PPT ON
POWER ELECTRONICS
V SEM (IARE-R16)

UNIT I
POWER SEMICONDUCTOR DEVICES AND COMMUTATION CIRCUITS

Introduction to power electronics

- Power Electronics refers to the process of controlling the flow of current and voltage and converting it to a form that is suitable for user loads

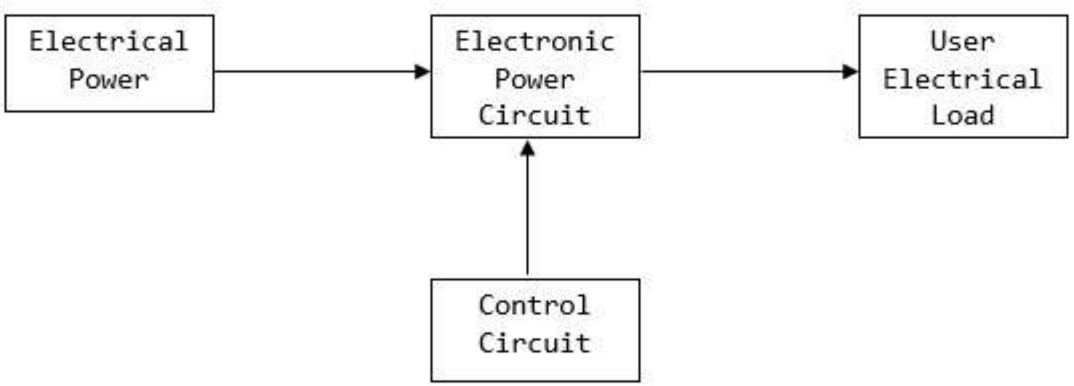
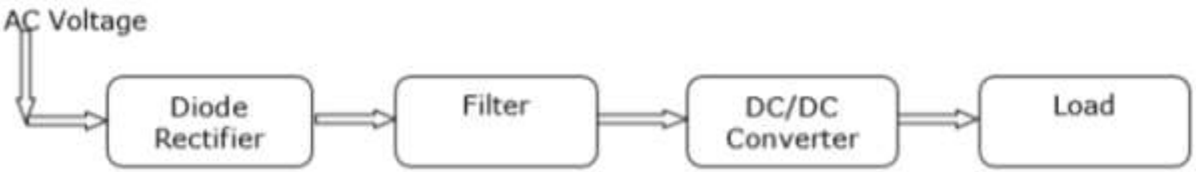


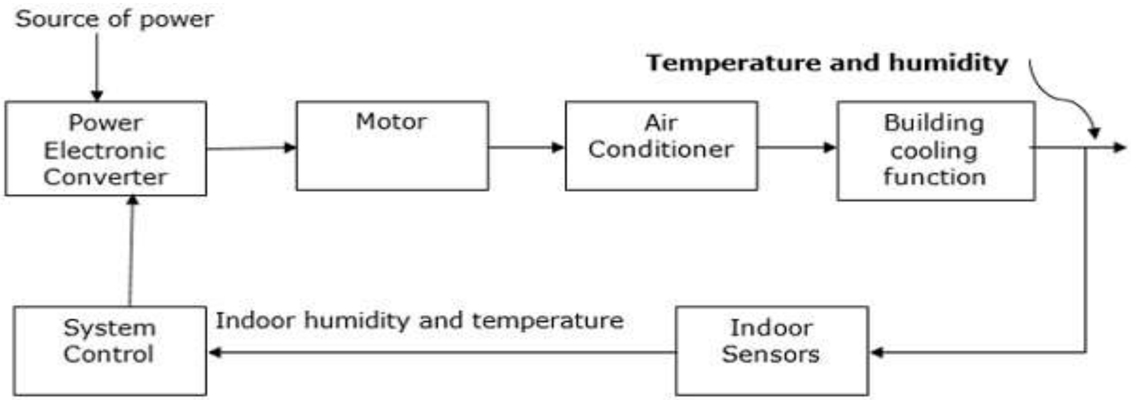
Figure: 1.1. Block diagram of DC power supply
supply

Static Applications

- This utilizes moving and/or rotating mechanical parts such as welding,heating, cooling, and electro-plating and DC power.



Drive Applications



A power electronic system converts electrical energy from one form to another and ensures the following is achieved

1. Maximum efficiency
2. Maximum reliability
3. Maximum availability
4. Minimum cost
5. Least weight
6. Small size

Types of power electronic converters

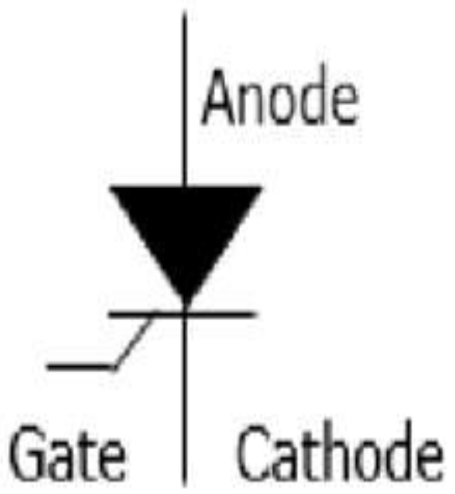
1. Rectifiers (AC to DC converters): These converters convert constant ac voltage to variable dc output voltage.
2. Choppers (DC to DC converters): Dc chopper converts fixed dc voltage to a controllable dc output voltage.
3. Inverters (DC to AC converters): An inverter converts fixed dc voltage to a variable ac output voltage.
4. AC voltage controllers: These converters converts fixed ac voltage to a variable ac output voltage at same frequency.
5. Cycloconverters: These circuits convert input power at one frequency to output power at a different frequency through on6e stage conversion.

Power semiconductor devices

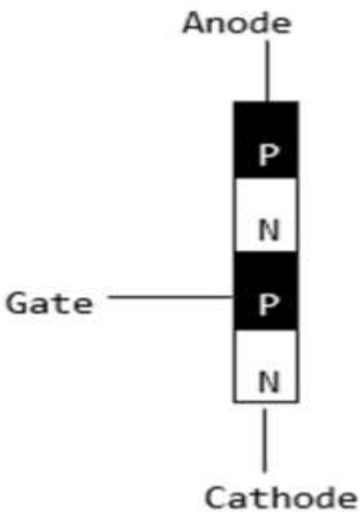
1. Power Diodes.
2. Power transistors (BJT's).
3. Power MOSFETS.
4. IGBT's.
5. Thyristors

Thyristors – Silicon Controlled Rectifiers

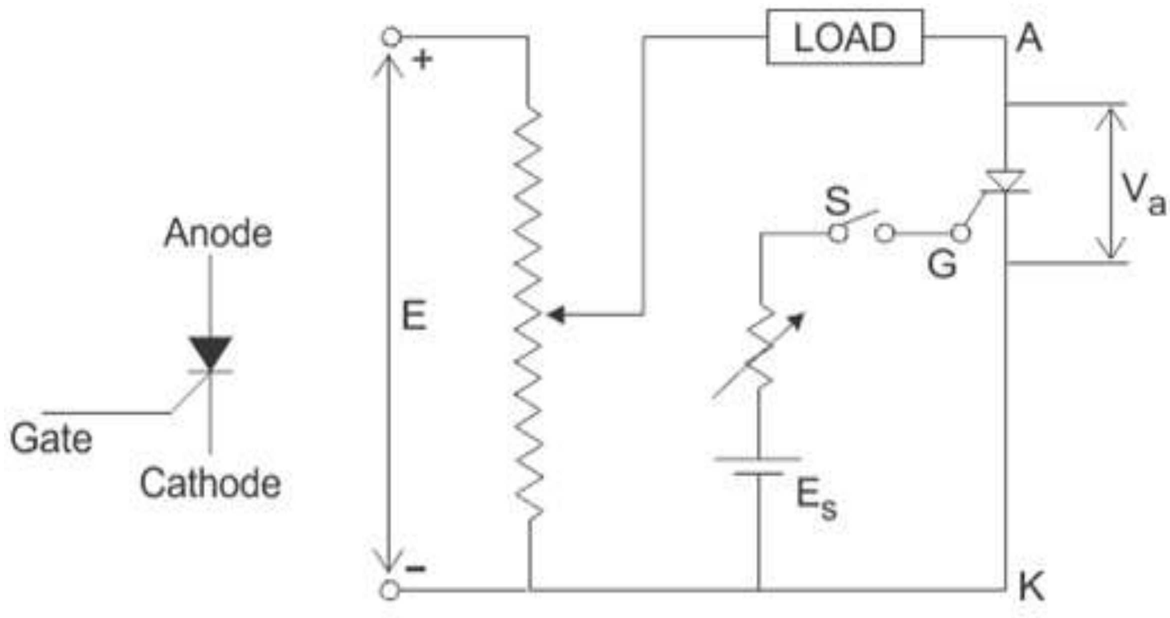
- A silicon controlled rectifier or semiconductor-controlled rectifier is a four-layer solidstate current-controlling device.
- The name "silicon controlled rectifier" is General Electric's trade name for a type of thyristor.



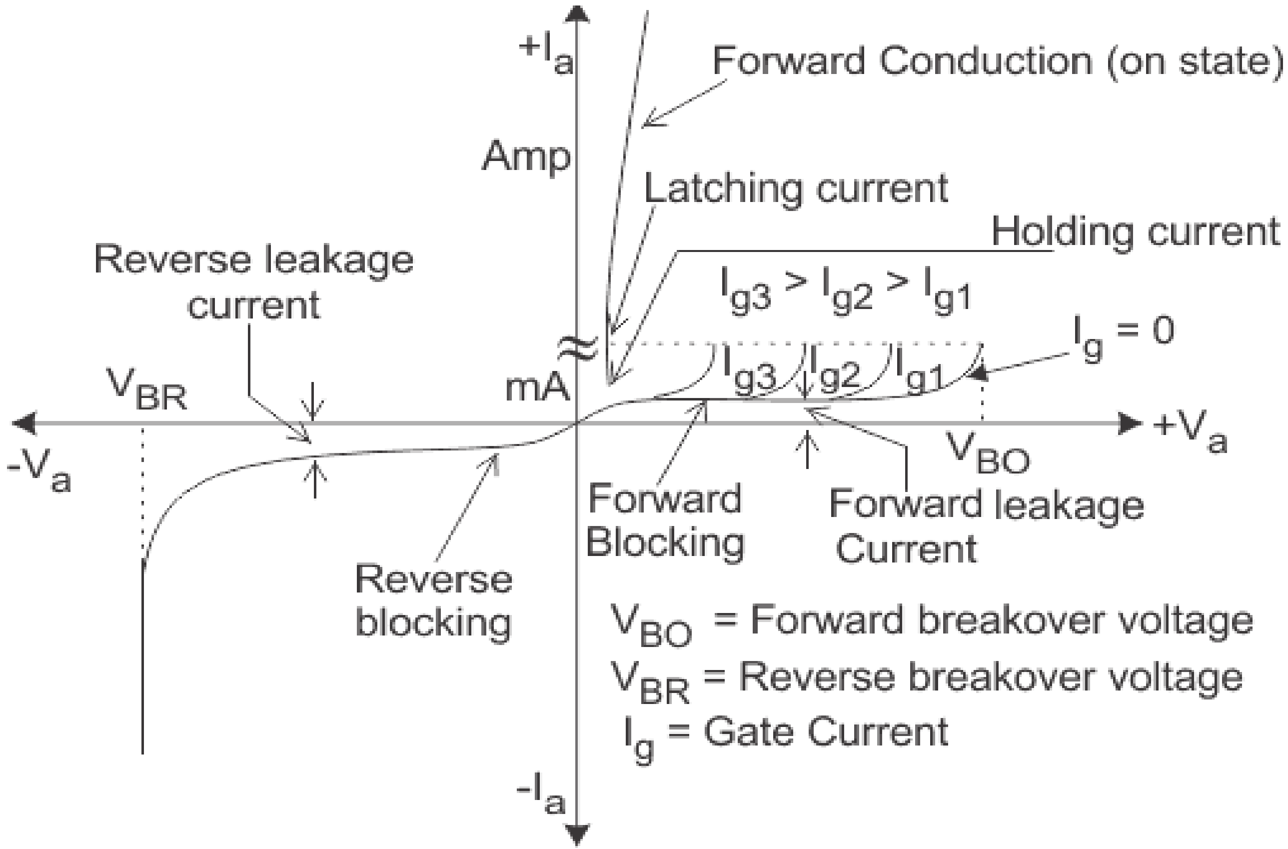
SYMBOL OF THYRISTOR



STRUCTURE OF THYRISTOR



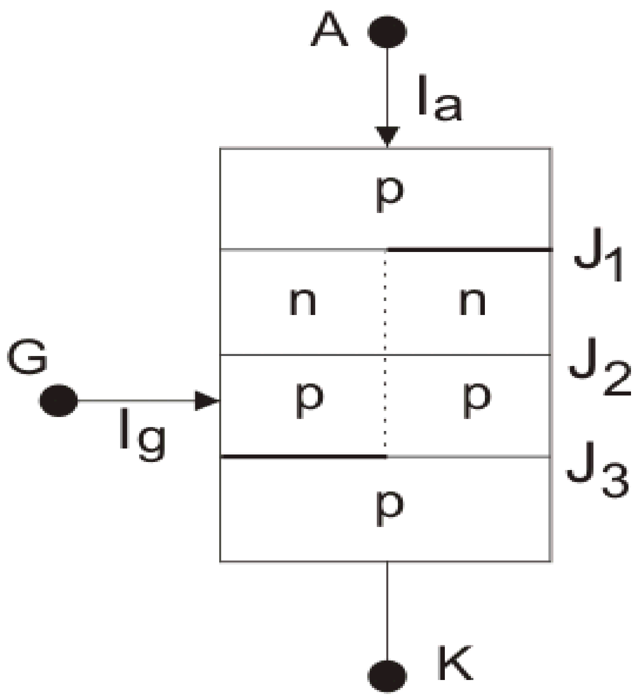
Circuit diagram for characteristics of SCR

