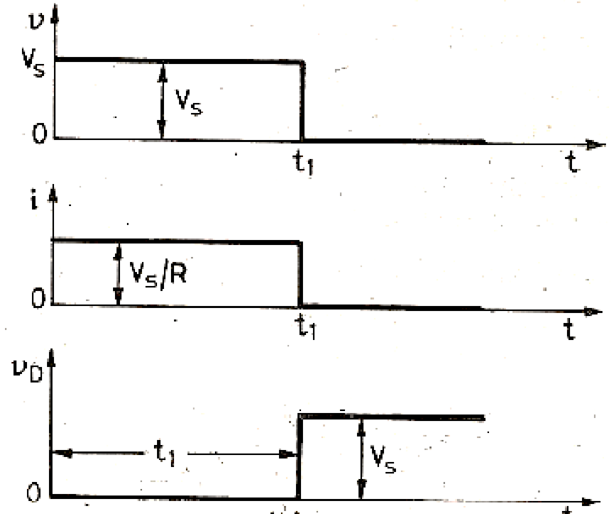
Diode circuits with DC source

Resistive load

- When switch S is closed, the current rises instantaneously to Vs/ R
- Vs is the dc source voltage and R is the load resistance
- When switch S is opened at t_1, the current at once falls to zero
- Voltage V_D across diode is zero during the time diode conducts and is equal to + Vs after diode stops conducting.

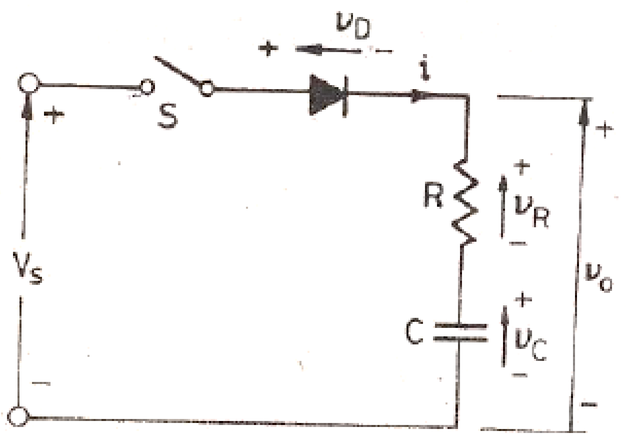


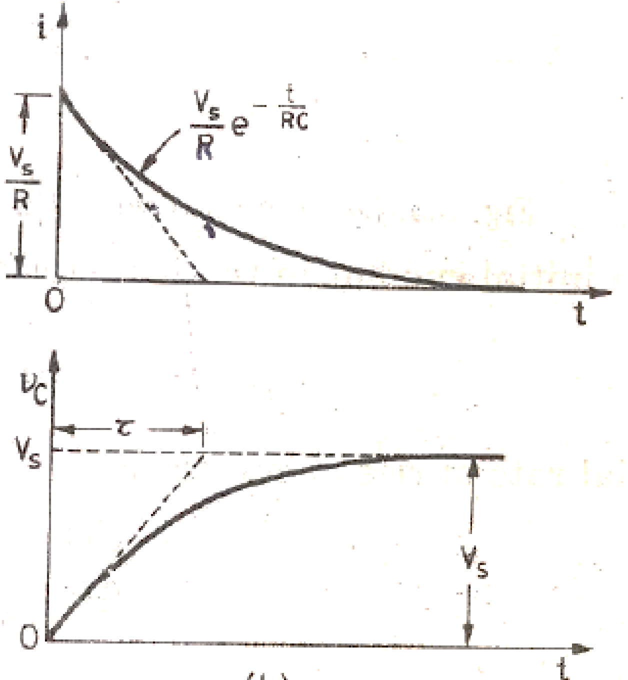
(a)



(b)

RC Load





(b)

When switch is closed at t=0, KVL gives

$$Ri + \frac{1}{C}\int i.dt = V_s$$

$$R\,I(s) + \frac{1}{C}\left[\frac{I(s)}{s} + \frac{q(o)}{s}\right] = \frac{V_s}{s}$$

$$I(s) = \frac{CV_s}{RC\left(s + \frac{1}{RC}\right)} = \frac{V_s}{R} \cdot \frac{1}{s + \frac{1}{RC}}$$

$$i(t) = \frac{V_s}{R} \cdot e^{-t/RC}$$

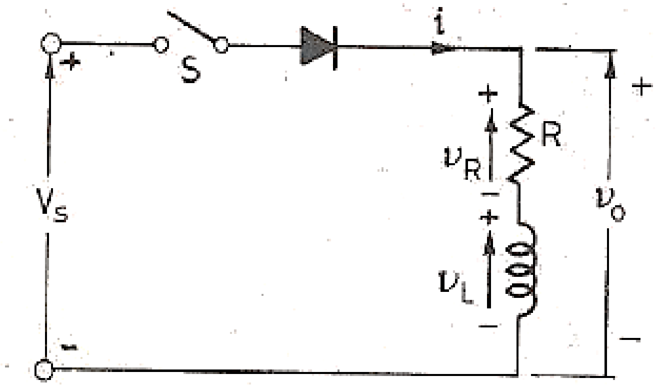
The voltage across capacitor is $$v_c(t) = \frac{1}{C}\int_0^t i\,dt = \frac{V_s}{RC}\int_0^t e^{-t/RC}$$

$$= V_s\,(1 - e^{-t/RC})$$

$$= V_s\,(1 - e^{-t/\tau})$$

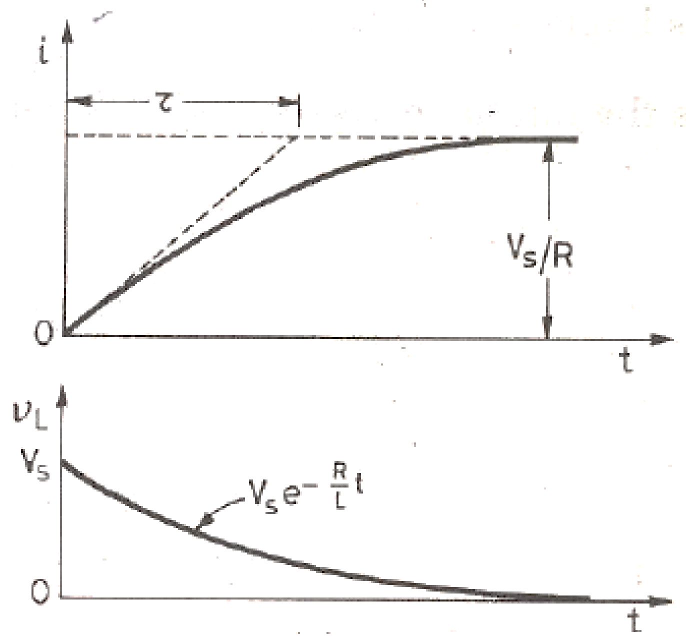
where $\tau = RC$ is the time constant for RC circuit

RL load



$$R\,i + L\frac{di}{dt} = V_s$$

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

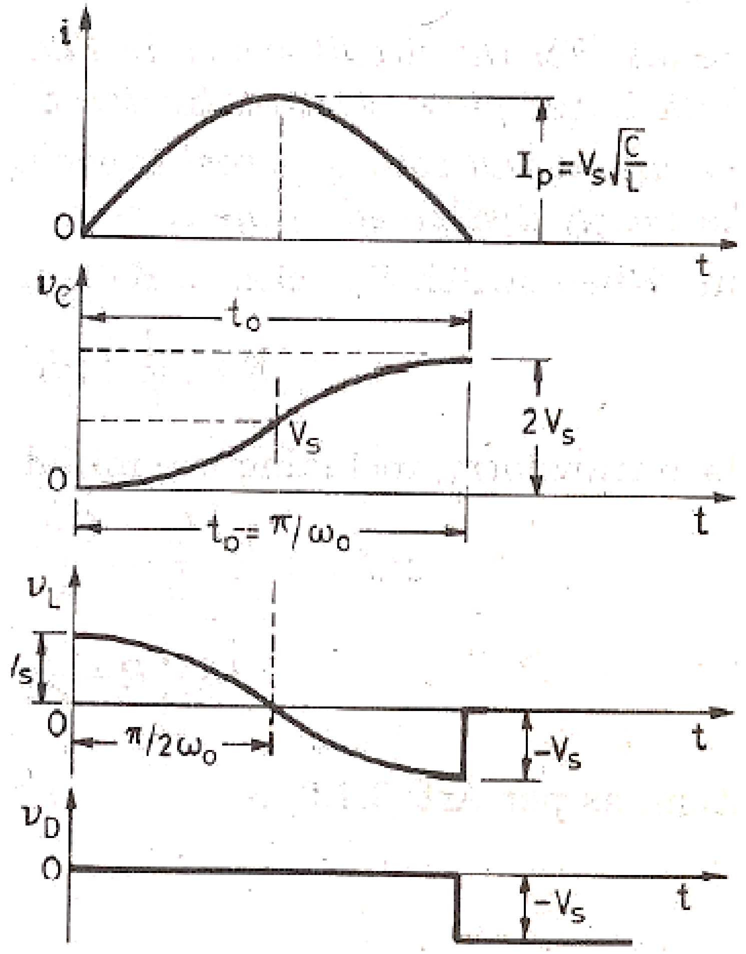


For RL circuit, $\frac{L}{C} = \tau$ is the time constant.

LC load

$$L\frac{di}{dt}+\frac{1}{C}\int i dt = V_s$$

$$L\,[s\,I(s)-i(0)]+\frac{1}{C}\left[\frac{I(s)}{s}+\frac{q(0)}{s}\right]=\frac{V_s}{s}$$



$i(0) = 0$ and $v_C(0) = 0$ or $q(0) = C \cdot v_C(0) = 0$

$$I(s)\left[sL+\frac{1}{sC}\right]=\frac{V_s}{s}$$

$$V_s \cdot \sqrt{\frac{C}{L}} \cdot \frac{\omega_0}{s^2+\omega_0^2} \qquad \omega_0 = \frac{1}{\sqrt{LC}}$$

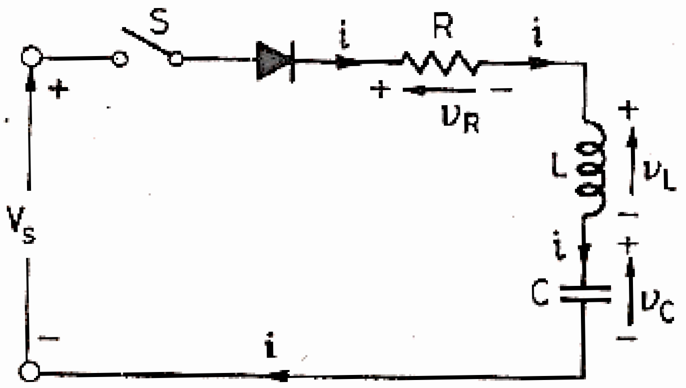
$$i(t) = V_s \cdot \sqrt{\frac{C}{L}}\sin\omega_0 t$$

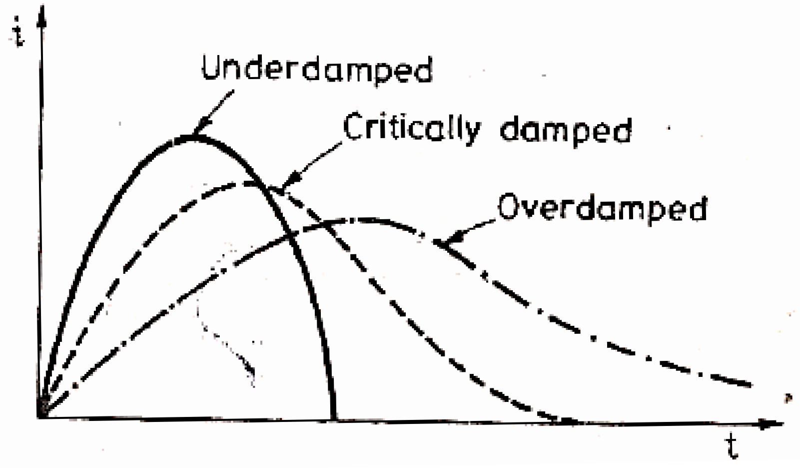
$$v_C(t) = \frac{1}{C}\int_0^t i(t)\cdot dt = \frac{1}{C}\int_0^t V_s \cdot \sqrt{\frac{C}{L}}\sin\omega_0 t$$
$$= V_s\,(1-\cos\omega_0 t)$$

$$v_L(t) = L\,\frac{di(t)}{dt} = V\cos\omega_0 t$$

RLC load

$$Ri + L\frac{di}{dt} + \frac{1}{C}\int i\,dt = V_s$$





$$I(s)\left[R + sL + \frac{1}{sC}\right] = \frac{V_s}{s}$$

$$I(s) = \frac{V_s}{L}\cdot\frac{1}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

$$s = -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

$$s = -\xi \pm \sqrt{\xi^2 - \omega_0^2}$$

$$\xi = \frac{R}{2L}$$

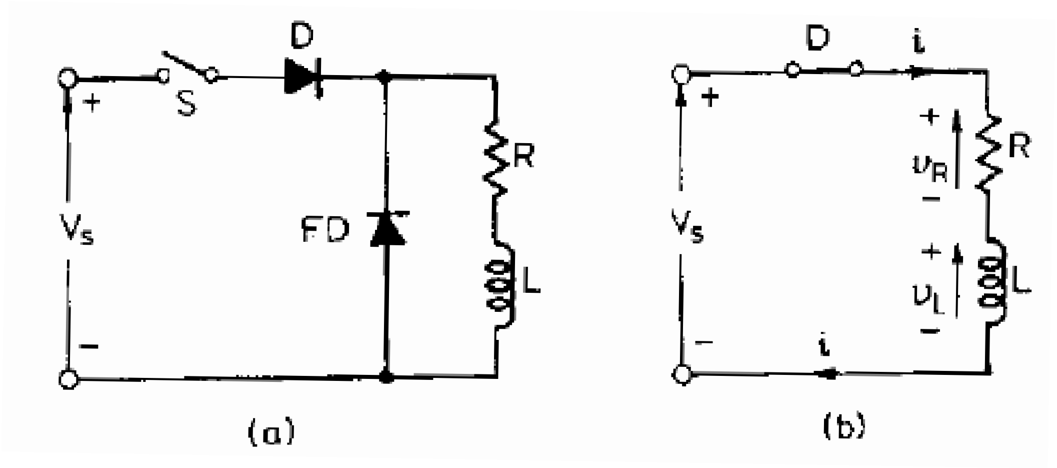
$$\omega_0 = \frac{1}{\sqrt{LC}}$$

Free wheeling diodes

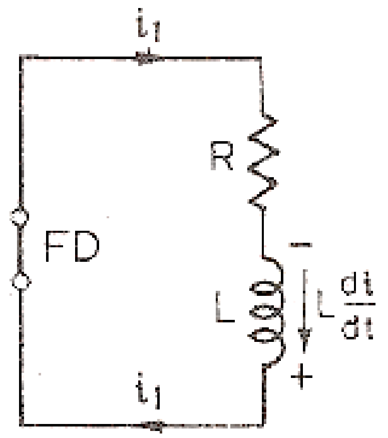
- Steady state current after switch S is closed is equal to V_s/ R.
- If switch S is opened, energy stored in inductance will appear in the form of arc at the opening contacts of switch S.
- In order to avoid such an occurrence, a diode called freewheeling, or flywheel, diode, is connected across RL
- : When switch S is closed in Fig. 3.9 (a) at t = 0, current flows through Vs, S, D, R and L as shown in Fig. 3.9 (b). In this circuit, current **i** is given by