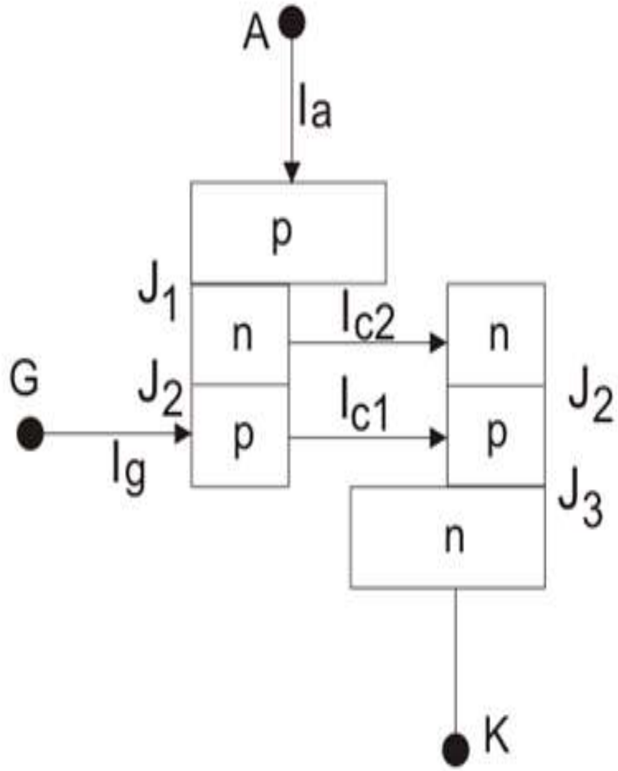


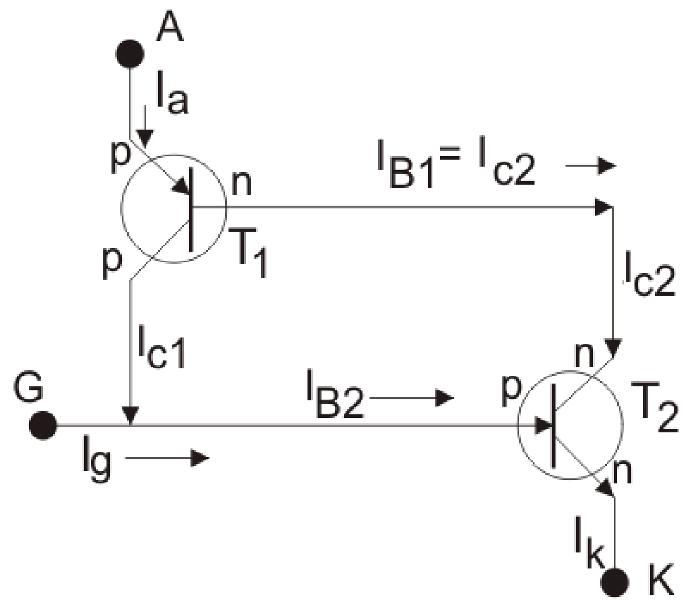
V- I characteristics of SCR

Two transistor analogy of SCR

- Basic operating principle of SCR, can be easily understood by the two transistor model of SCR or analogy of silicon controlled rectifier, as it is also a combination of P and N layers, shown in figure below







Two transistors connection

- The anode current of the thyristor in terms of transistor parameters is

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

Where

- α1 and α2 are current gains of the two transistors
- ICBO1 and ICBO2 are leakage currents of the two transistors

Turn on methods of SCR

- The turning on Process of the SCR is known as Triggering. In other Words, turning the SCR from Forward-Blocking state to Forward-Conduction state is known as Triggering. The various methods of SCR triggering are discussed here.

The various SCR triggering methods are

- Forward Voltage Triggering
- Thermal or Temperature Triggering
- Radiation or Light triggering
- dv/dt Triggering
- Gate Triggering

Forward Voltage Triggering

- In this mode, an additional forward voltage is applied between anode and cathode.
- When the anode terminal is positive with respect to cathode (V_{AK}), Junction J1 and J3 is forward biased and junction J2 is reverse biased.
- No current flow due to depletion region in J2 is reverse biased (except leakage current).
- As V_{AK} is further increased, at a voltage V_{BO} (Forward Break Over Voltage) the junction J2 undergoes avalanche breakdown and so a current flows and the device tends to turn ON

Thermal (or) Temperature Triggering

- The width of depletion layer of SCR decreases with increase in junction temperature.
- Therefore in SCR when V_{AR} is very near its breakdown voltage, the device is triggered by increasing the junction temperature.
- By increasing the junction temperature the reverse biased junction collapses thus the device starts to conduct.

Radiation Triggering (or) Light Triggering

- For light triggered SCRs a special terminal niche is made inside the inner P layer instead of gate terminal.
- When light is allowed to strike this terminal, free charge carriers are generated.
- When intensity of light becomes more than a normal value, the thyristor starts conducting.
- This type of SCRs are called as LASCR

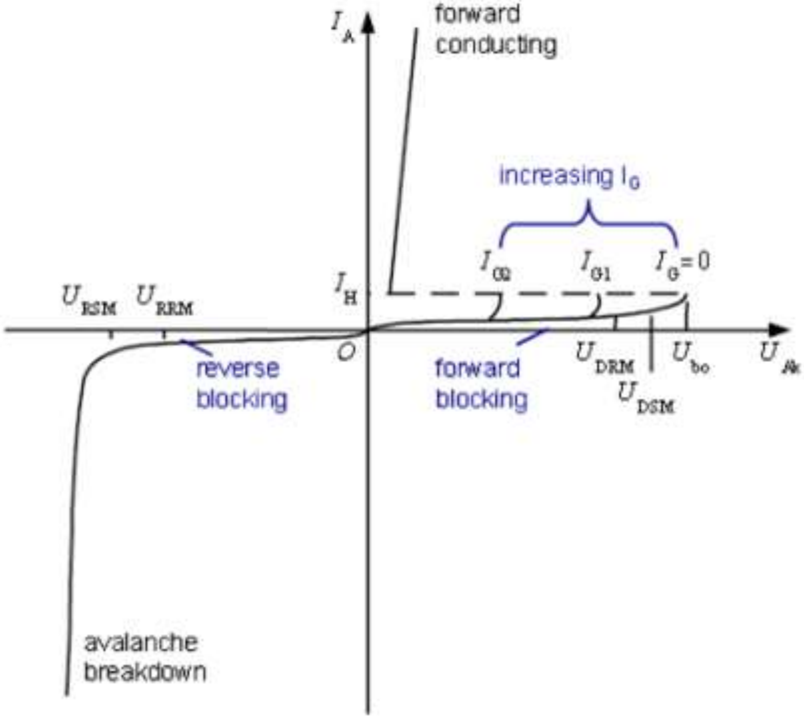
dv/dt Triggering

- When the device is forward biased, J1 and J3 are forward biased, J2 is reverse biased.
- Junction J2 behaves as a capacitor, due to the charges existing across the junction.

$$i_c = dQ/dt$$
$$Q = CV$$
$$i_c = d(CV)/dt$$
$$= CdV/dt + VdC/dt$$
$$\text{as } dC/dt = 0$$
$$i_c = CdV/dt$$

Gate Triggering

- This is most widely used SCR triggering method.
- Applying a positive voltage between gate and cathode can Turn ON a forward biased thyristor.
- When a positive voltage is applied at the gate terminal, charge carriers are injected in the inner P-layer, thereby reducing the depletion layer thickness.
- As the applied voltage increases, the carrier injection increases, therefore the voltage at which forward break-over occurs decreases.



V - I characteristics of SCR

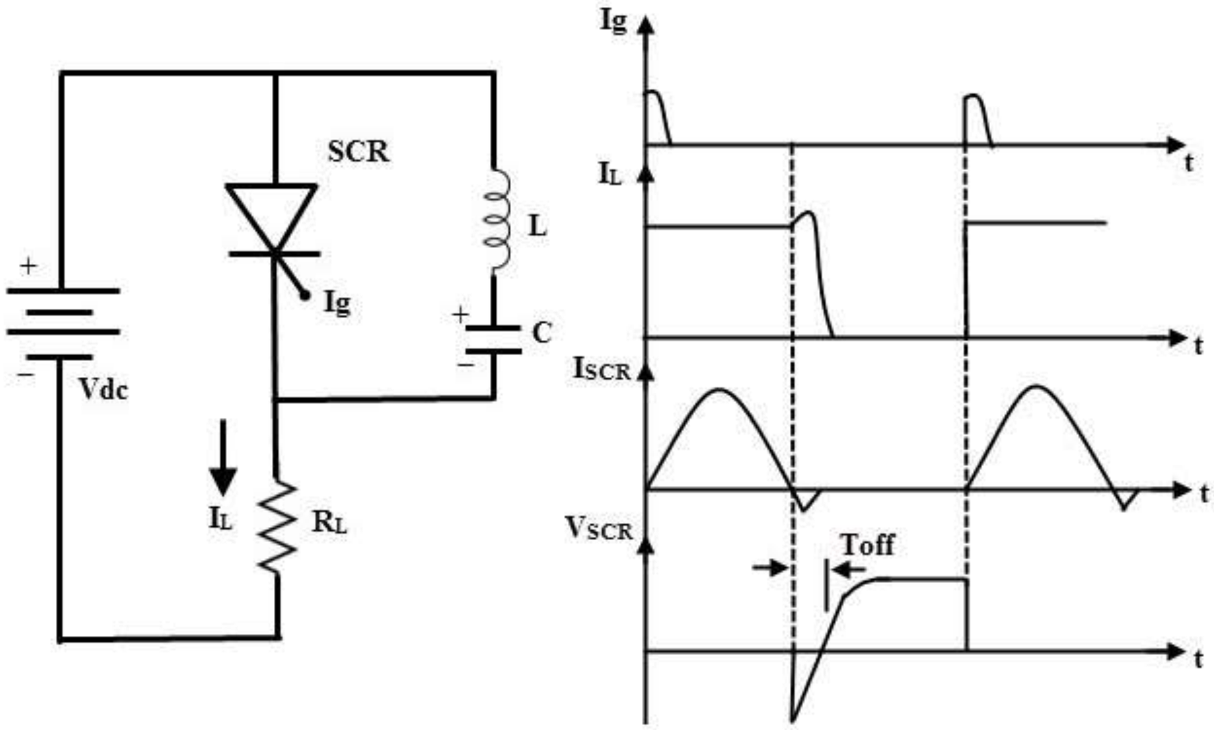
Turn off methods of SCR

The turn OFF process of an SCR is called commutation. The term commutation means the transfer of currents from one path to another. So the commutation circuit does this job by reducing the forward current to zero so as to turn OFF the SCR or Thyristor.

- To turn OFF the conducting SCR the below conditions must be satisfied.
- The anode or forward current of SCR must be reduced to zero or below the level of holding current and then,
- A sufficient reverse voltage must be applied across the SCR to regain its forward blocking state.

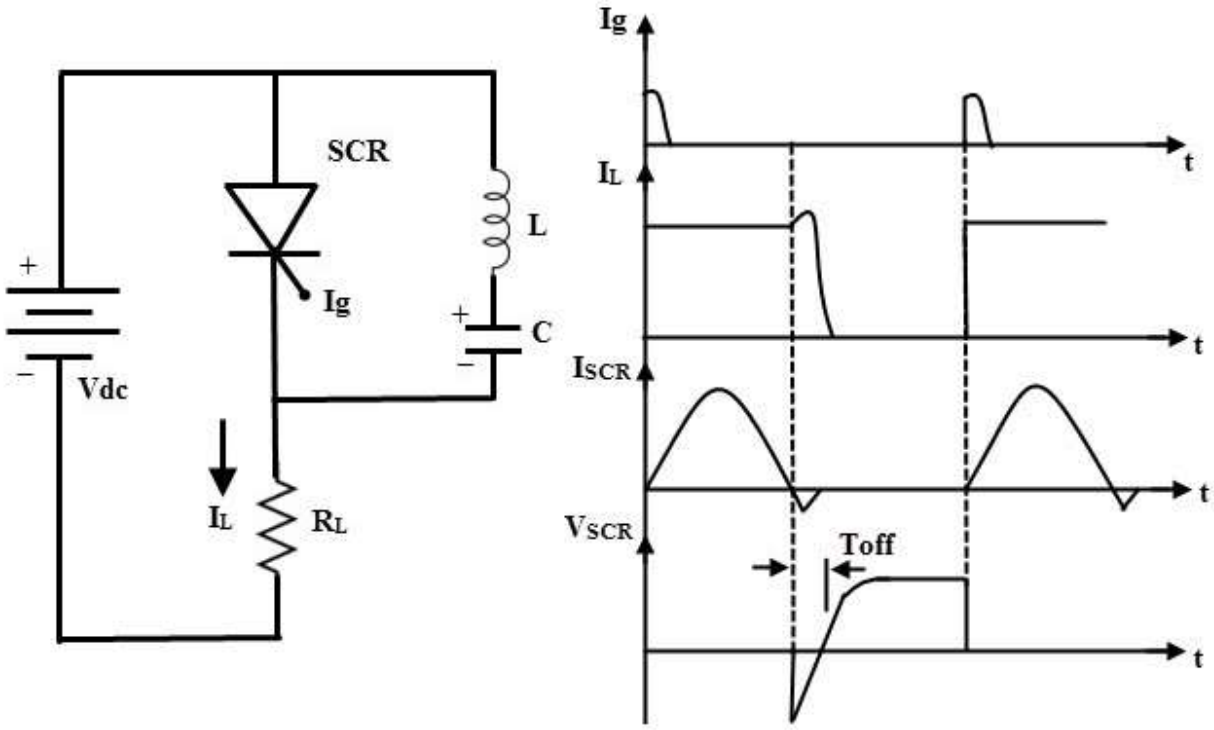
SCR Turn OFF Methods

- The reverse voltage which causes to commutate the SCR is called commutation voltage. Depending on the commutation voltage located, the commutation methods are classified into two major types.
- Those are 1) Forced commutation and 2) Natural commutation. Let us discuss in brief about these methods.



Class A Commutation circuit and waveforms

- This is also known as self commutation, or resonant commutation, or load commutation. In this commutation, the source of commutation voltage is in the load. This load must be an under damped R-L-C supplied with a DC supply so that natural zero is obtained.
- The commutating components L and C are connected either parallel or series with the load resistance R as shown below with waveforms of SCR current, voltage and capacitor voltage.

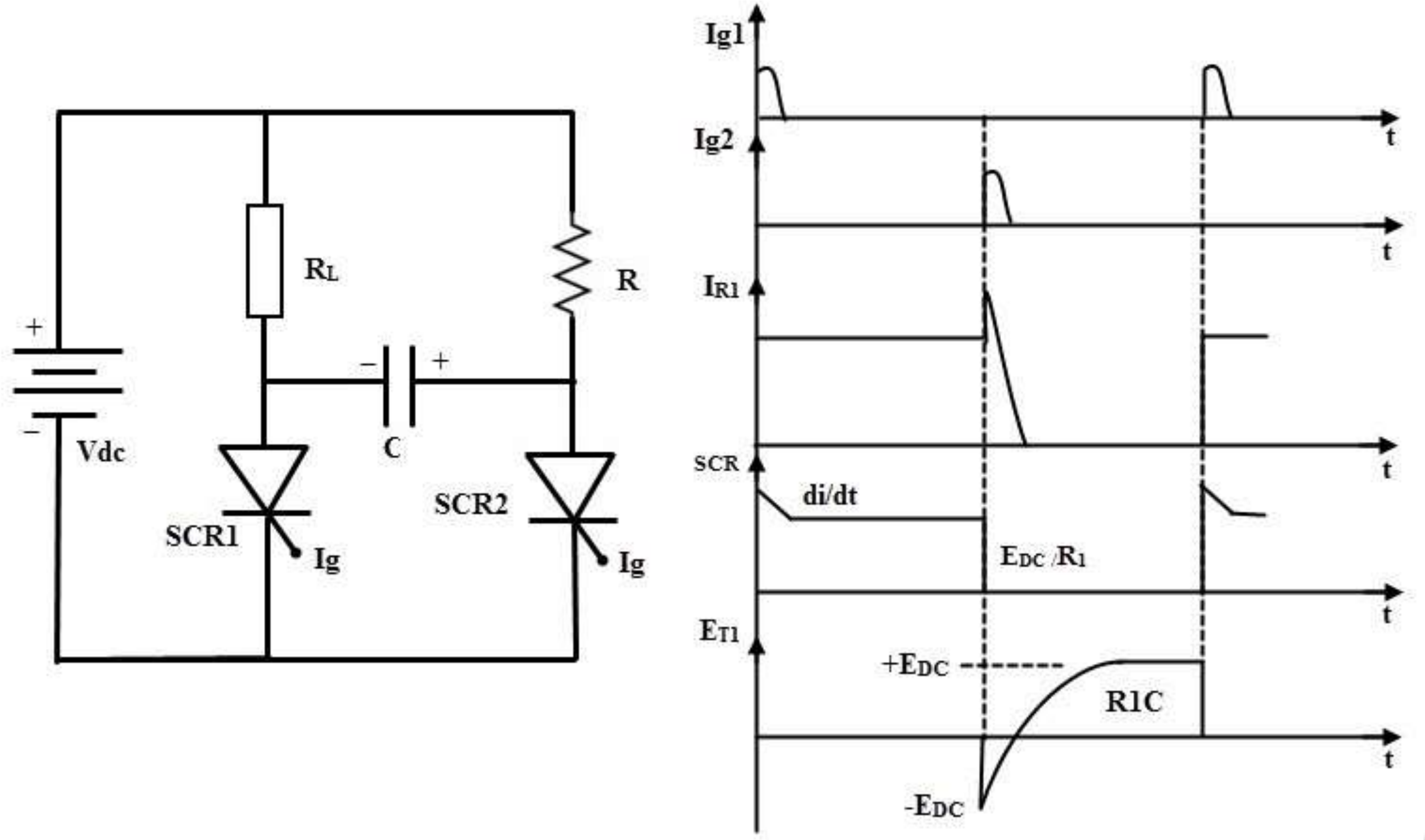


Class B Commutation circuit and waveforms

- This is also a self commutation circuit in which commutation of SCR is achieved automatically by L and C components, once the SCR is turned ON. In this, the LC resonant circuit is connected across the SCR but not in series with load as in case of class A commutation and hence the L and C components do not carry the load current

Class C Commutation

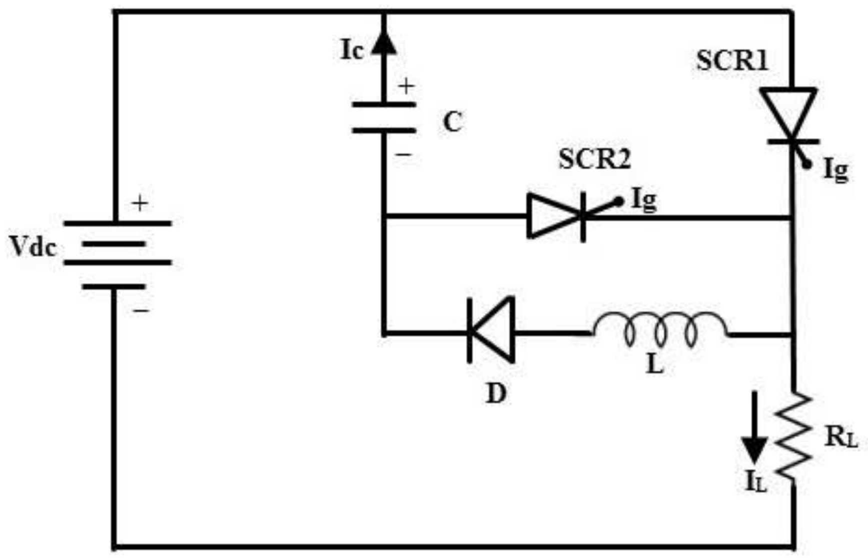
- In this commutation method, the main SCR is to be commutated is connected in series with the load and an additional or complementary SCR is connected in parallel with main SCR. This method is also called as complementary commutation.
- In this , SCR turns OFF with a reverse voltage of a charged capacitor. The figure below shows the complementary commutation with appropriate waveforms.

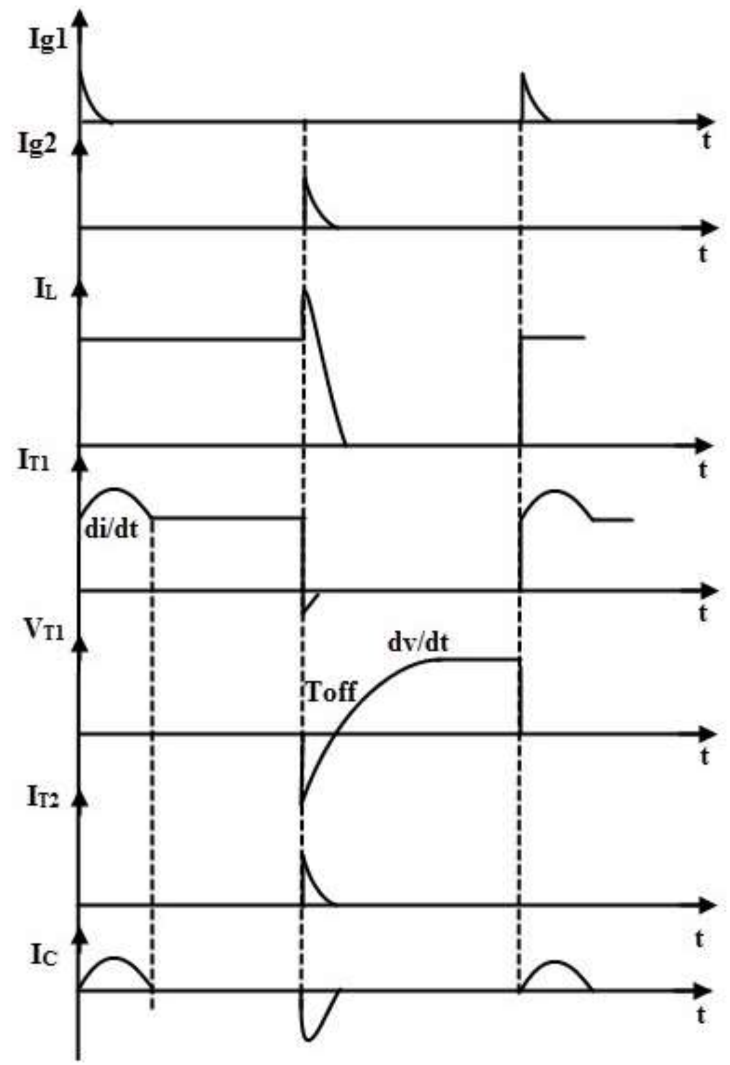


Class C Commutation circuit and waveforms

Class D Commutation

- This is also called as auxiliary commutation because it uses an auxiliary SCR to switch the charged capacitor. In this, the main SCR is commutated by the auxiliary SCR. The main SCR with load resistance forms the power circuit while the diode D, inductor L and SCR2 forms the commutation circuit.
- This commutation method is mainly used in inverters and also used in the Jones chopper circuit.