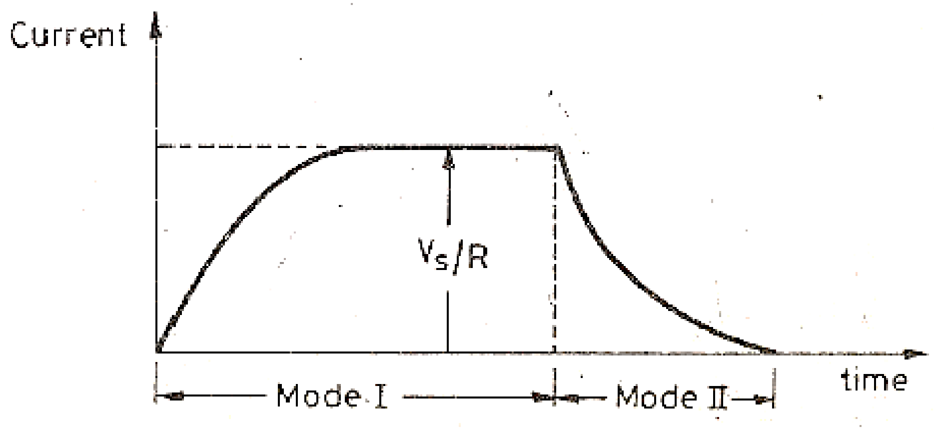
$$i = \frac{V_s}{R}\left(1 - e^{-\frac{R}{L}t}\right).$$

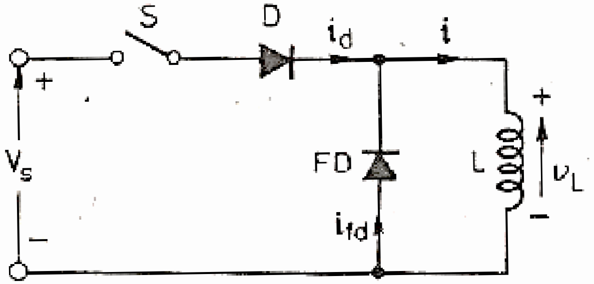
$$I = \frac{V_s}{R}$$

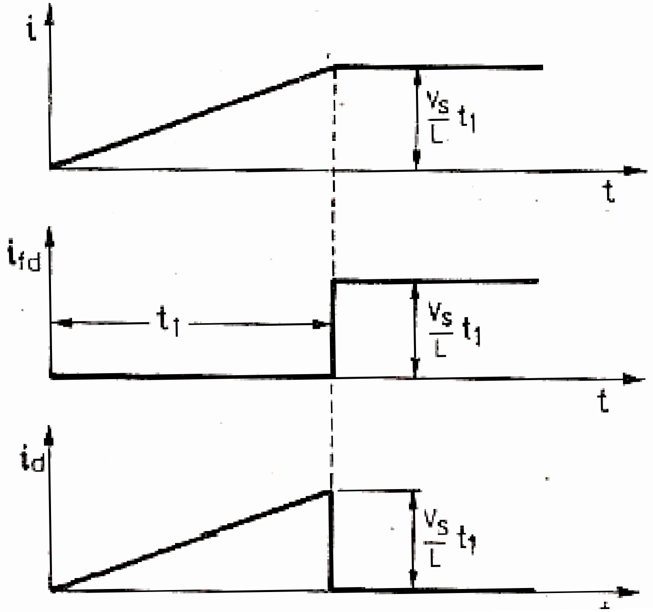


- When switch is opened at t=0, current in circuit tend to decay
- a voltage is induced in L which forward biases freewheeling diode
- The current is transferred to the circuit consisting of FD, R and L
- Current in the circuit is given by $$i_1 = \frac{V_s}{R} \cdot e^{-\frac{R}{L}t}$$





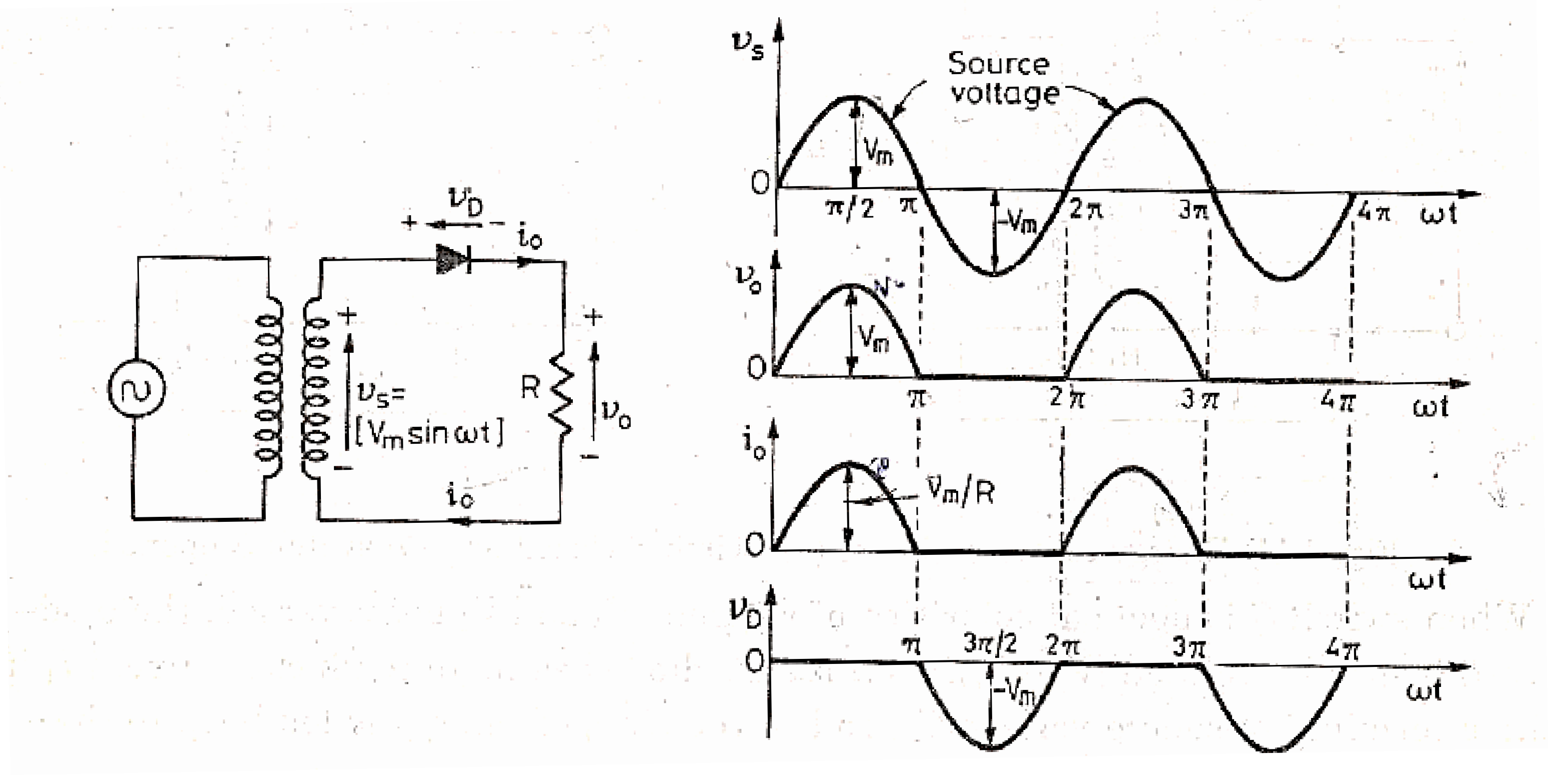




$$V_s = L\,\frac{di}{dt}$$

$$i = \frac{V_s}{L}\,t$$

Single phase diode rectifiers



Average value of output (or load) voltage,

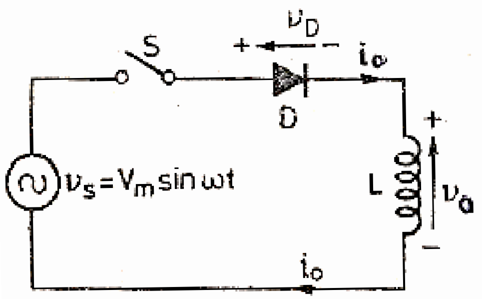
$$V_0 = \frac{1}{2\pi}\left[\int_0^{\pi} V_m \sin \omega t \, d(\omega t)\right]$$

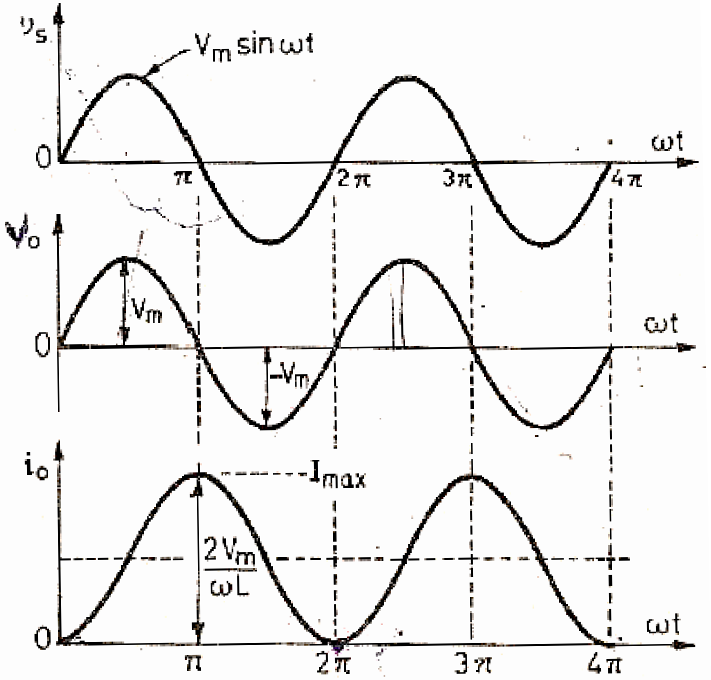
$$= \frac{V_m}{2\pi} \left| -\cos \omega t \right|_0^{\pi} = \frac{V_m}{\pi}$$

Rms value of output voltage, $V_{or} = \left[\frac{1}{2\pi}\int_0^{\pi} V_m^2 \sin^2 \omega t \cdot d(\omega t)\right]^{1/2}$

$$= \frac{V_m}{\sqrt{2\pi}}\left[\int_0^{\pi} \frac{1-\cos 2\omega t}{2} \cdot d(\omega t)\right]^{1/2}$$

$$= \frac{V_m}{2}$$





$$v_s = v_0 = L\,\frac{di_o}{dt} = V_m \sin \omega t$$

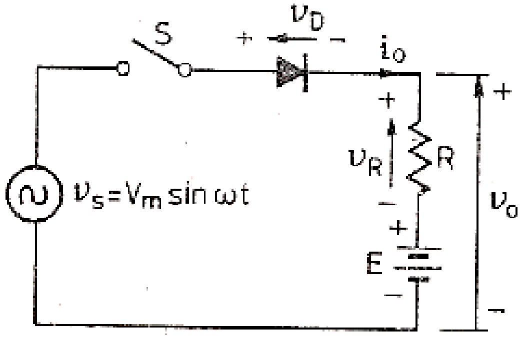
$$i_0 = \frac{V_m}{L}\int \sin \omega t \cdot dt$$

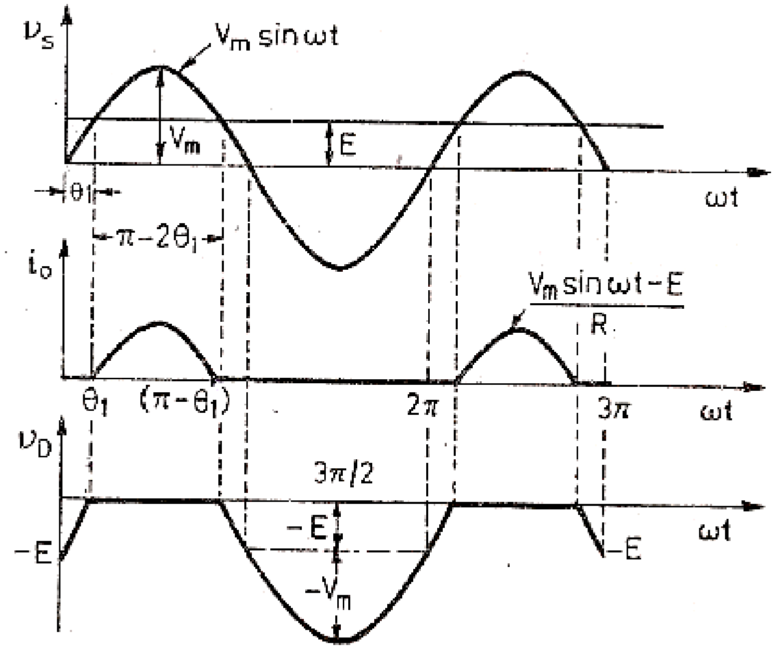
$$= -\frac{V_m}{\omega L}\cos \omega t + A$$

$$i_0 = \frac{V_m}{\omega L}\,(1 - \cos \omega t)$$

$$v_0 = L\,\frac{di_o}{dt} = L\,\frac{V_m}{\omega L}\,[\sin \omega t]\,\omega = V_m \sin \omega t = v_s$$

• RE load





- Single-phase half-wave rectifier with load resistance R and load counter emf E

- If the switch S is closed at t = 0

- Diode would not conduct at t = 0 because diode is reverse biased until source voltage V_s equals E

- When $V_m \sin\theta_1 = E$, diode D starts conducting and the turn-on angle θ_1 is given by $\theta_1 = \sin^{-1}\left(\frac{E}{V_m}\right)$

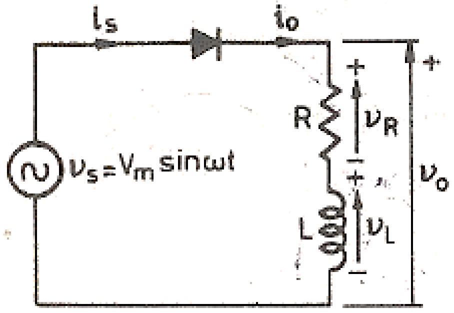
$$V_m \sin \omega t = E + i_0 R$$

$$i_0 = \frac{V_m \sin \omega t - E}{R}$$

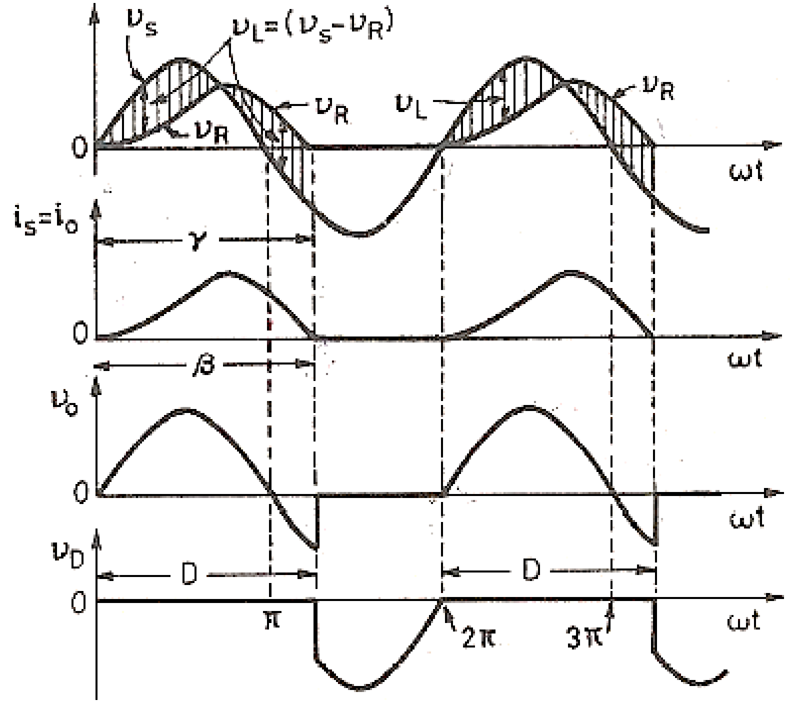
Average value

$$I_0 = \frac{1}{2\pi R}\left[\int_{\theta_1}^{\pi-\theta_1} (V_m \sin \omega t - E)\, d(\omega t)\right]$$

RL load



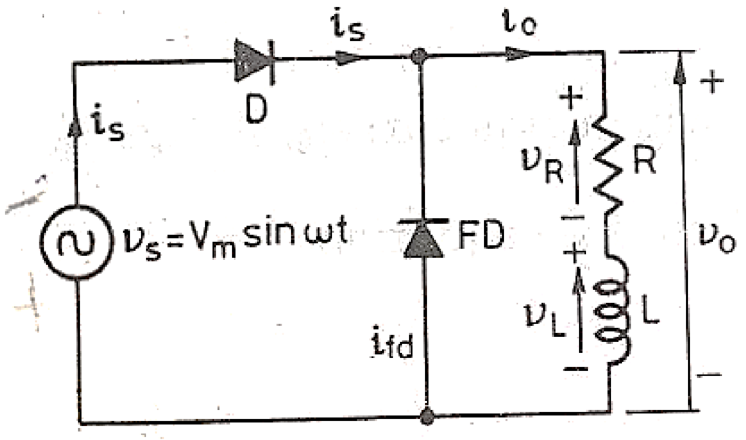
- Current i_o continues to flow-even after source voltage V_s has become negative.
- Because of the presence of inductance L in the load circuit.
- Voltage $V_R = i_o$ R has the same waveshape as that of i_o.
- The current i_o flows till the two areas A and B are equal.
- Area A represents the energy stored by L and area B the energy released by L
- It must be noted that average value of voltage across inductor L is zero.



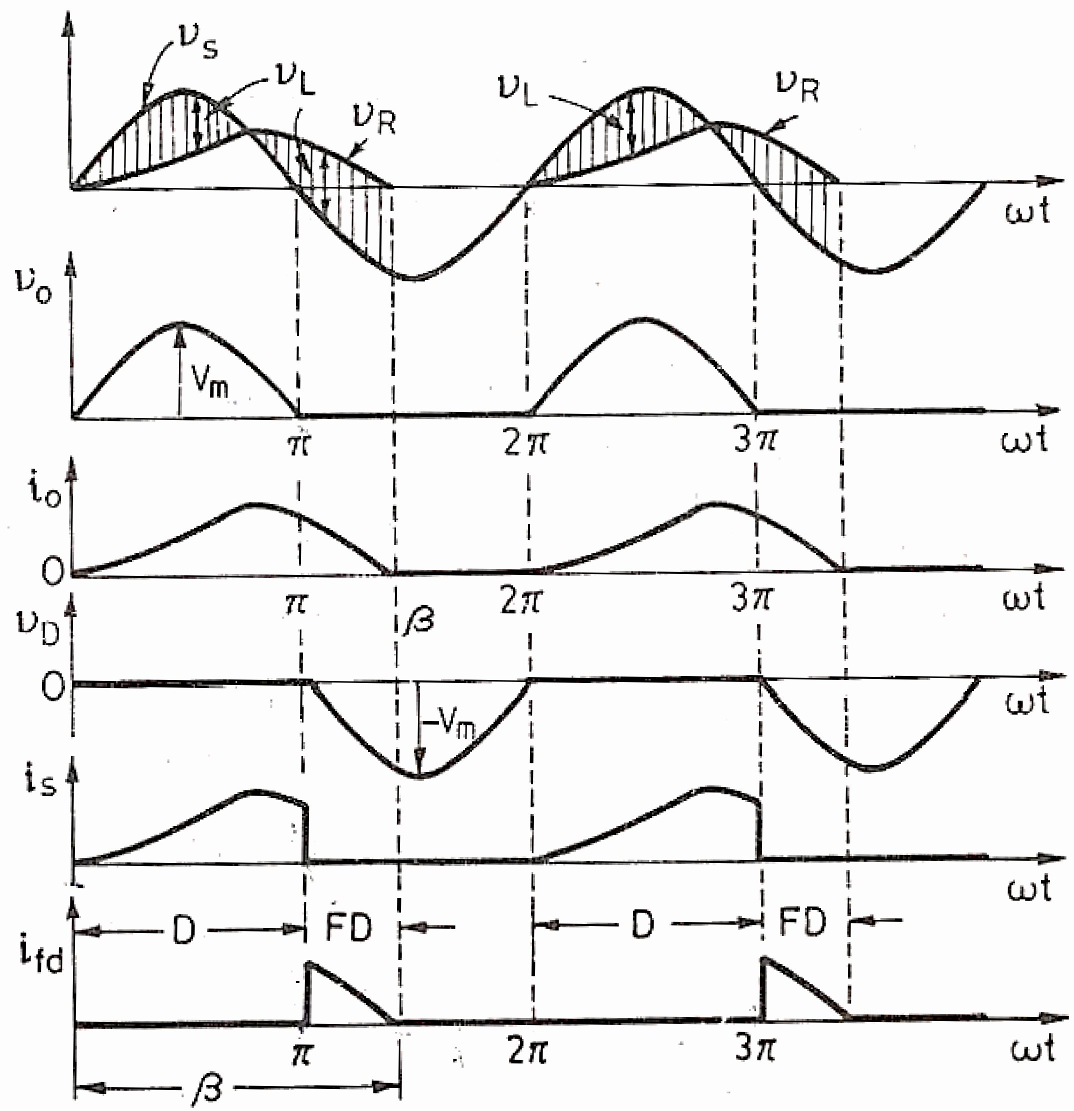
Average value of output voltage,

$$V_0 = \frac{1}{2\pi}\int_0^{\beta} V_m \sin \omega t \cdot d(\omega t)$$

$$= \frac{V_m}{2\pi}(1 - \cos \beta)$$



i_s
i_o
D
i_s
+
ν_R
R
$\nu_s = V_m \sin \omega t$
FD
−
+
ν_o
i_{fd}
ν_L
L
−
+
−



ν_s
ν_L
ν_R
ν_L
ν_R
ωt
ν_o
V_m
π
2π
3π
ωt
i_o
0
π
β
2π
3π
ωt
ν_D
0
$-V_m$
ωt
i_s
ωt
D
FD
D
FD
i_{fd}
π
2π
3π
ωt
β

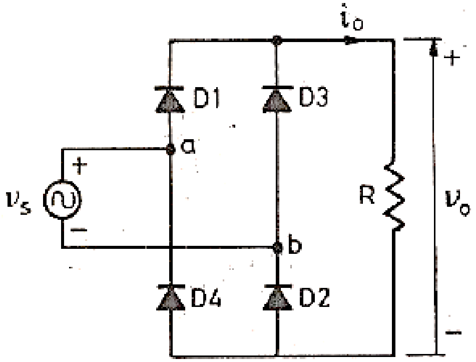
The effects of using free wheeling diode are:

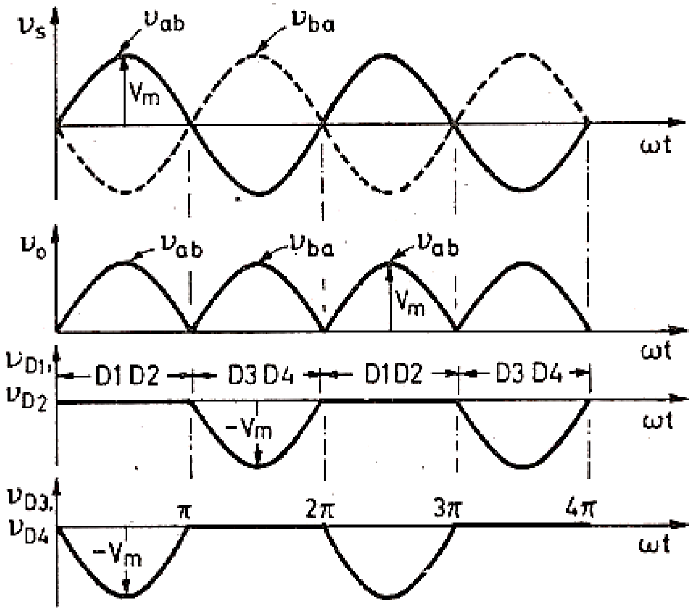
(i) It prevents the output (or load) voltage from becoming negative

(ii) As the energy stored in L is transferred to load through FD, the system efficiency is improved

(iii) The load current waveform is more smooth, the load performance is improved

Single phase full wave diode bridge rectifier





Average output voltage, $V_0 = \frac{1}{\pi} \int_0^{\pi} V_m \sin \omega t \, d(\omega t) = \frac{2V_m}{\pi}$

Average output current, $I_0 = \frac{V_0}{R}$

Rms value of output voltage, $V_{or} = \left[\frac{1}{\pi} \int_0^{\pi} V_m^2 \sin^2 \omega t \, d(\omega t) \right]^{1/2}$

$$= \frac{V_m}{\sqrt{2}} = V_s$$

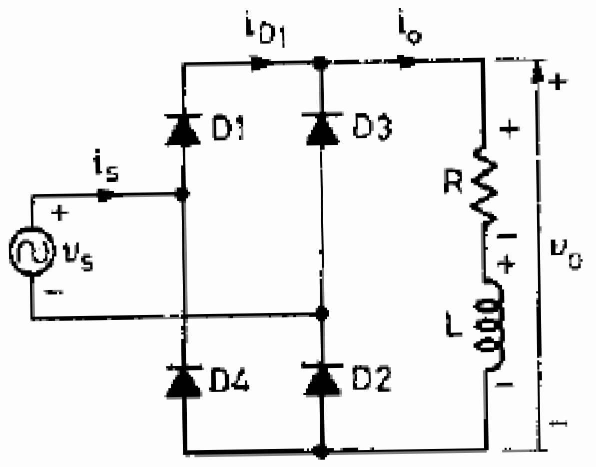
Rms value of load current, $I_{or} = \frac{V_s}{R}$