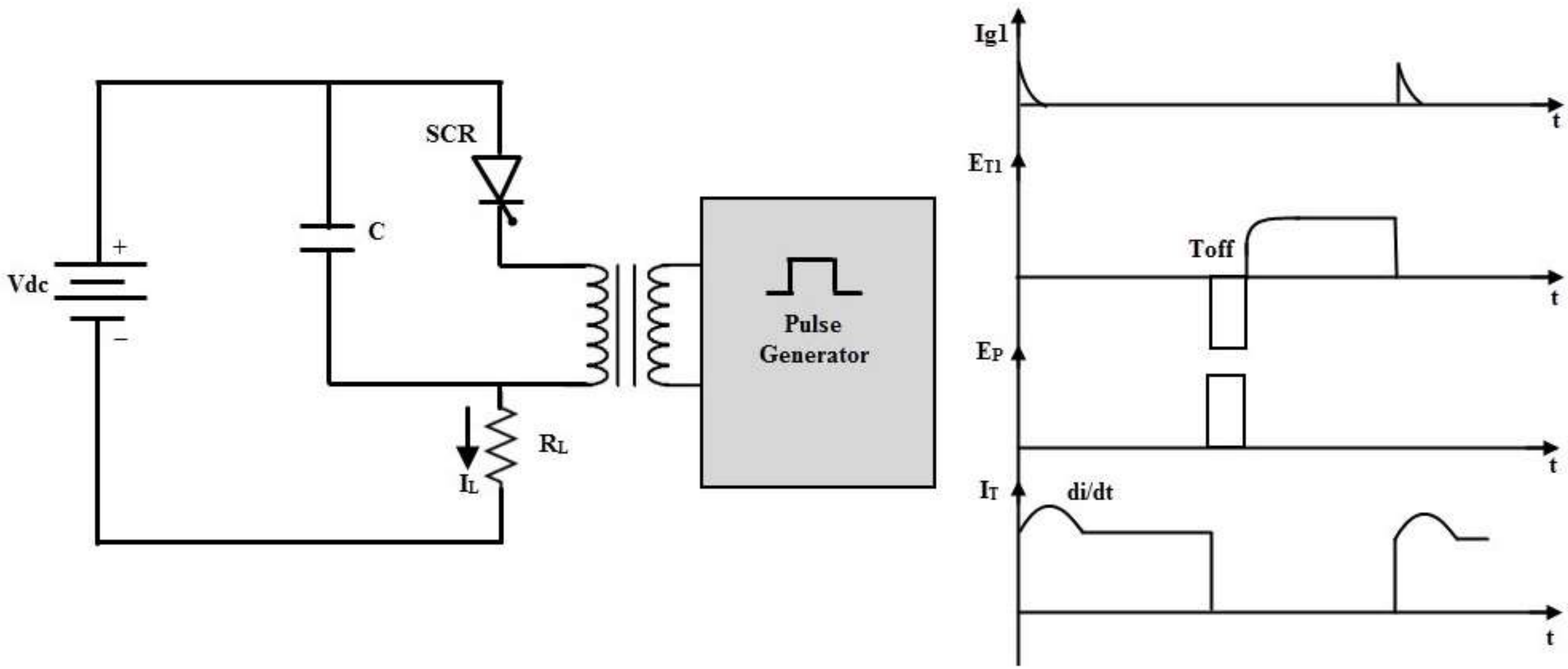




Class D Commutation circuit and waveforms

Class E Commutation

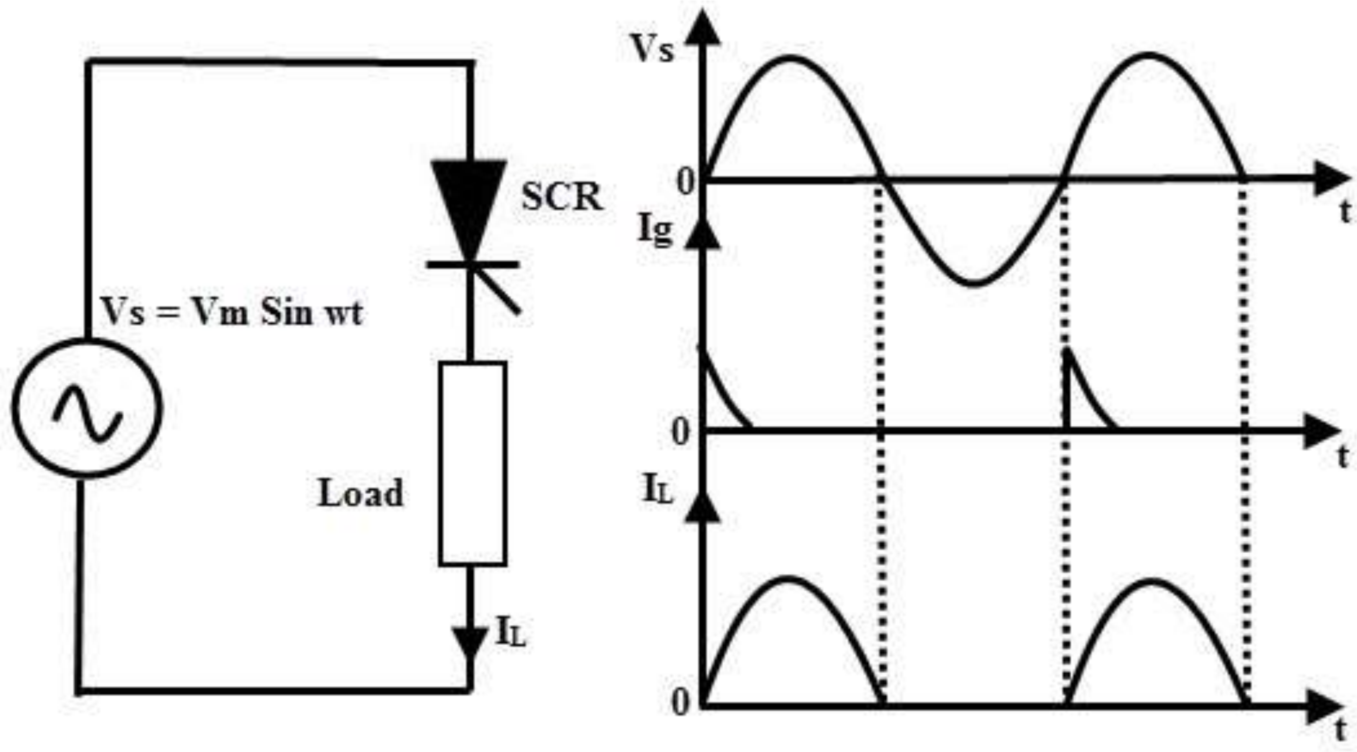
- This is also known as external pulse commutation. In this, an external pulse source is used to produce the reverse voltage across the SCR. The circuit below shows the class E commutation circuit which uses a pulse transformer to produce the commutating pulse and is designed with tight coupling between the primary and secondary with a small air gap.



Class E Commutation circuit and waveforms

Natural Commutation

- In natural commutation, the source of commutation voltage is the supply source itself. If the SCR is connected to an AC supply, at every end of the positive half cycle the anode current goes through the natural current zero and also immediately a reverse voltage is applied across the SCR. These are the conditions to turn OFF the SCR.



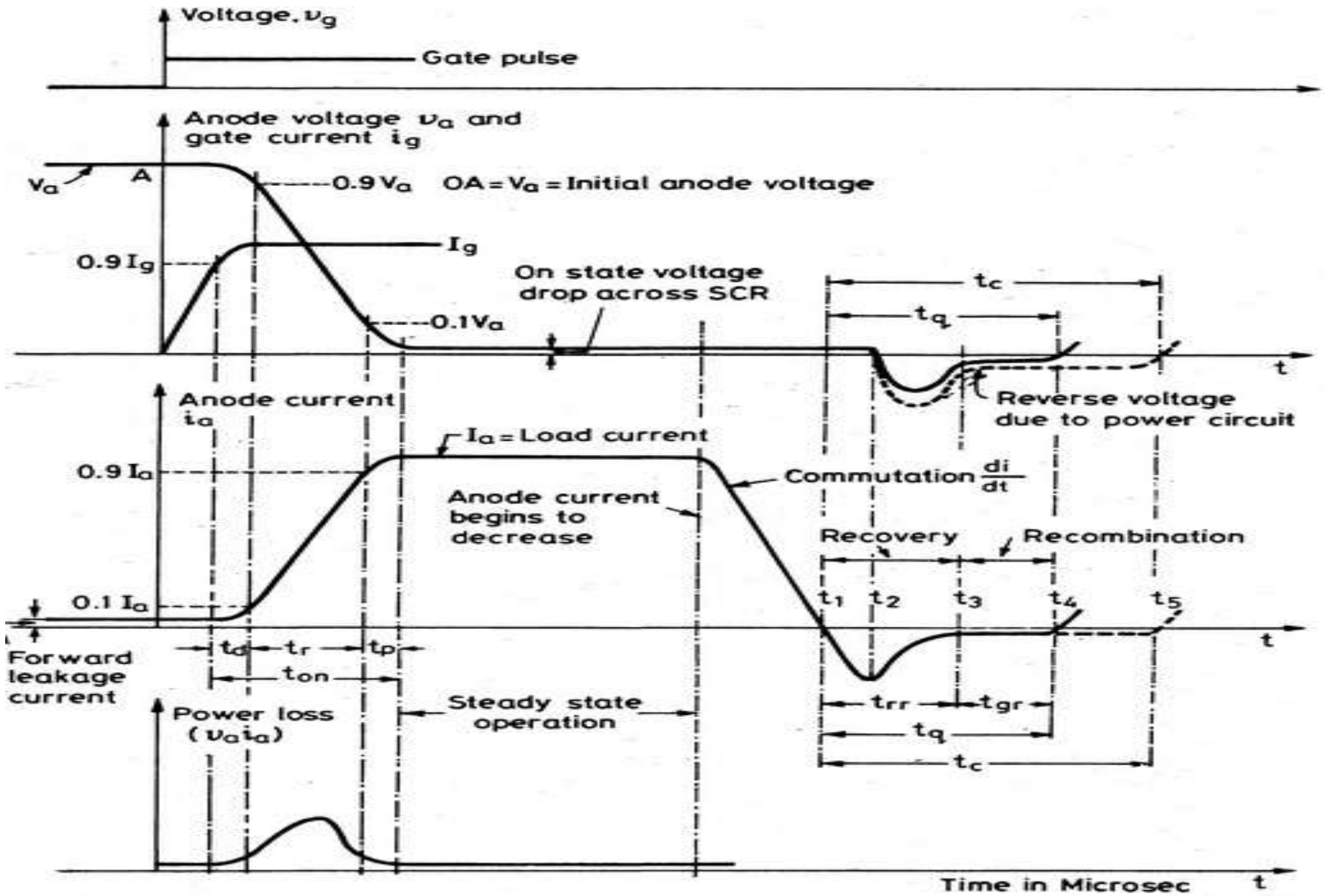
Natural Commutation circuit and waveforms

Dynamic Turn OFF Switching Characteristics

- The transition of an SCR from forward conduction state to forward blocking state is called as turn OFF or commutation of SCR. As we know that once the SCR starts conducting, the gate has no control over it to bring back to forward blocking or OFF state.
- To turn OFF the SCR, the current must be reduced to a level below the holding current of SCR. We have discussed various methods above to turn OFF the SCR in which SCR turn OFF is achieved by reducing the forward current to zero. But if we apply the forward voltage immediately after the current zero of SCR, it starts conducting again even without gate triggering.

- This is due to the presence of charge carriers in the four layers. Therefore, it is necessary to apply the reverse voltage, over a finite time across the SCR to remove the charge carriers.
- Hence the turn OFF time is defined as the time between the instant the anode current becomes zero and the instant at which the SCR retains the forward blocking capability. The excess charge carriers from the four layers must be removed to bring back the SCR to forward conduction mode.
- This process takes place in two stages. In a first stage excess carriers from outer layers are removed and in second stage excess carriers in the inner two layers are to be recombined. Hence, the total turn OFF time t_q is divided into two intervals; reverse recovery time t_{rr} and gate recovery time t_{gr}.
- $t_q = t_{rr} + t_{gr}$

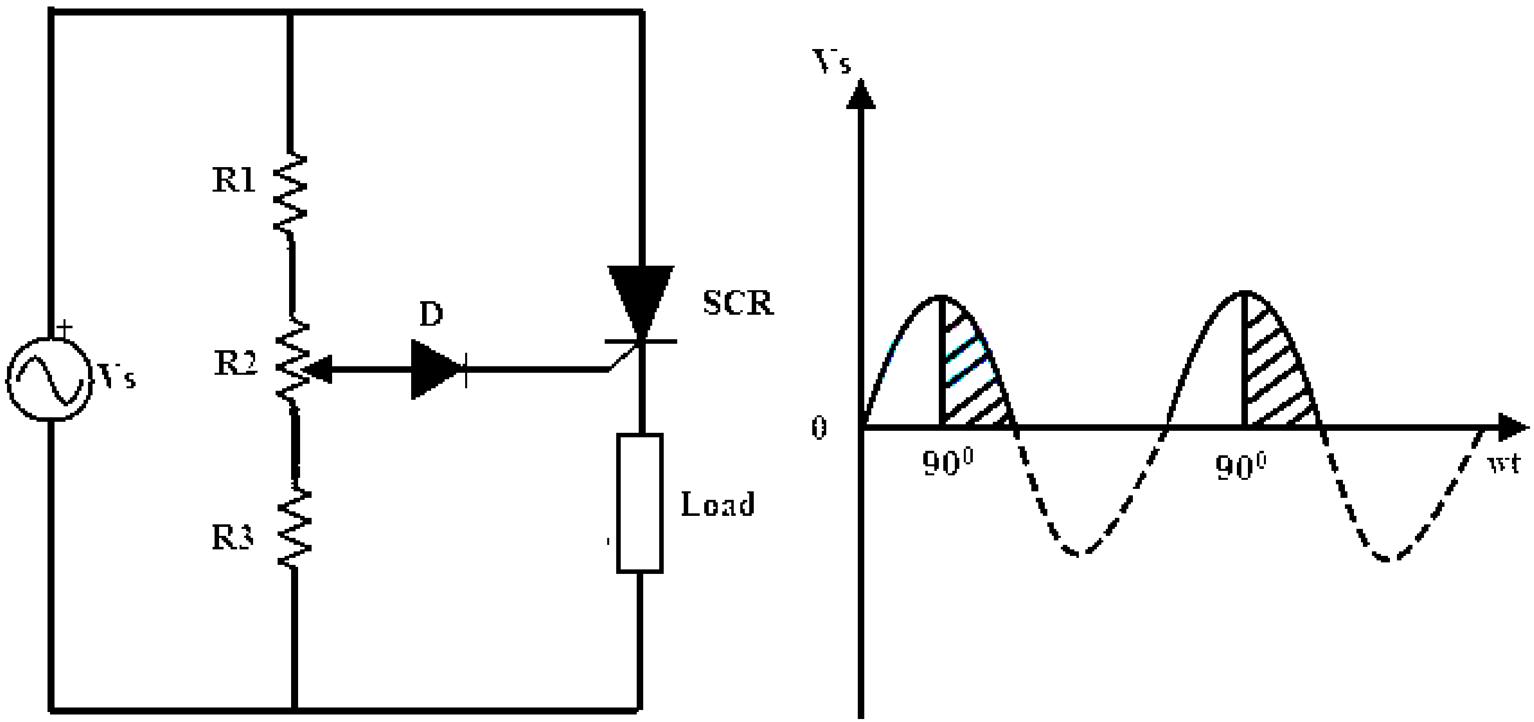
- The figure below shows the switching characteristics of SCR during turn ON and OFF. The time t_1 to t_3 is called as reverse recovery time; at the instant $t_1$the anode current is zero and builds up in the reverse direction which is called as reverse recovery current. This current removes the excess charge carriers from outer layers during the time t_1 to t_3.
- At instant t_3, junctions J_1 and J_3 are able to block the reverse voltage but, the SCR is not yet able to block the forward voltage due to the presence of excess charge carriers in junction J_2. These carriers can be disappeared only by the way of recombination and this could be achieved by maintaining a reverse voltage across the SCR.



Dynamic characteristics of SCR

Resistance Firing Circuit

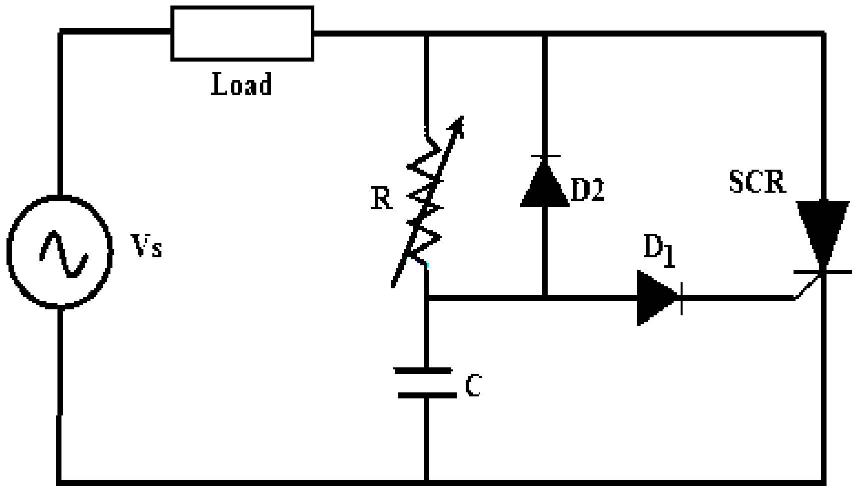
- The circuit below shows the resistance triggering of SCR where it is employed to drive the load from the input AC supply. Resistance and diode combination circuit acts as a gate control circuitry to switch the SCR in the desired condition.
- As the positive voltage applied, the SCR is forward biased and doesn’t conduct until its gate current is more than minimum gate current of the SCR.
- When the gate current is applied by varying the resistance R2 such that the gate current should be more than the minimum value of gate current, the SCR is turned ON. And hence the load current starts flowing through the SCR.

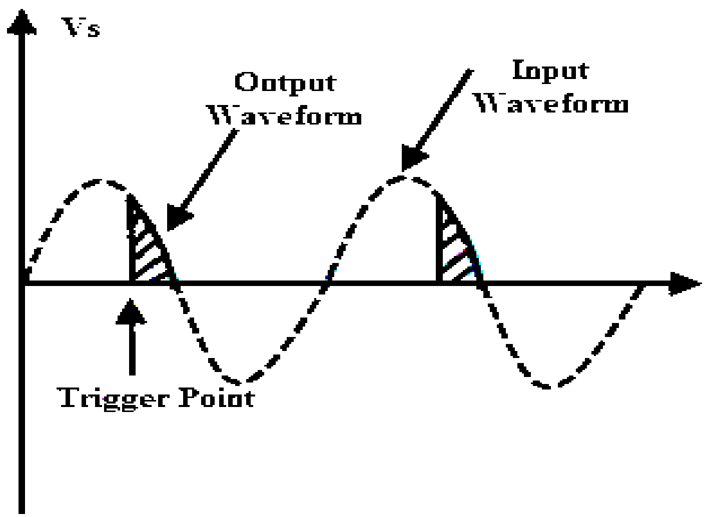


R Firing circuit for SCR and corresponding waveforms

Resistance – Capacitance (RC) Firing Circuit

- The limitation of resistance firing circuit can be overcome by the RC triggering circuit which provides the firing angle control from 0 to 180 degrees. By changing the phase and amplitude of the gate current, a large variation of firing angle is obtained using this circuit.
- Below figure shows the RC triggering circuit consisting of two diodes with an RC network connected to turn the SCR.
- By varying the variable resistance, triggering or firing angle is controlled in a full positive half cycle of the input signal.

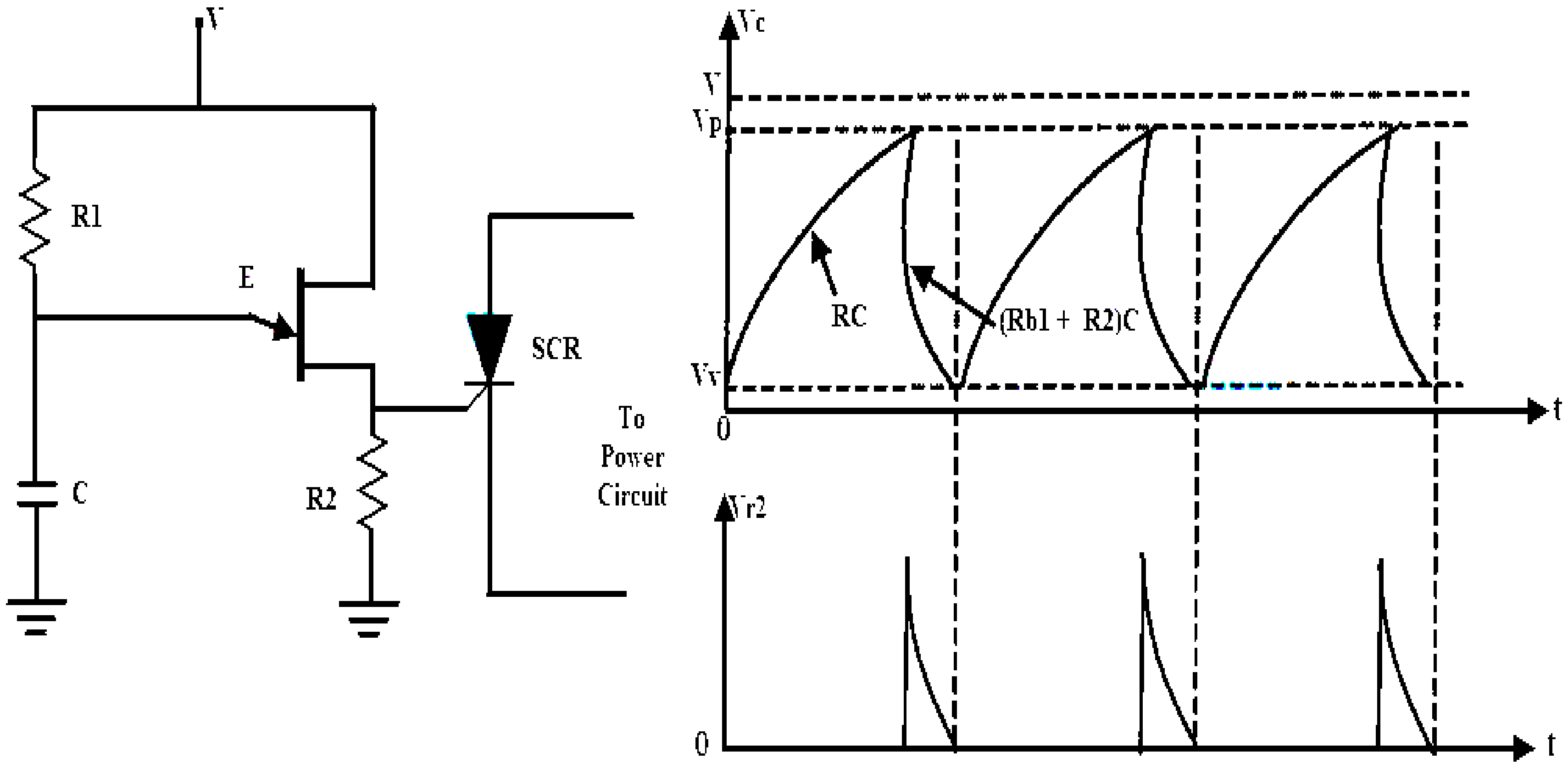




R Firing circuit for SCR and waveforms

UJT Firing Circuit

- It is the most common method of triggering the SCR because the prolonged pulses at the gate using R and RC triggering methods cause more power dissipation at the gate so by using UJT (Uni Junction Transistor) as triggering device the power loss is limited as it produce a train of pulses.
- The RC network is connected to the emitter terminal of the UJT which forms the timing circuit. The capacitor is fixed while the resistance is variable and hence the charging rate of the capacitor depends on the variable resistance means that the controlling of the RC time constant.
- When the voltage is applied, the capacitor starts charging through the variable resistance. By varying the resistance value voltage across the capacitor get varied. Once the capacitor voltage is equal to the peak value of the UJT, it starts conducting and hence produce a pulse output till the voltage across the capacitor equal to the valley voltage Vv of the UJT. This process repeats and produces a train of pulses at base terminal 1.



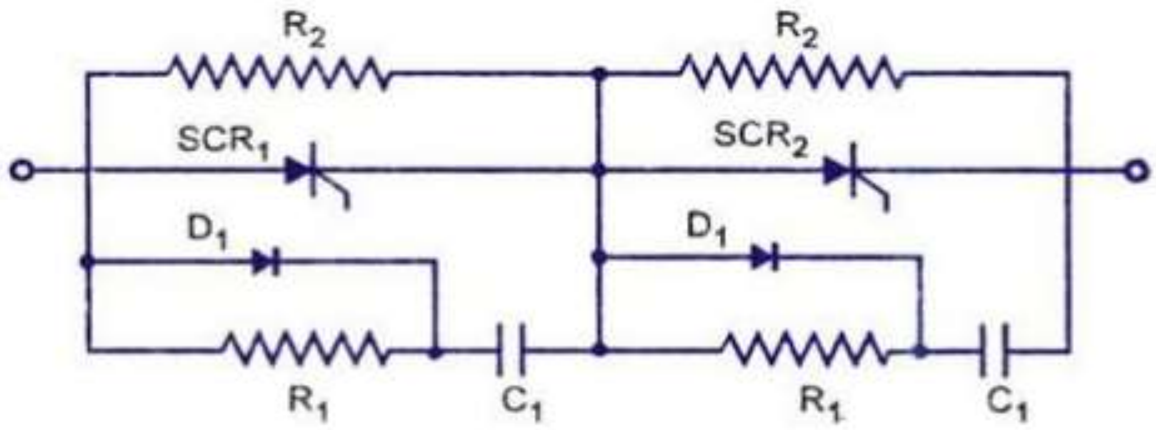
UJT Firing circuit for SCR and corresponding waveforms

Series and Parallel connections of SCRs

In many power control applications the required voltage and current ratings exceed the voltage and current that can be provided by a single SCR.