Power delivered to load $= V_{or} \cdot I_{or} = I_{or}^2 \cdot R$

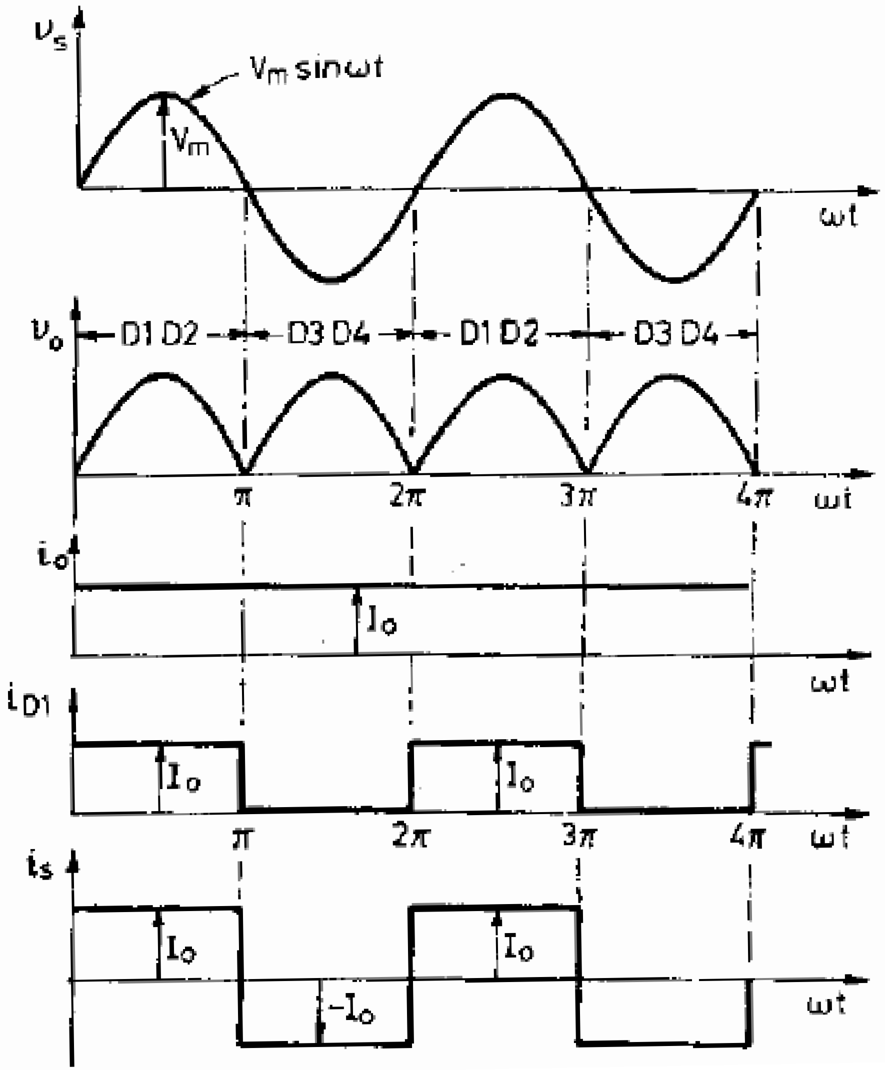
Question

A single-phase full bridge diode rectifier is supplied from 230 V, 50 Hz
source. The load consists of R = 10 ohms and a large inductance so as to render the load current constant. Determine:

a) Draw waveform
b) average values of output voltage and output current,
c) average and rms values of diode currents,
d) rms values of output and input currents, and supply pf



i_{D1}
i_o
D1
D3
i_s
+
v_s
−
R
L
D4
D2
v_o



v_s
$V_m \sin\omega t$
V_m
ωt
v_o
D1 D2
D3 D4
D1 D2
D3 D4
π
2π
3π
4π
i_o
I_o
i_{D1}
i_s
$-I_o$

(*a*) Average value of output voltage,

$$V_0 = \frac{2V_m}{\pi} = \frac{2\sqrt{2} \times 230}{\pi} = 207.04 \text{ V}$$

Average value of output current,

$$I_0 = \frac{V_0}{R} = \frac{207.04}{10} = 20.704 \text{ A}$$

(*b*) Average value of diode current,

$$I_{DAV} = \frac{I_0 \cdot \pi}{2\pi} = \frac{I_0}{2} = \frac{20.704}{2} = 10.352 \text{ A}$$

Rms value of diode current, $I_{Dr} = \sqrt{\frac{I_0^2 \pi}{2\pi}} = \frac{I_0}{\sqrt{2}} = \frac{20.704}{\sqrt{2}} = 14.642 \text{ A}$

As load, or output, current is ripple free, rms value of output current

$= \text{average value of output current} = I_0 = 20.704 \text{ A}$

Rms value of source current, $I_s = \sqrt{\frac{I_0^2 \pi}{\pi}} = I_0 = 20.704 \text{ A}$

Load power $= V_0 I_0 = 207.04 \times 20.704 \text{ W}$

Input power $= V_s I_s \cos \phi$

$\therefore \quad 230 \times 20.704 \times \cos \phi = 207.04 \times 20.704$

$\therefore$ Supply pf $= \cos \phi = \frac{207.04}{230} = 0.90$ lagging.

Phase controlled rectifiers

- Application:

(a) Paper mills, printing presses and textile mills employing dc motor drives
(b) Traction systems working on dc
(c) Electrochemical and electrometallurgical processes
(d) High-voltage dc transmission

- Earlier, AC-DC conversion done using- MG set, mercury arc rectifiers

- Phase-controlled ac to dc converters employing thyristors are extensively used for changing constant ac input voltage to controlled dc output voltage

- mercury-arc rectifiers and thyratrons are being replaced by thyristors

- In phase-controlled rectifiers, a thyristor is turned off as ac supply voltage reverse biases it, provided anode current has fallen to a level below the holding current.

- The turning-off, or commutation, of a thyristor by supply voltage itself is called natural, or line commutation.

- Phase controlled rectifiers need no commutation circuitry.

- Simple , less expensive and widely used in industries

- Assumptions:

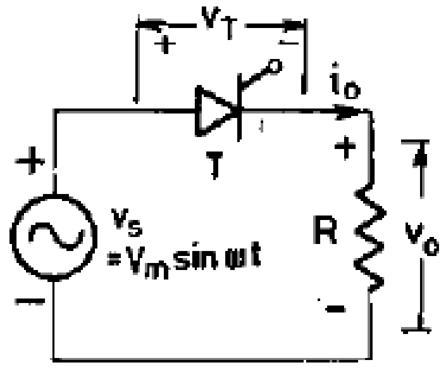
a) SCRs and diodes are assumed ideal switches
b) There is no voltage drop across them
c) No reverse current exists under reverse voltage conditions
d) Holding current is zero
e) Trigger circuits are not shown in SCR circuit for convenience

- The **firing angle** may defined as the angle between the instant thyristor would conduct if it were a diode and the instant it is triggered

- Angle measured from the instant that gives largest output voltage to the instant it is triggered

- Angle measured from the instant SCR gets forward biased to the instant it is triggered

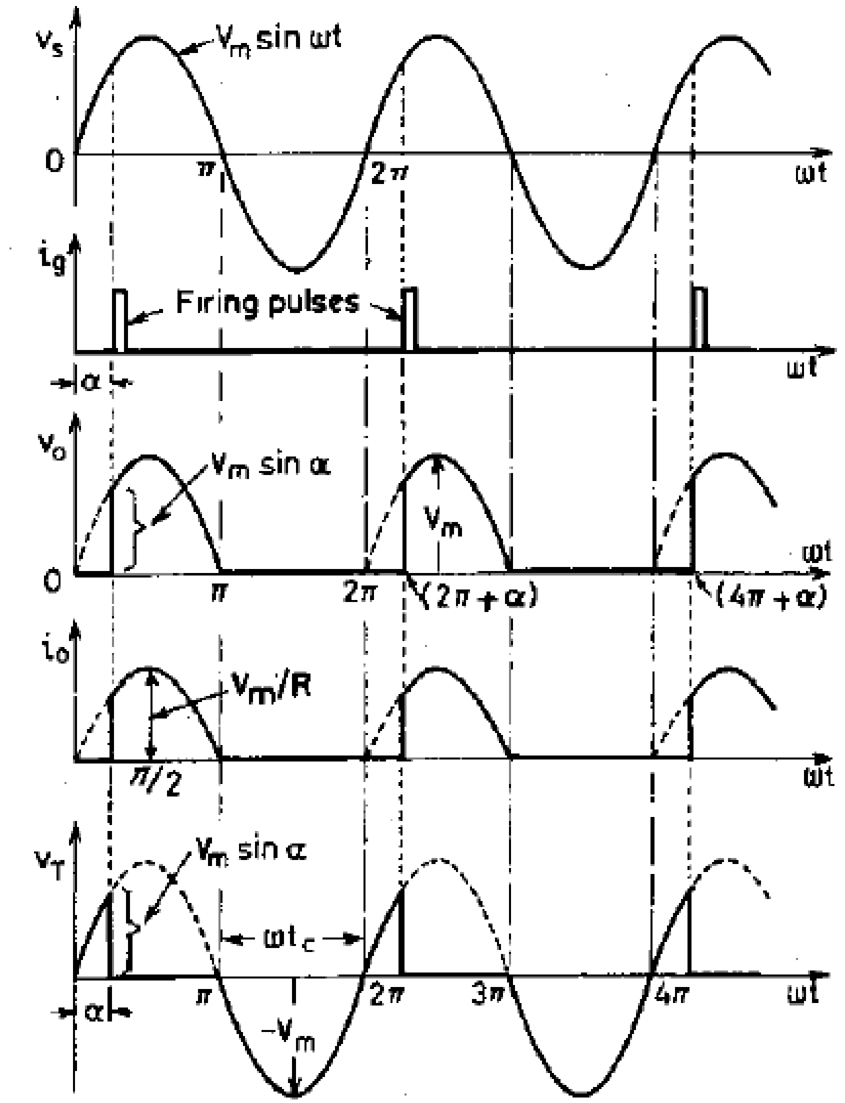
Single phase half wave circuit with R load



- An SCR can conduct only when anode voltage is positive and a gating signal is applied
- Thyristor blocks the flow of load current io until it is triggered.
- At some delay angle α, a positive gate signal applied between gate and cathode turns on the SCR
- At the instant of α, v_o rises from zero to V_m sin α.
- For resistive load, current i_o is in phase with v_o
- Once the SCR is on, load current flows, until it is turned-off by reversal of voltage at ω=π, 3π, etc.
- At these angles load current falls to zero and soon after the supply voltage reverse biases the SCR, the device is therefore turned off
- By varying α, the phase relationship between the start of load current and supply voltage can be controlled
- One pulse of load current during one cycle of supply voltage

Single-phase half-wave thyristor circuit with R load

- As firing angle is increased from zero to π, the average load voltage decreases from the largest value to zero.
- Thyristor remains on from α to π, $(2\pi+\alpha)$ to 3π etc., during these intervals $V_T = 0$
- It is off from π to $(2\pi+\alpha)$, 3π to $(4\pi+\alpha)$, etc., during these intervals V_T has the waveshape of supply voltage V_s. It may be observed that $V_s = V_o + V_T$
- As the thyristor is reverse biased for π radians, the circuit turn-off time is given by $t_c = \frac{\Pi}{\omega}$, where $\omega = 2\pi f$, f is supply frequency



- The circuit turn-off time t_c must be than the SCR turn-off time t_q as specified by the manufacturers
- Average voltage v_0 across R load

$$V_0 = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin \omega t \cdot d(\omega t) = \frac{V_m}{2\pi}(1 + \cos \alpha)$$

Average load current, $I_0 = \dfrac{V_0}{R} = \dfrac{V_m}{2\pi R}(1 + \cos \alpha)$

- R.M.S value of voltage

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

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

$$I_{or} = \frac{V_{or}}{R}$$

Power delivered to resistive load = (rms load voltage) (rms load current)

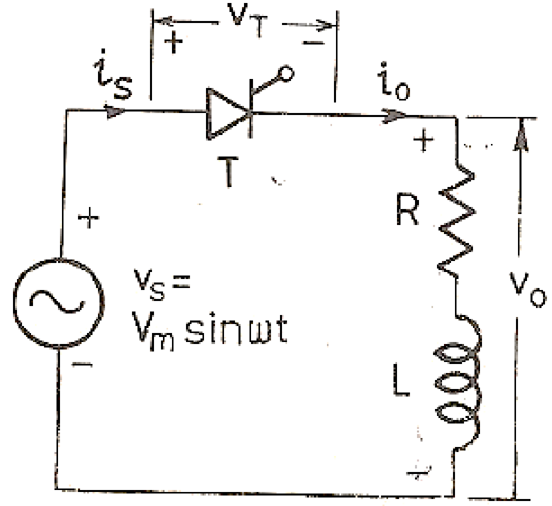
$$= V_{or} I_{or} = \frac{V_{or}^2}{R} = I_{or}^2 R$$

Input voltamperes = (rms source voltage) (total rms line current)

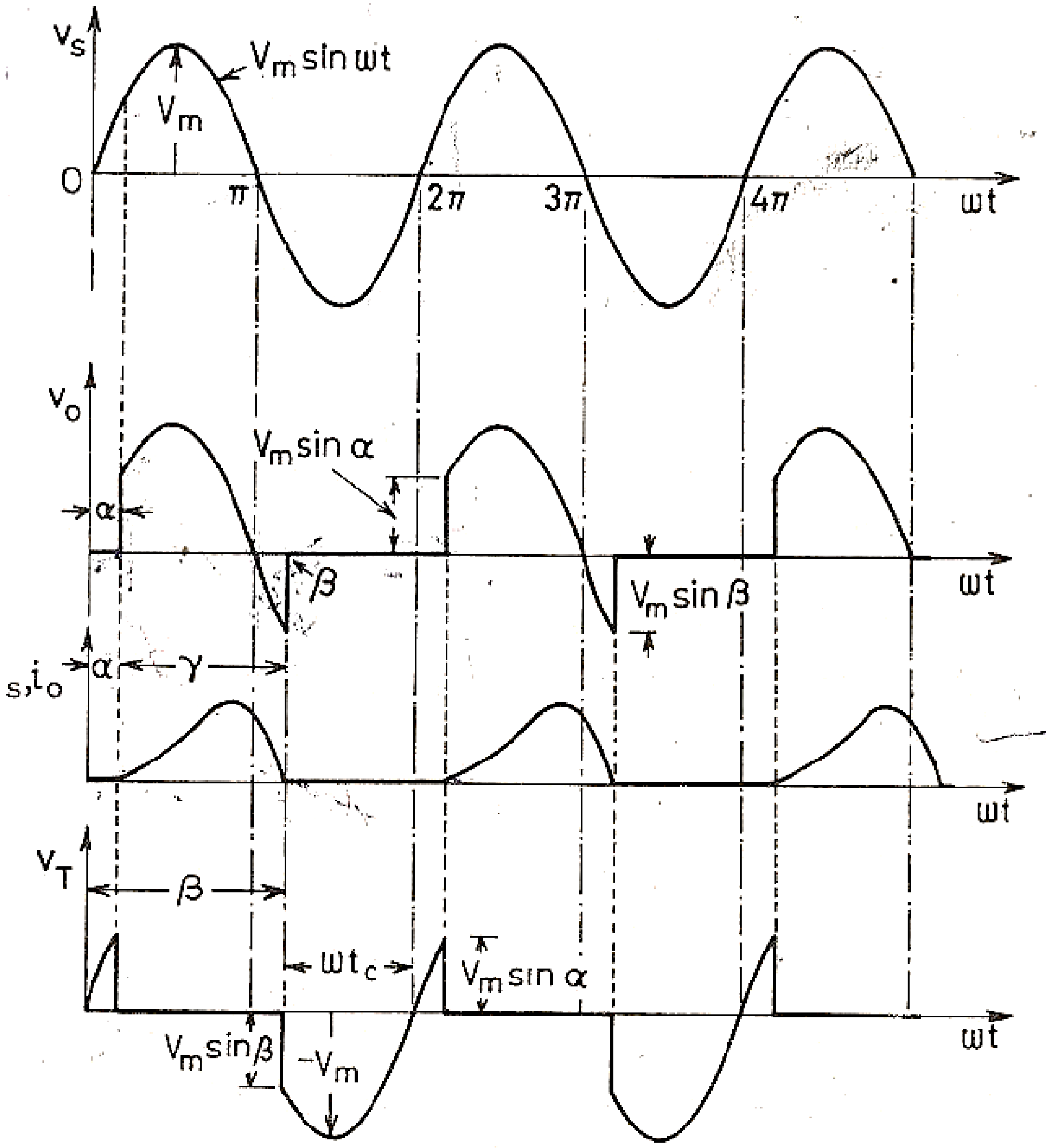
$$= V_s \cdot I_{or} = \frac{\sqrt{2}\, V_s^2}{2R\sqrt{\pi}} \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right]^{1/2}$$

Input power factor $= \dfrac{\text{Power delivered to load}}{\text{Input VA}} = \dfrac{V_{or} \cdot I_{or}}{V_s \cdot I_{or}} = \dfrac{V_{or}}{V_s}$

RL load

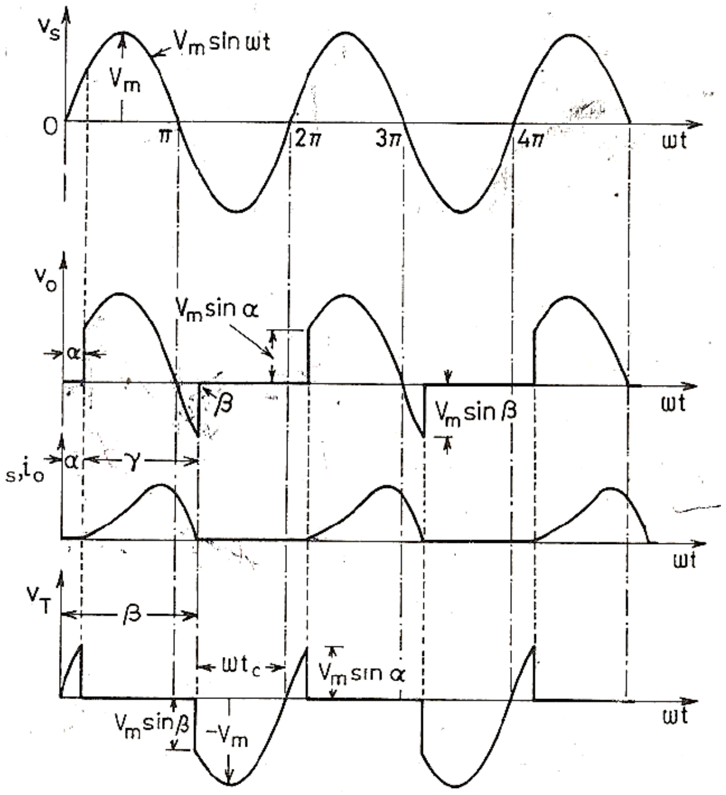


v_T
+
−
i_s
i_o
T
+
R
+
v_S =
$V_m \sin\omega t$
−
L
v_o



v_s
$V_m \sin \omega t$
V_m
0
π
2π
3π
4π
ωt
v_o
$V_m \sin \alpha$
α
β
$V_m \sin \beta$
ωt
i_s, i_o
α
γ
ωt
v_T
β
ωt_c
$V_m \sin \alpha$
$V_m \sin \beta$
$-V_m$
ωt

- At $\omega t = \alpha$, thyristor is turned on by gating signal.
- The load voltage v_o at once becomes equal to source voltage v_s
- But the inductance L forces the load or output current i_o to rise gradually.
- After some time, i_o reaches maximum value and then begins to decrease.
- At $\omega t = \pi$, v_o is zero but i_o is not zero because of the load inductance L.
- Eventhough SCR is subjected to reverse anode voltage but it will not be turned off as load current io is not less than the holding current.
- At some angle $\beta > \pi$, i_o reduces to zero and SCR is turned off as it is already reverse biased.
- At $\omega t = 2\pi + \alpha$, SCR is triggered again, V_s is applied to the load



- Angle β is called the extinction angle and (β-α) =γ is called the conduction angle
- The waveform of voltage V_T across thyristor T reveals that when ωt= α, $V_T = V_m \sin \alpha$; from ωt= α to β, $V_T = 0$ and at ωt= β , V_T = Vm sin β. As β > π, V_T is negative
- Thyristor is therefore reverse biased from ωt= β to 2 π.
- Thus, circuit turn-off time (t_c) $t_C = \dfrac{2\pi - \beta}{\omega}$ sec
- I_0 has two components: steady-state (i_s) and transient components (i_t)

$$V_m \sin \omega t = R\, i_0 + L \frac{di_0}{dt}$$

$$i_s = \frac{V_m}{\sqrt{R^2 + X^2}} \sin(\omega t - \phi)$$

$$\phi = \tan^{-1} \frac{X}{R} \text{ and } X = \omega L.$$

$$R\, i_t + L \frac{di_t}{dt} = 0$$

$$i_t = A\, e^{-(R/L)t}$$

$$i_o = i_s + t_t = \frac{V_m}{Z} \sin(\omega t - \phi) + A_e^{-(R/L)t}$$

$$Z = \sqrt{R^2 + X^2}$$

At this time $t = \frac{\alpha}{\omega}$, $i_0 = 0$

$$0 = \frac{V_m}{Z} \sin(\alpha - \phi) + Ae^{-R\alpha/L\omega}$$

$$A = -\frac{V_m}{Z} \sin(\alpha - \phi)\, e^{R\alpha/\omega L}$$

$$i_0 = \frac{V_m}{Z} \sin(\omega t - \phi) - \frac{V_m}{Z} \sin(\alpha - \phi) \exp. \left\{ -\frac{R}{\omega L} (\omega t - \alpha) \right\}$$

$$\alpha < \omega t < \beta$$

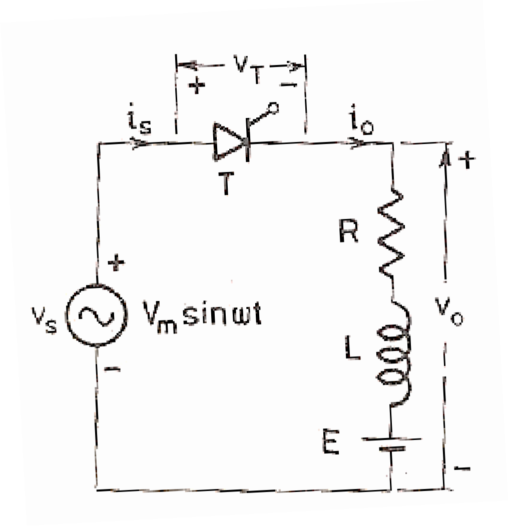
$$V_0 = \frac{1}{2\pi} \int_\alpha^\beta V_m \sin \omega t \, d(\omega t) = \frac{V_m}{2\pi} (\cos \alpha - \cos \beta)$$

Average load current, $I_0 = \frac{V_m}{2\pi R} (\cos \alpha - \cos \beta)$

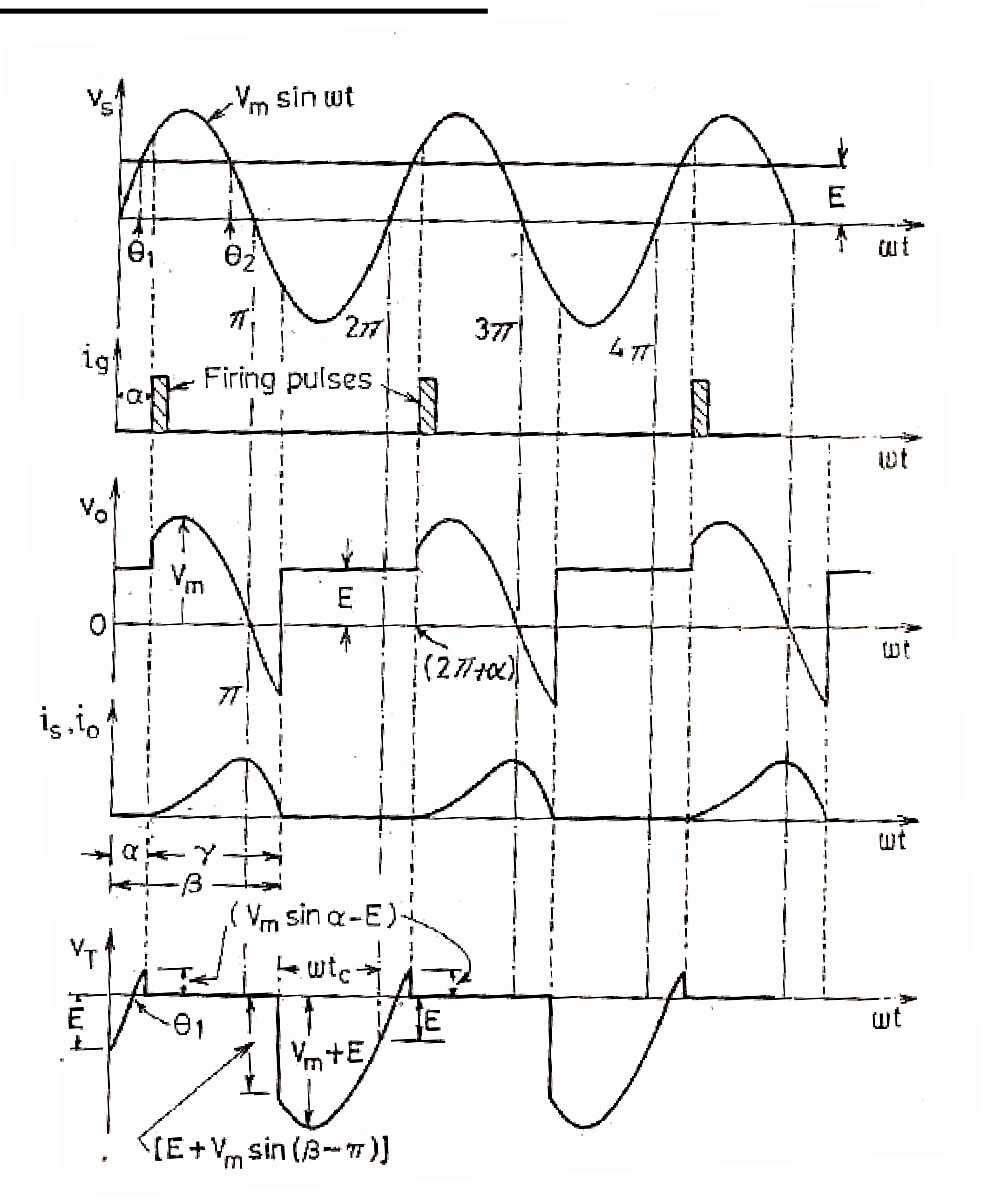
Rms load voltage, $V_{or} = \left[\frac{1}{2\pi} \int_\alpha^\beta V_m^2 \sin^2 \omega t \cdot d(\omega t) \right\}^{1/2}$

$$= \frac{V_m}{2\sqrt{\pi}} \left[(\beta - \alpha) - \frac{1}{2} \{\sin 2\beta - \sin 2\alpha\} \right]^{1/2}$$