The mismatching of SCRs is due to differences in

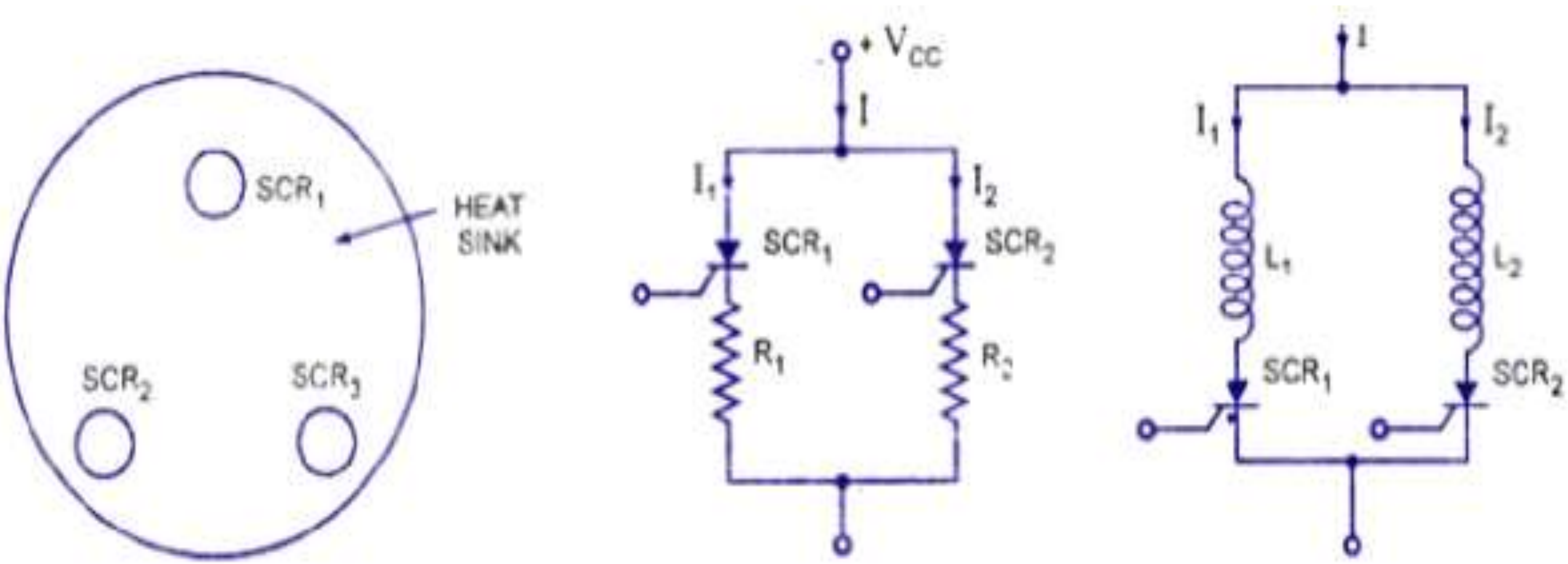
1. turn-on time
2. turn-off time
3. Leakage current in forward direction
4. Leakage current in reverse direction and
5. Recovery voltage.



Series connection of SCRs

- String efficiency = $\dfrac{\text{Voi or actual current rating of the whole string}}{\text{No of SCRs in string} \times \text{Voi or current rating of individual SCR}}$
- This phenomenon increases the reliability of the string, but reduces the utilization of each SCR. Thus string efficiency decreases. Reliability of string is measured by derating factor (DRF) which is given by the expression
- DRF = 1- string efficiency

Parallel Connection of an SCR



Parallel connection of SCRs

- When the load current exceeds the SCR current rating, SCRs are connected in parallel to share the load current. But when SCRs are operated in parallel, the current sharing between them may not be proper. The device having lower dynamic resistance will tend to share more current. This will raise the temperature of that particular device in comparison to other, thereby reducing further its dynamic resistance and increasing current through it. This process is cumulative and continues till the device gets punctured.

Numerical Problems:

1. The trigger circuit of a thyristor has a source voltage of 15V and the load line has a slope of -120V per ampere. The minimum gate current to turn on the SCR is 25mA. Compute
   i. Source resistance required in the gate circuit
   ii. The trigger voltage and trigger current for an average gate power dissipation of 0.4 watts

Solution:

The slope of load line gives the required gate source resistance. From the load line, series resistance required in the gate circuit is 120Ω

Here $V_g I_g = 0.4W$

For the gate circuit $E_s = R_s I_g + V_g$

$$15 = 120 I_g + 0.4/I_g$$

$$120 I_g^2 - 15\, I_g + 0.4 = 0$$

Its solution gives Ig = 38.56mA or 86.44 mA

- $V_g = \frac{0.4 \times 1000}{38.56} = 10.37V$
- $V_g = \frac{0.4 \times 1000}{86.44} = 4.627V$

So choose the value for Ig which gives less voltage Ig = 86.44 mA and V_g = 4.627V from minimum gate current of 25mA.

2. For an SCR the gate-cathode characteristic has a straight line slope of 130. For trigger source voltage of 15V and allowable gate power dissipation of 0.5 watts, compute the gate source resistance.
3. SCRs with a rating of 1000V and 200A are available to be used in a string to handle 6kV and 1kA. Calculate the number of series and parallel units required in case de-rating factor is 0.1 and 0.2

Snubber circuit

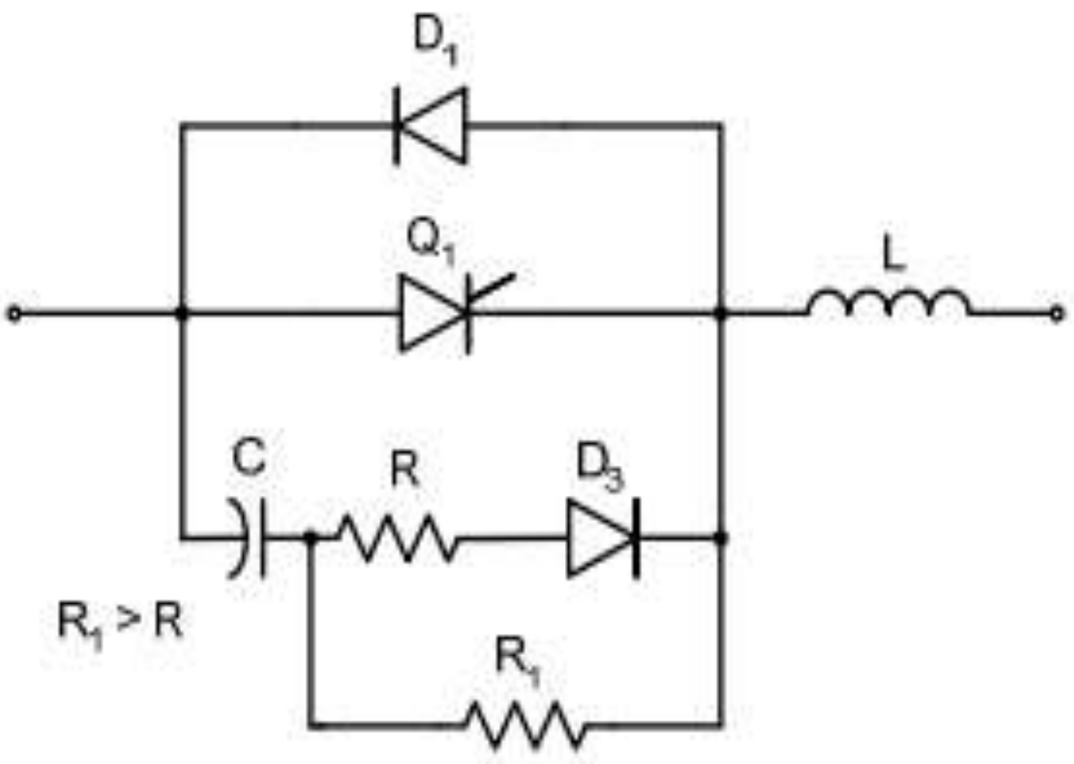
- Due to overheating, over voltage, over current or excessive change in voltage or current switching devices and circuit components may fail. From over current they can be protected by placing fuses at suitable locations. Heat sinks and fans can be used to take the excess heat away from switching devices and other components. Snubber circuits are needed to limit the rate of change in voltage or current

Necessity of Using the Snubber Circuit

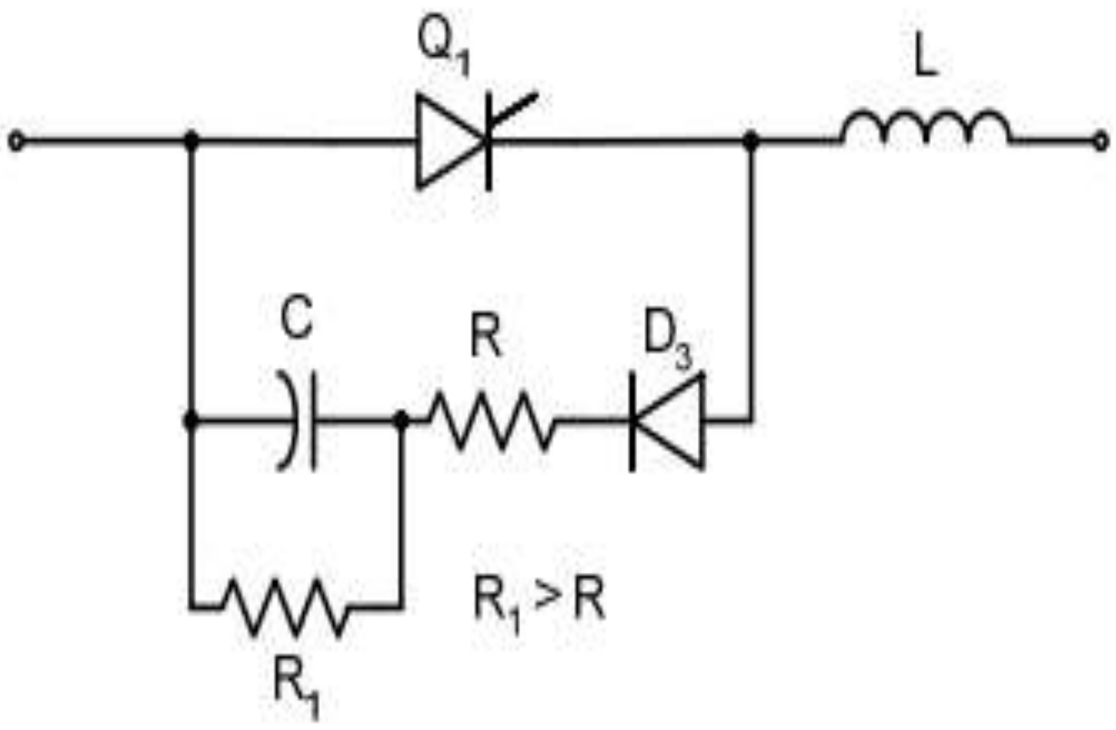
- These are placed across the various switching devices like transistors, thyristors, etc. Switching from ON to OFF state results the impedance of the device suddenly changes to the high value. But this allows a small current to flow through the switch. This induces a large voltage across the device. If this current reduced at faster rate more is the induced voltage across the device and also if the switch is not capable of withstanding this voltage the switch becomes burn out. So auxiliary path is needed to prevent this high induced voltage

Design of RC Snubber Circuits:

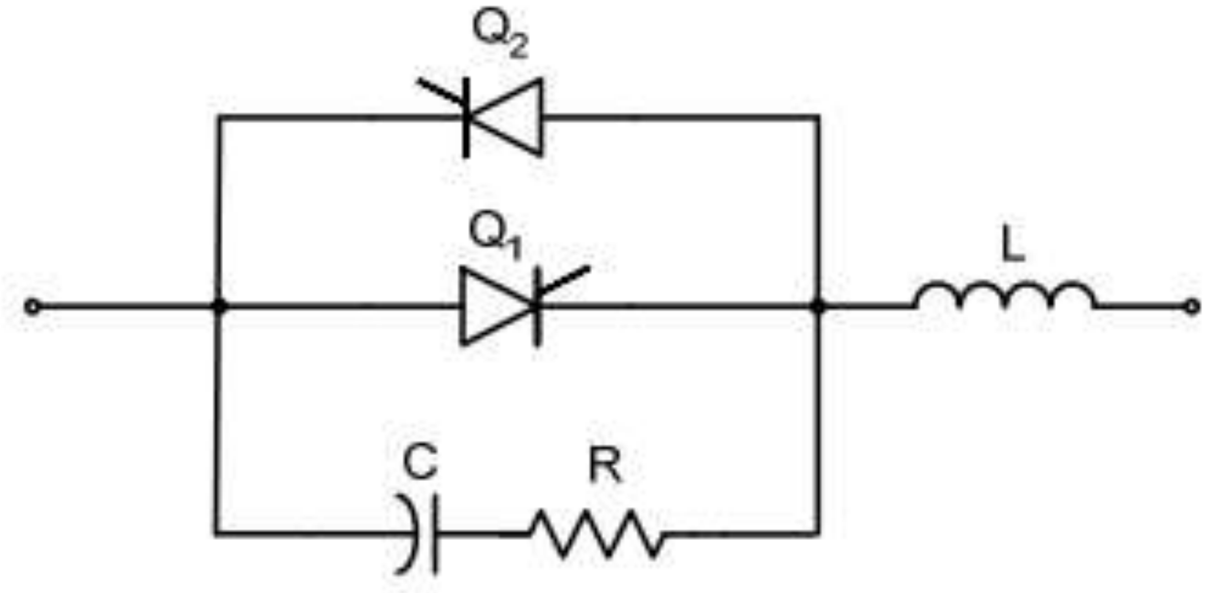
- There are many kinds of snubbers like RC, diode and solid state snubbers but the most commonly used one is RC snubber circuit. This is applicable for both the rate of rise control and damping.
- This circuit is a capacitor and series resistor connected across a switch. For designing the Snubber circuits. The amount of energy is to dissipate in the snubber resistance is equal to the amount of energy is stored in the capacitors. An RC Snubber placed across the switch can be used to reduce the peak voltage at turn-off and to lamp the ring. An RC snubber circuit can be polarized or non-polarized. If you assume the source has negligible impedance, the worst case peak current in the snubber circuit is
- I = Vo/Rs and I = C.dv/dt



Forward-Polarized RC Snubber Circuit



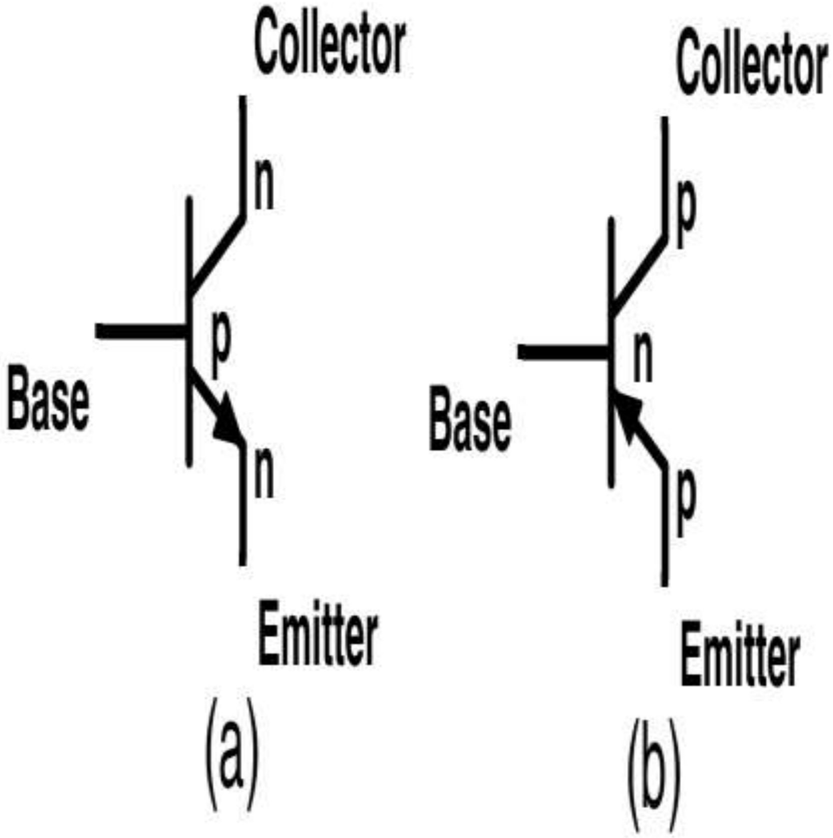
Reverse Polarized RC Snubber Circuit



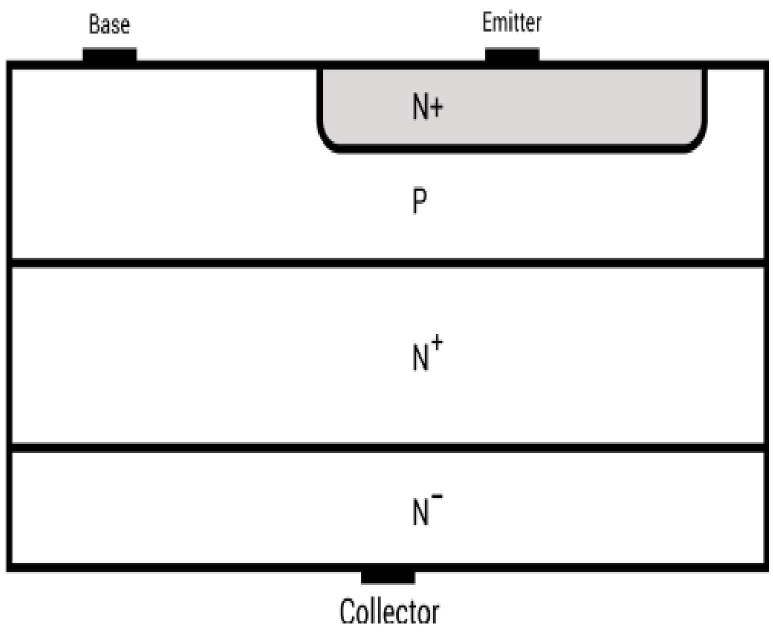
An un-polarized snubber circuit

Power Bipolar Junction Transistor

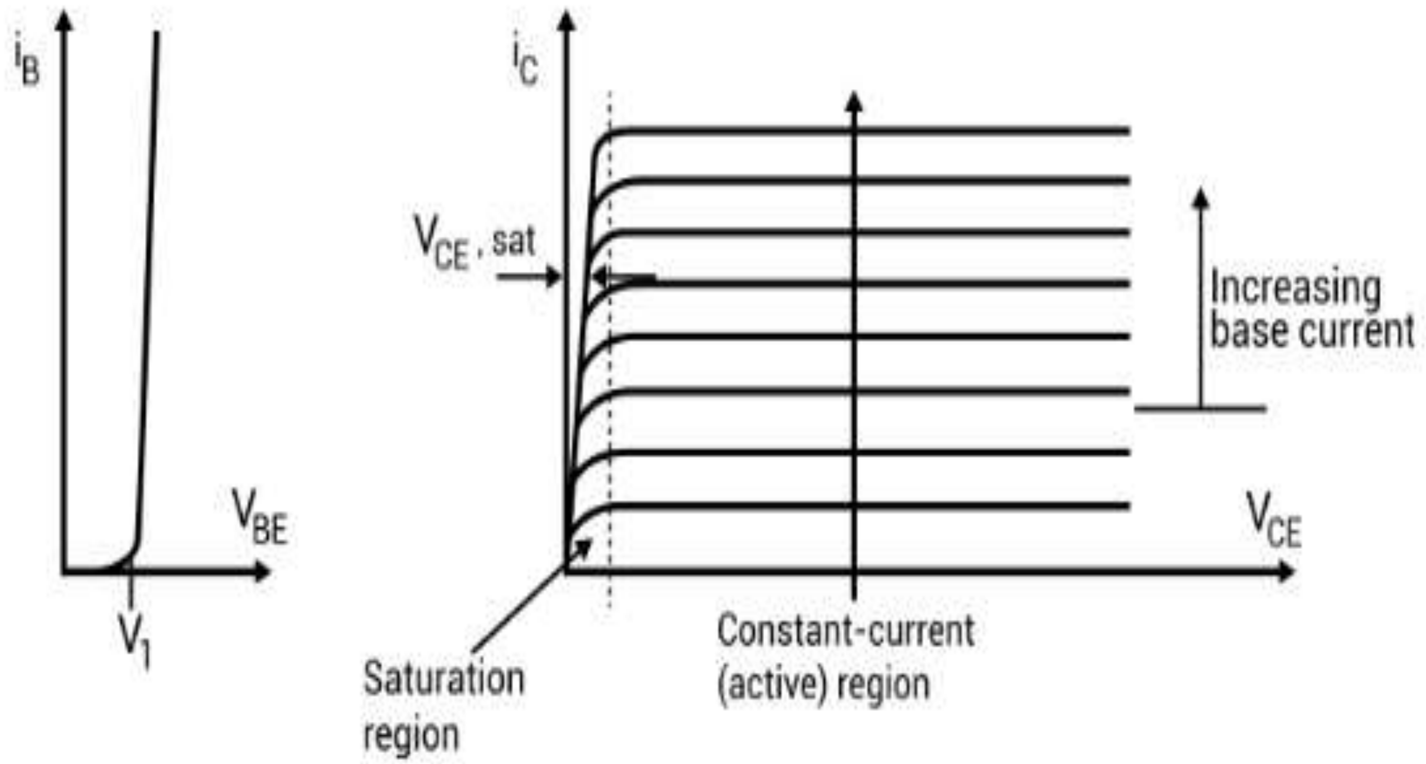
- Power BJT is used traditionally for many applications. However, IGBT (Insulated-Gate Bipolar Transistor) and MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) have replaced it for most of the applications but still they are used in some areas due to its lower saturation voltage over the operating temperature range. IGBT and MOSFET have higher input capacitance as compared to BJT. Thus, in case of IGBT and MOSFET, drive circuit must be capable to charge and discharge the internal capacitances.