Single phase half wave circuit with RLE load



$$V_m \sin \omega t = R\, i_0 + L \frac{d\, i_0}{dt} + E$$



- The counter emf E in the load may be due to a battery or a dc motor
- The minimum value of firing angle is obtained from the relation $V_m \sin \omega t = E$
- This is shown to occur at an angle θ_1 where

$$\theta_1 = \sin^{-1}(E/V_m)$$

- In case thyristor T is fired at an angle $\alpha < \theta_1$, then $E > V_s$, SCR is reverse biased and therefore it will not turn on.
- maximum value of firing angle is $\theta_2 = \pi - \theta_1$
- During the interval load current i_o is zero, load voltage $V_o = E$
- During the time i_o is not zero, V_o follows V_s curve
- Average voltage across inductance is zero. Thus, average value of load current can be obtained by integrating $(V_m \sin\omega t - E)/ R$ between α and β.

$$I_0 = \frac{1}{2\pi R}\left[\int_\alpha^\beta (V_m \sin \omega t - E)\, d(\omega t)\right]$$

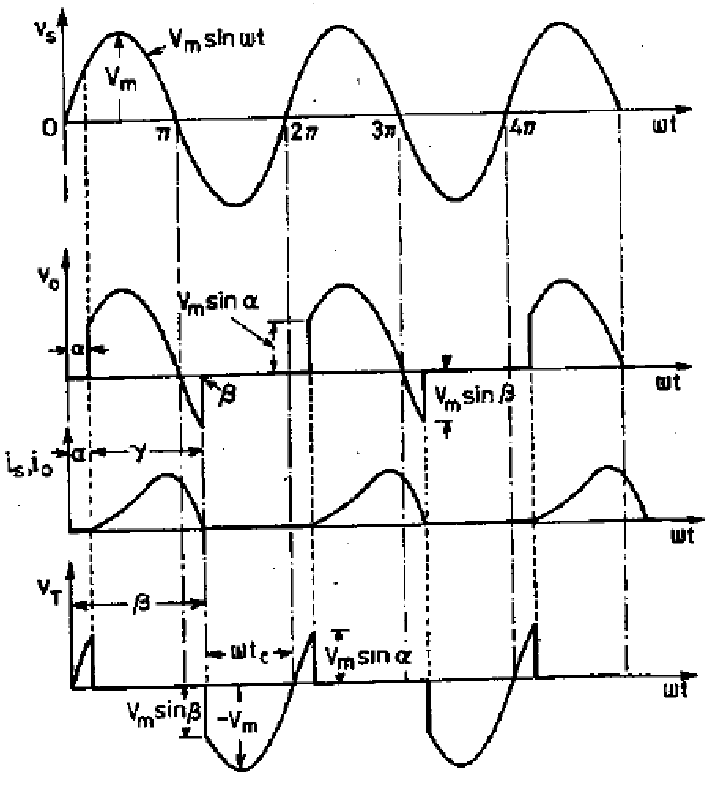
$$= \frac{1}{2\pi R}\left[V_m (\cos \alpha - \cos \beta) - E (\beta - \alpha)\right]$$

Here conduction angle $\gamma = \beta - \alpha$. Putting $\beta = \gamma + \alpha$

$$I_0 = \frac{1}{2\pi R}\left[V_m \{\cos \alpha - \cos (\gamma + \alpha)\} - E \cdot \gamma\right]$$

A 230 V, 50 Hz, one-pulse SCR controlled converter is at a firing angle of 40^0 and the load current extinguishes at an of 210^0. Find the circuit turn off time, average output voltage and the average load current for:

(a) R= 5 ohm L = 2mH
(b) R= 5 ohm L = 2mH E=110 V.



$$= \frac{2\pi - \beta}{\omega} =$$

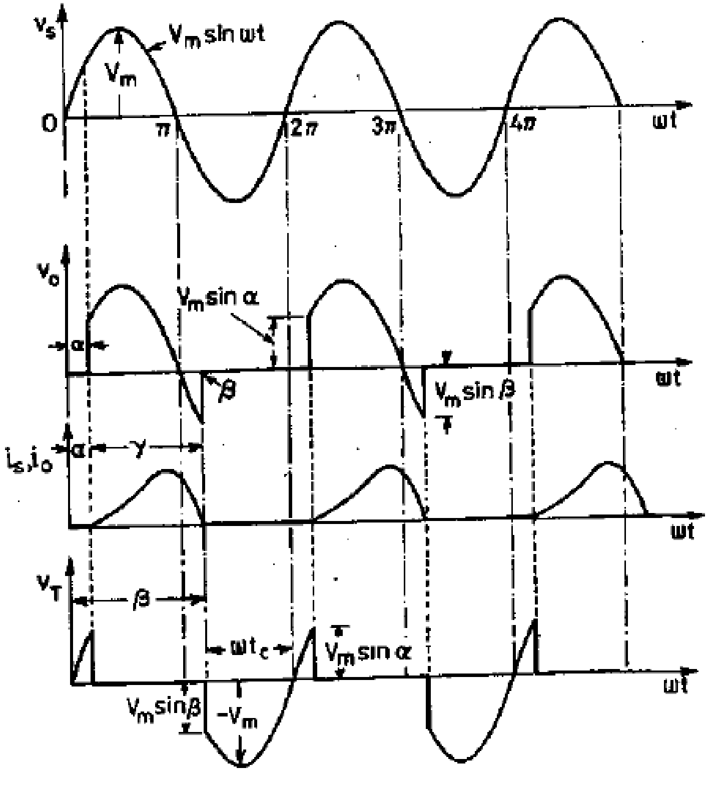
From Eq. (6.8), average output voltage

$$V_0 = \frac{V_m}{2\pi}(\cos \alpha - \cos \beta)$$

Average load current $\quad I_0 =$

A 230 V, 50 Hz, one-pulse SCR controlled converter is at a firing angle of 40^0 and the load current extinguishes at an of 210^0. Find the circuit turn off time, average output voltage and the average load current for:

(a) R= 5 ohm L = 2mH
(b) R= 5 ohm L = 2mH E=110 V.



$$= \frac{2\pi - \beta}{\omega} = \frac{(360 - 210)\,\pi}{180 \times 2\pi \times 50} = 8.333 \text{ m-sec}$$

From Eq. (6.8), average output voltage

$$V_0 = \frac{\sqrt{2} \cdot 230}{2\pi} [\cos 40° - \cos 210°] = 84.477 \text{ V}$$

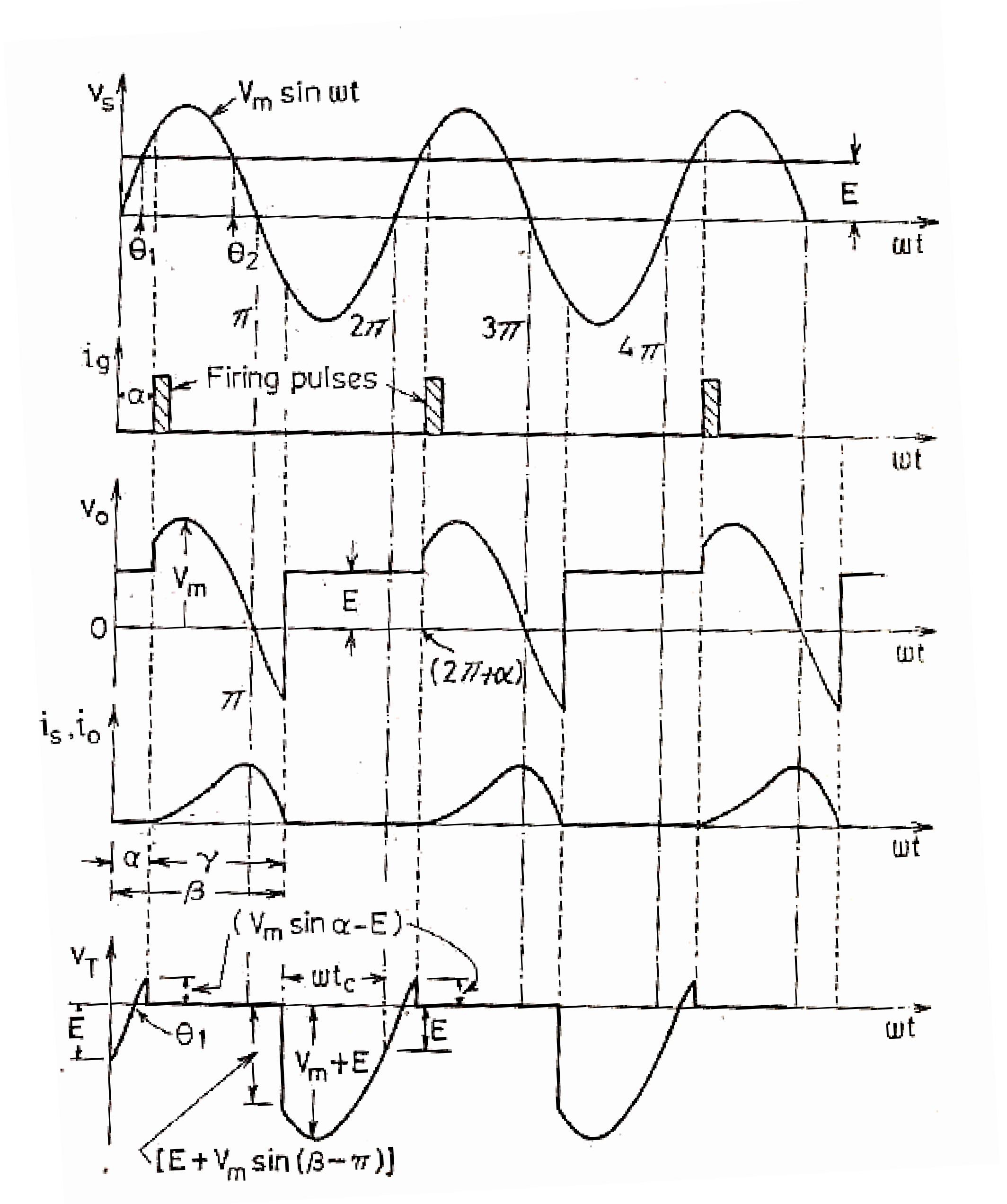
Average load current $\quad I_0 = \dfrac{V_0}{R} = \dfrac{84.477}{5} = 16.8954 \text{ A.}$

turn-off time is $\dfrac{2\pi - \beta}{\omega}$ sec.

$$I_0 = \frac{1}{2\pi R}\left[\int_\alpha^\beta (V_m \sin \omega t - E)\, d(\omega t)\right]$$

$$= \frac{1}{2\pi R}\left[V_m (\cos \alpha - \cos \beta) - E(\beta - \alpha)\right]$$

$$V_0 = E + I_0 R$$



turn-off time is $\frac{2\pi - \beta}{\omega}$ sec.

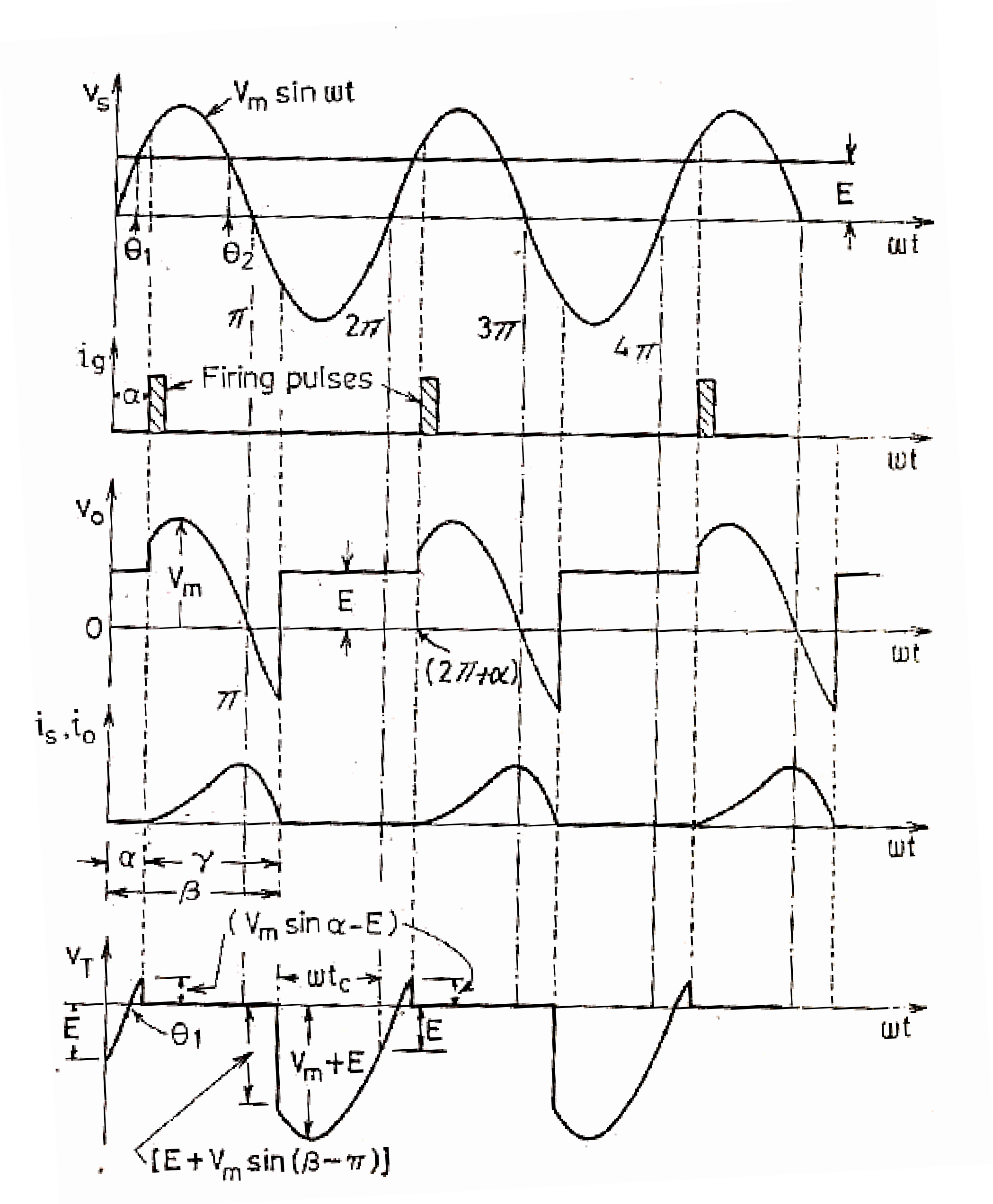
$$I_0 = \frac{1}{2\pi R}\left[\int_{\alpha}^{\beta} (V_m \sin \omega t - E)\, d(\omega t)\right]$$

$$= \frac{1}{2\pi R}\left[V_m (\cos \alpha - \cos \beta) - E (\beta - \alpha)\right]$$

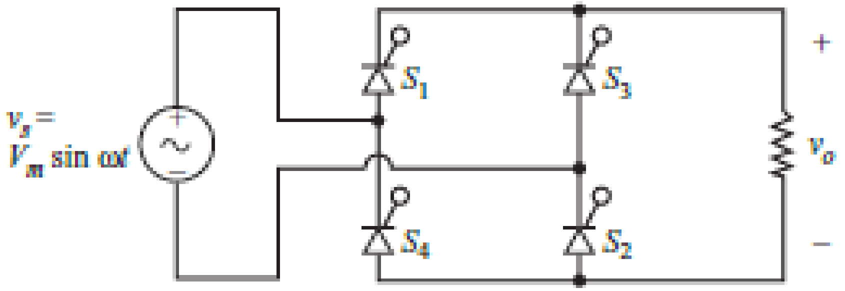
$$I_0 = \frac{1}{2\pi \cdot 5}\left[\sqrt{2} \cdot 230 (\cos 40° - \cos 210°) - 110 (210 - 40) \frac{\pi}{180}\right] = 6.5064 \text{ A}.$$

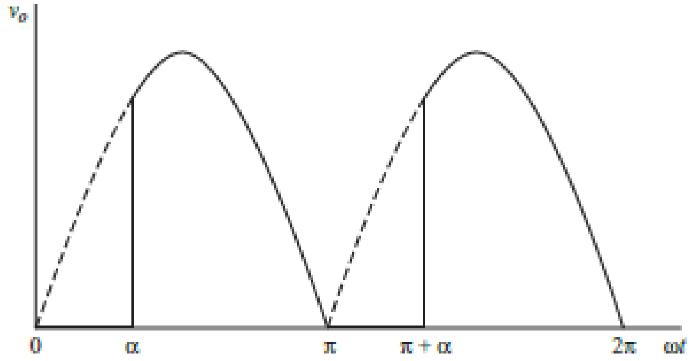
$$V_0 = E + I_0 R$$

Average load voltage, $V_0 = E + I_0 R = 110 + 6.5064 \times 5 = 149.04$ V.



Single phase fully controlled bridge rectifier with R load





- For a controlled full wave bridge rectifier, SCRs S_1 and S_2 will become forward-biased when the source becomes positive but will not conduct until gate signals are applied.

- Similarly, S_3 and S_4 become forward-biased when the source becomes negative but will not conduct until they receive gate signals

- If the delay angle is zero, the rectifiers behave exactly as uncontrolled rectifiers with diodes

- Average output voltage: $$\boxed{V_o = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin(\omega t)\, d(\omega t) = \frac{V_m}{\pi}(1 + \cos\alpha)}$$

Average output current is then

$$I_o = \frac{V_o}{R} = \frac{V_m}{\pi R}(1 + \cos \alpha)$$

- The power delivered to the load is a function of the input voltage, the delay angle, and the load components
- $P = I^2_{rms} R$ is used to determine the power in a resistive load

$$I_{rms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi}\left(\frac{V_m}{R}\sin \omega t\right)^2 d(\omega t)}$$

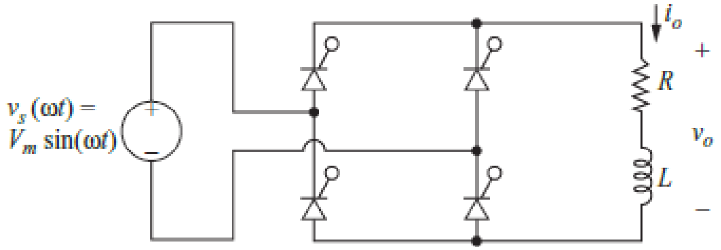
$$= \frac{V_m}{R}\sqrt{\frac{1}{2} - \frac{\alpha}{2\pi} + \frac{\sin(2\alpha)}{4\pi}}$$

Single phase fully controlled bridge rectifier with RL load

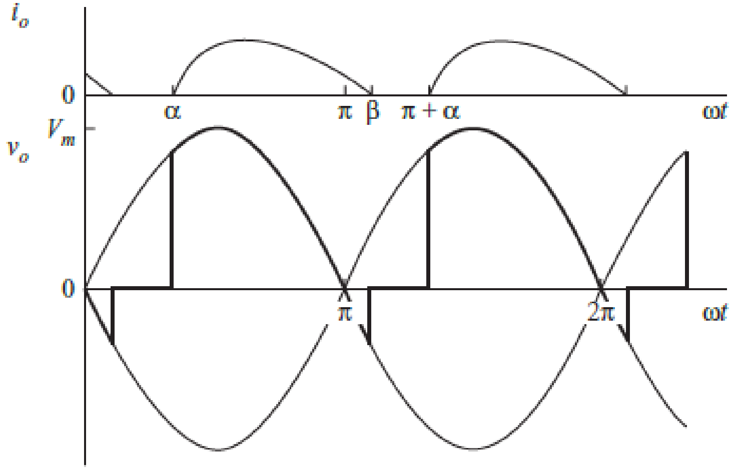
- Load current for a controlled full-wave rectifier with an *RL* load can be either continuous or discontinuous

Discontinuous conduction

- SCRs *S*1 and *S*2 in the bridge rectifier will be forward-biased and *S*3 and *S*4 will be reverse-biased as the source voltage becomes positive



(a)



- Gate signals are applied to *S*1 and *S*2 at ωt= α, turning *S*1 and *S*2 on

- With *S*1 and *S*2 on, the load voltage is equal to the source voltage

- In this condition, the circuit is identical to controlled halfwave rectifier

- The above current function becomes zero at ω*t*=β . If β <π +α, the current remains at zero until ω*t*= π +α

- This mode of operation is called *discontinuous current*,

- Analysis of the controlled full-wave rectifier operating in the discontinuous current mode is identical to that of controlled half-wave rectifier except that the period for the output current is π rather than 2π rad.

$$i_o(\omega t) = \frac{V_m}{Z}\left[\sin(\omega t - \theta) - \sin(\alpha - \theta)\, e^{-(\omega t - \alpha)/\omega\tau}\right] \qquad \text{for } \alpha \le \omega t \le \beta$$

where (4-26)

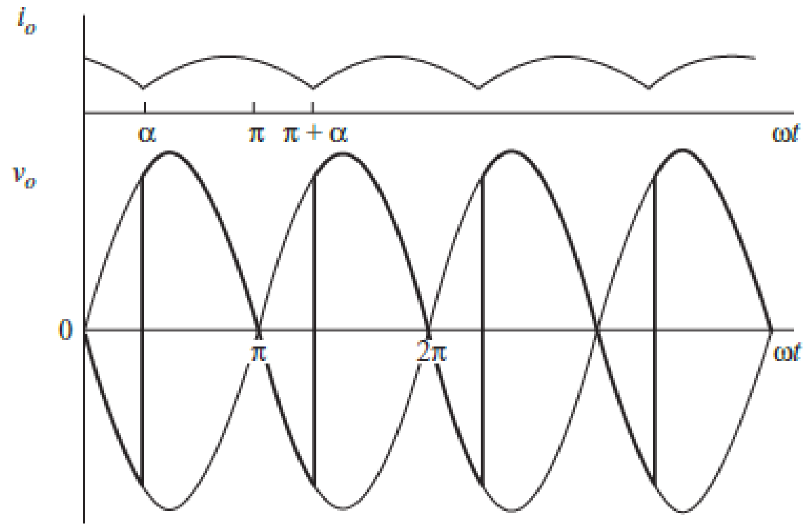
$$Z = \sqrt{R^2 + (\omega L)^2} \qquad \theta = \tan^{-1}\left(\frac{\omega L}{R}\right) \qquad \text{and} \qquad \tau = \frac{L}{R}$$

Continuous conduction

- If the load current is still positive at ωt=π+α, when gate signals are applied to S3 and S4 in the above analysis

- S3 andS4 are turned on and S1 and S2 are forced off

- The current at $\omega t = \pi + \alpha$ must be greater than zero for continuous-current operation.



$$\alpha \le \tan^{-1}\left(\frac{\omega L}{R}\right) \qquad \text{for continuous current}$$

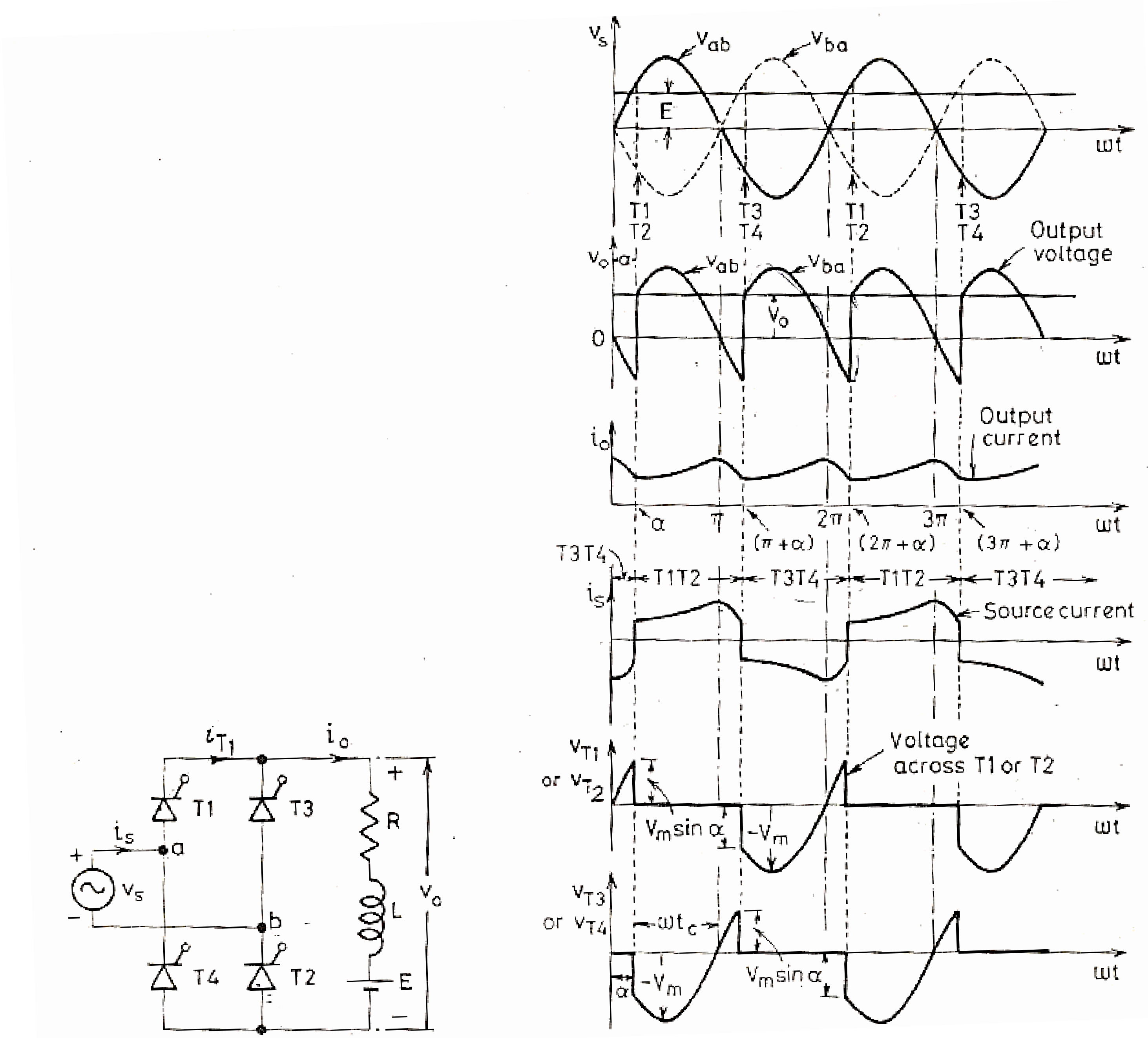
$$\beta < \alpha + \pi \rightarrow \text{discontinuous current}$$

The dc (average) value is

$$\boxed{V_o = \frac{1}{\pi}\int_{\alpha}^{\alpha+\pi} V_m \sin(\omega t)\, d(\omega t) = \frac{2V_m}{\pi}\cos\alpha}$$

$$\boxed{V_{or} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} {V_m}^2 \sin^2 \omega t . d(\omega t)\right]^{1/2}}$$

Single phase fully controlled bridge rectifier with RLE load



- The load is of RLE type, where E is the load circuit emf
- Voltage E may be due to a battery in the load circuit or may be generated emf of a dc motor
- Thyristor pair T1, T2 is simultaneously triggered and π radians later, T3, T4 is gated together.
- When a is positive with respect to b, supply voltage waveform is shown as v_{ab} in the figure.
- When b is positive with respect to a, supply voltage waveform is v_{ba}
- The current directions and voltage polarities shown in Fig. are treated as positive
- Load current i_o is assumed continuous over the working range ;
- This means that load is always connected to the ac voltage source through the thyristors.
- Between $\omega t = 0$ and $\omega t = \alpha$; T 1, T2 are forward biased through already conducting SCRs T3 and T4 and block the forward voltage
- For continuous current, thyristors T3, T4 conduct after $\omega t = 0$ even though these are reverse biased.
- Forward biased SCRs T1, T2 are triggered at $\omega t = \alpha$
- T3 and T4 turns off due to reverse voltage across them (natural commutation)

- Load current flowing through T3 & T4 transferred to T1 & T2

- SCR will turn on only when $V_m \sin\alpha > E$

- Maximum reverse voltage across T1, T2, T3 or T4 is V_m and at the instant of triggering with firing angle α, each SCR is subjected to a reverse voltage of Vm sin α .

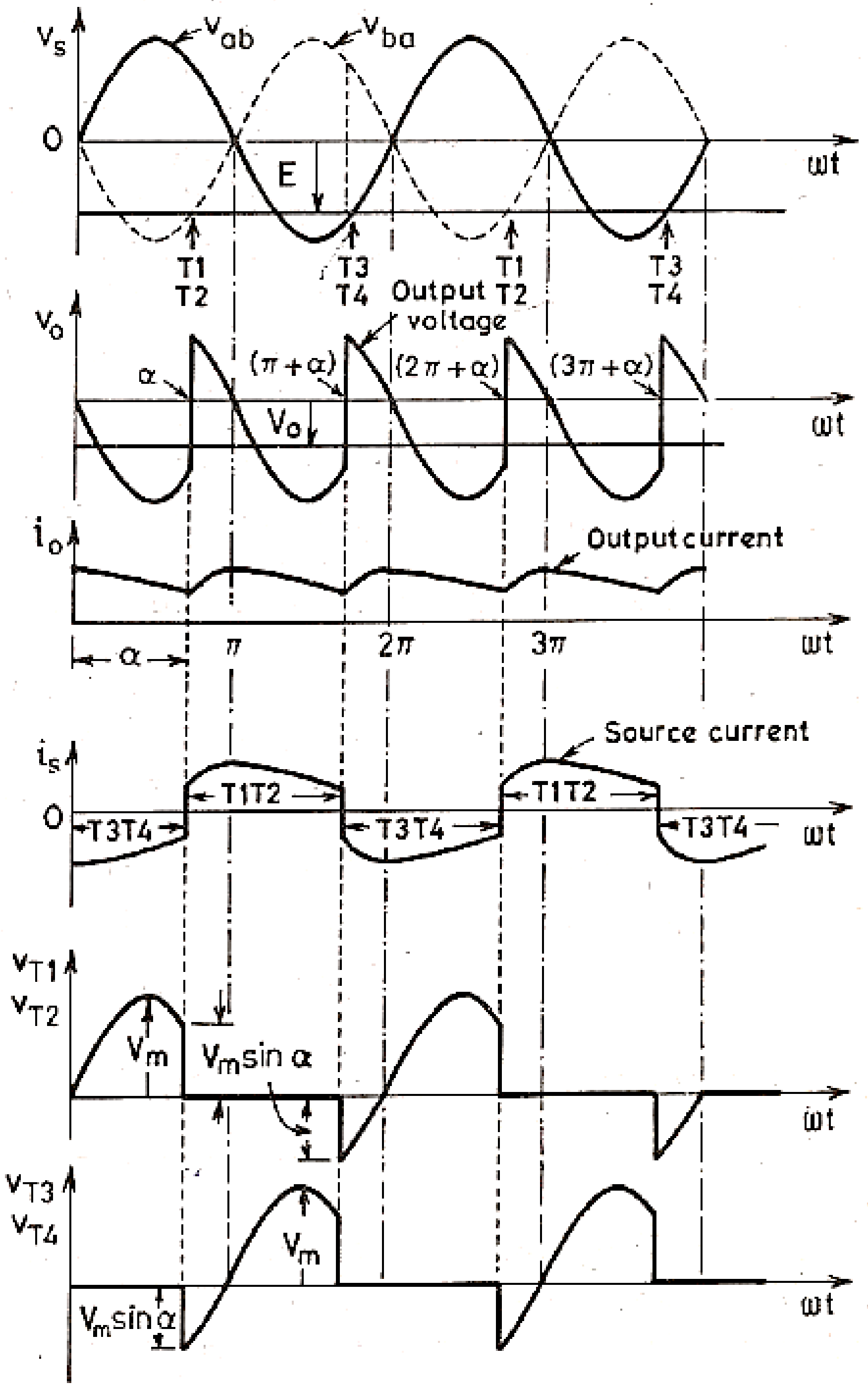
- Considering source current, during α to π, both v_s and i_s are positive, power therefore flows from ac source to load.

- During the interval π to (π+ α), v_s is negative but i_s is positive, the load therefore returns some of its energy to the supply system.

- But the net power flow is from ac source to dc load.

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \cdot d(\omega t) = \frac{2V_m}{\pi}\cos\alpha$$

- If $\alpha > 90^0$, V_o is negative
- average terminal voltage V_o is negative
- If the load circuit emf E is reversed, this source E will feed power back to ac supply
- This operation of full converter is known as inverter operation of the converter
- The full converter with firing angle delay greater than 90^0 is called **line-commutated inverter**
- Such an operation is used in the regenerative braking mode of a dc motor in which case then E is counter emf of dc motor



- During 0 to α, ac source voltage is positive but ac source current is negative, power therefore flows from dc source to ac source

- From α to π, both v_s and i_s are positive, power flows from ac source to dc source.

- Net power flow is from dc source to ac source, because (π -α) < α

- In converter operation, the average value of output voltage Vo must be greater than load circuit emf E

- During inverter operation load circuit emf when inverted to ac must be more than ac supply voltage

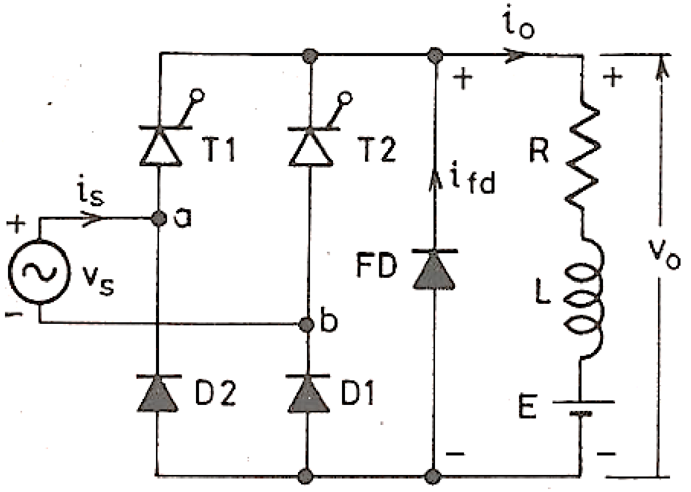
- DC source voltage E must be more than inverter voltage Vo, only when power would flow from dc source to ac supply system

- Output current i_o is positive and source current is positive when T1, T2 are conducting

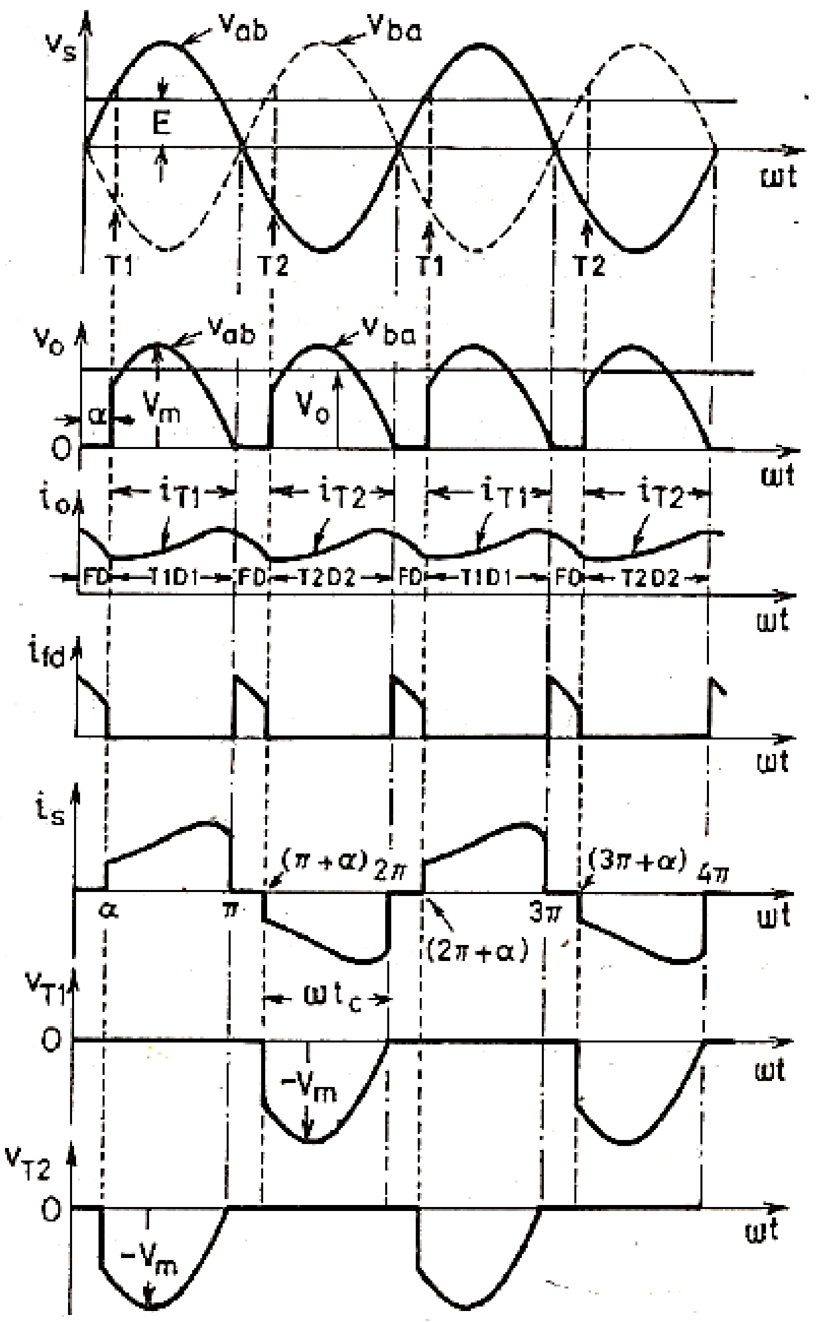
- circuit turn-off time for both converter and inverter operations is given by $t_c = \dfrac{\pi - \alpha}{\omega}$ sec

Single-phase semiconverter

- A single-phase semiconverter bridge with two thyristors and two diodes.
- Symmetrical and Asymmetrical configuration
- Sometimes third diode is connected across load as free wheeling diode
- The load can be R, RL,RLE, RE type
- Load current is assumed continuous over the working range.



- Thyristor T1 is forward biased only when source voltage $V_m \sin\omega t$ exceeds E.
- T1 is triggered at a firing angle delay α such that $V_m \sin\alpha > E$.
- With T1 on, load gets connected to source through T1 and D1
- For the period $\omega t = \alpha$ to π, load current i_o flows through RLE, D1, source and T1 and the load terminal voltage v_o is of the same waveshape as the ac source voltage
- Soon after $\omega t = \pi$,load voltage v_o tends to reverse as the ac source voltage changes polarity.
- Just as vo tends to reverse, FD is forward biased and starts conducting.
- The load current io is transferred from T1, D1 to FD.
- As SCR T1 is reverse biased at $\omega t = \pi+$ through FD, TI is turned off at $\omega t = \pi+$.



- The load terminals are short circuited through FD, therefore load, or output, voltage Vo is zero during $\pi < \omega t < (\pi + \alpha)$.

- After $\omega t = \pi$, during the negative half cycle, T2 will be forward biased only when source voltage is more than E.

- At $\omega t = \pi + \alpha$, source voltage exceeds E, T2 is therefore triggered

- Soon after that, FD is reverse biased and is therefore turned off

- load current now shifts from FD to T2, D2.

- At $\omega t = 2\pi$, FD is again forward biased and output current i_o is transferred from T2, D2 to FD

Semi converter with R load

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t.\, d(\omega t) = \frac{V_m}{\pi}(1+\cos\alpha)$$

Semi converter with RL load (Continuous conduction)

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t.\, d(\omega t) = \frac{2V_m}{\pi}(\cos\alpha)$$

Semi converter with RL load and free wheeling diode

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t.\, d(\omega t) = \frac{V_m}{\pi}(1+\cos\alpha)$$

Semi converter with RLE load (Continuous conduction)

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t.\, d(\omega t) = \frac{2V_m}{\pi}(\cos\alpha)$$

Semi converter with RLE load and free wheeling diode

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t.\, d(\omega t) = \frac{V_m}{\pi}(1+\cos\alpha)$$