Symbol of transistor



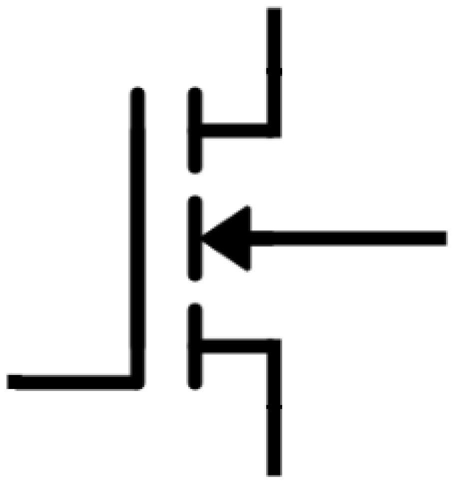
Structure of transistor



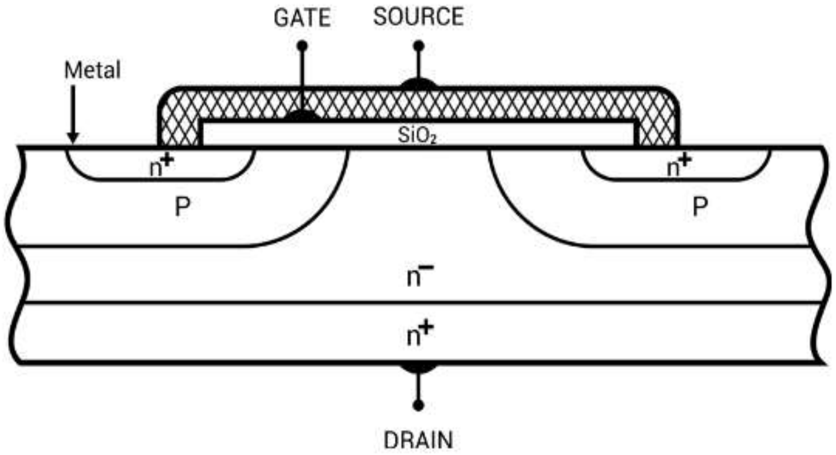
Input and output characteristics of BJT

Metal-Oxide Semiconductor Field-Effect Transistor

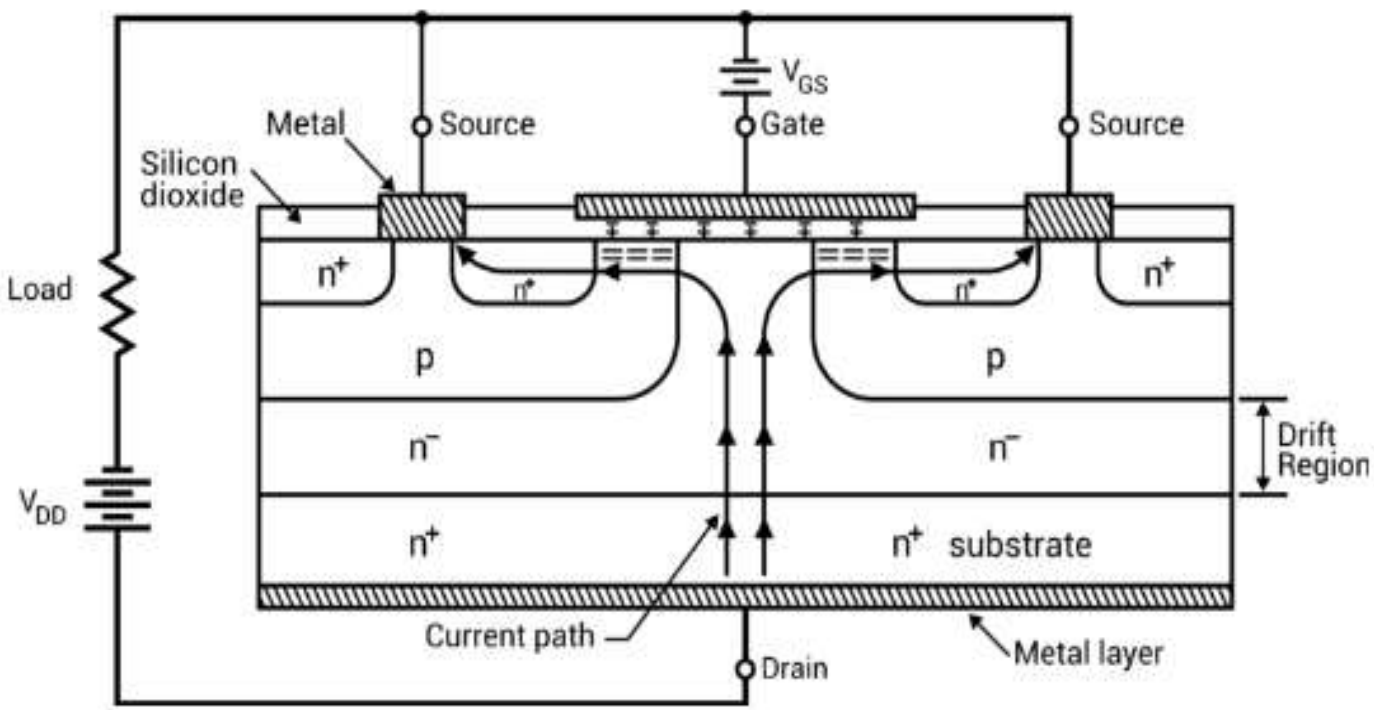
- MOSFET is a voltage-controlled majority carrier (or unipolar) three-terminal device. As compared to the simple lateral channel MOSFET for low-power signals, power MOSFET has different structure. It has a vertical channel structure where the source and the drain are on the opposite side of the silicon wafer as shown in Figure. This opposite placement of the source and the drain increases the capability of the power MOSFET to handle larger power.
- N-channel enhancement type MOSFET is more common due to high mobility of electrons



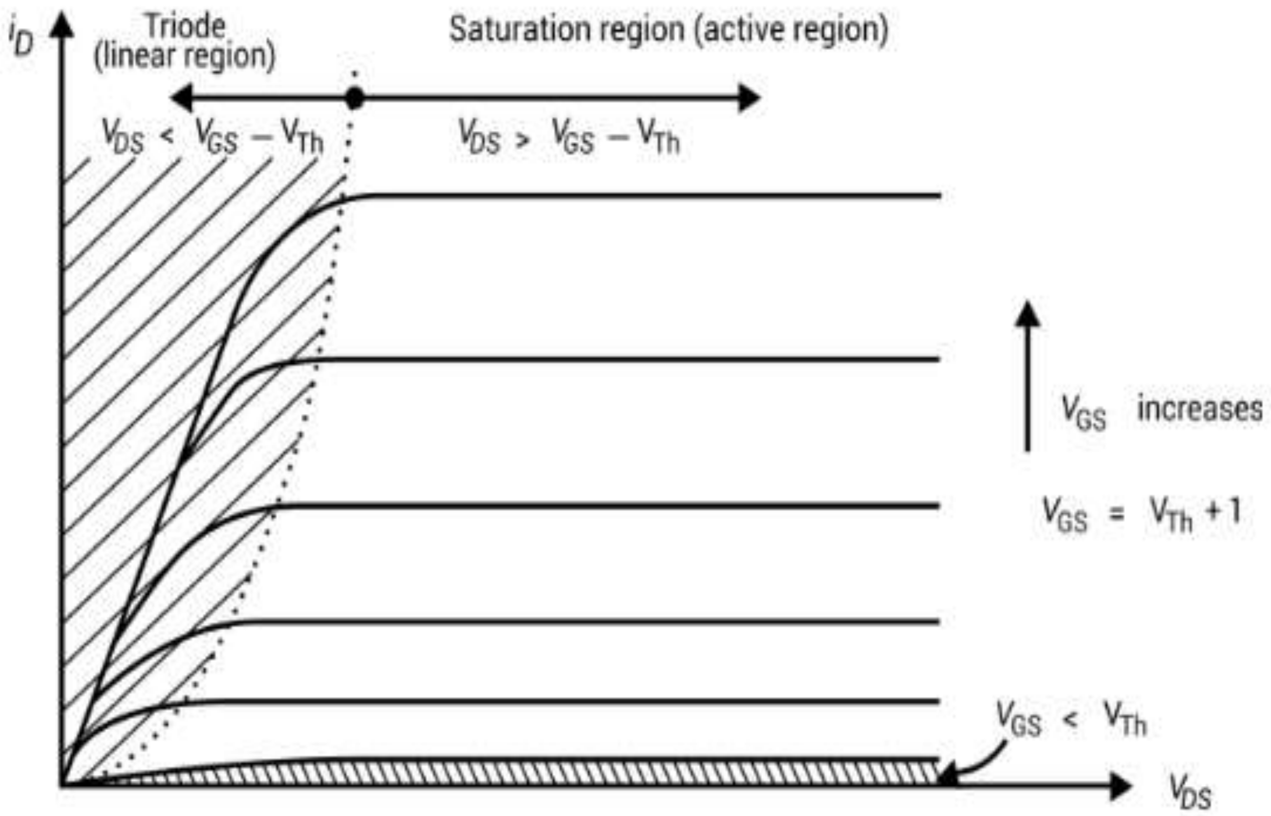
Symbol of MOSFET



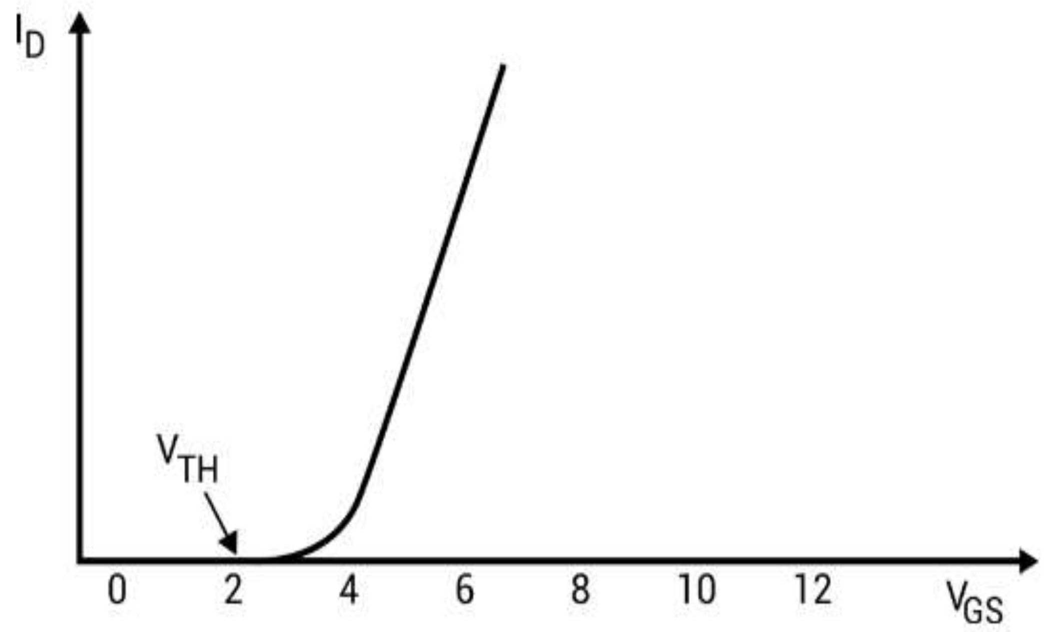
Structure of MOSFET



Basic circuit diagram of n-channel enhancement power MOSFET



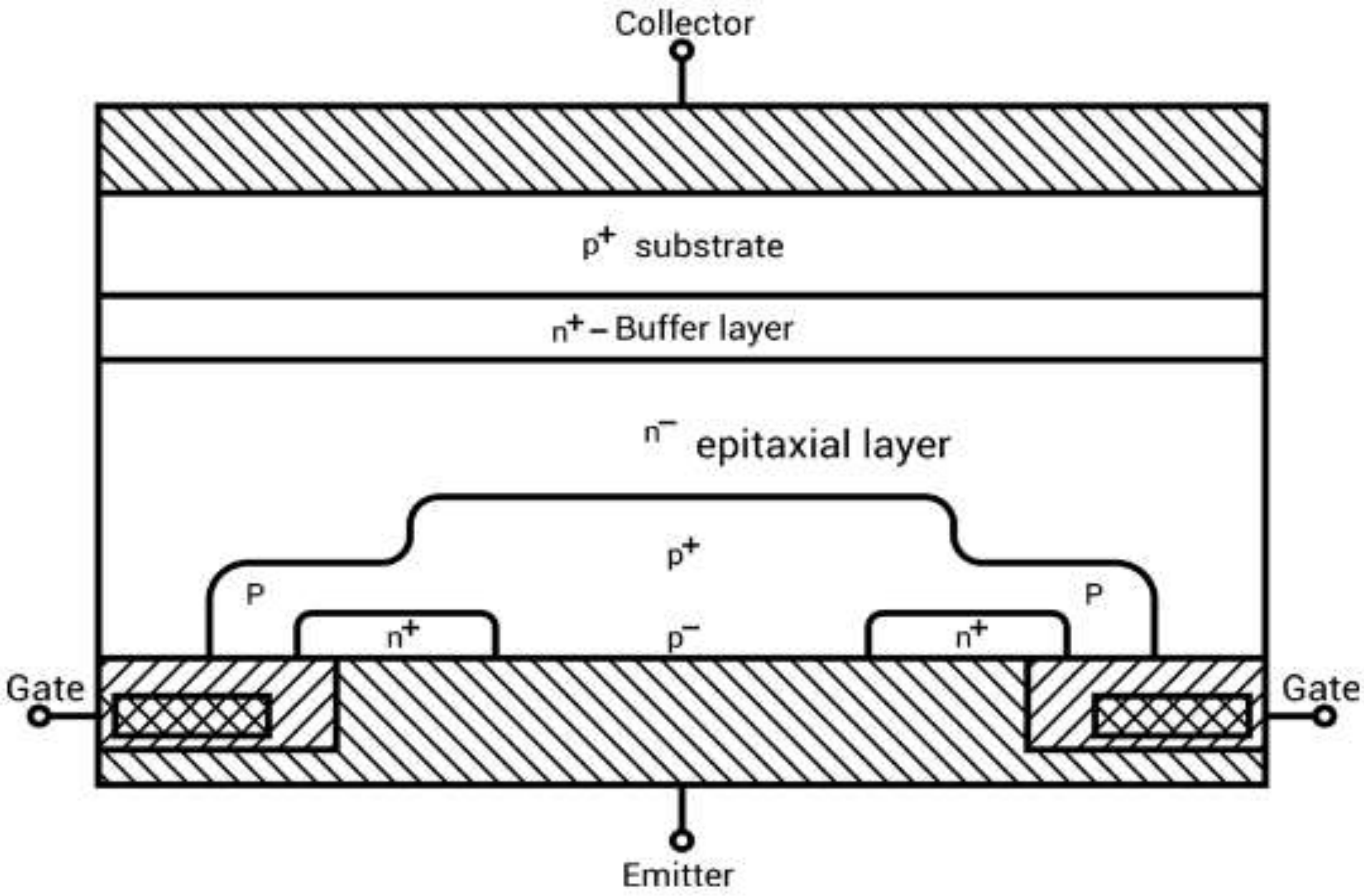
Output characteristics of an n-channel enhancement power MOSFET



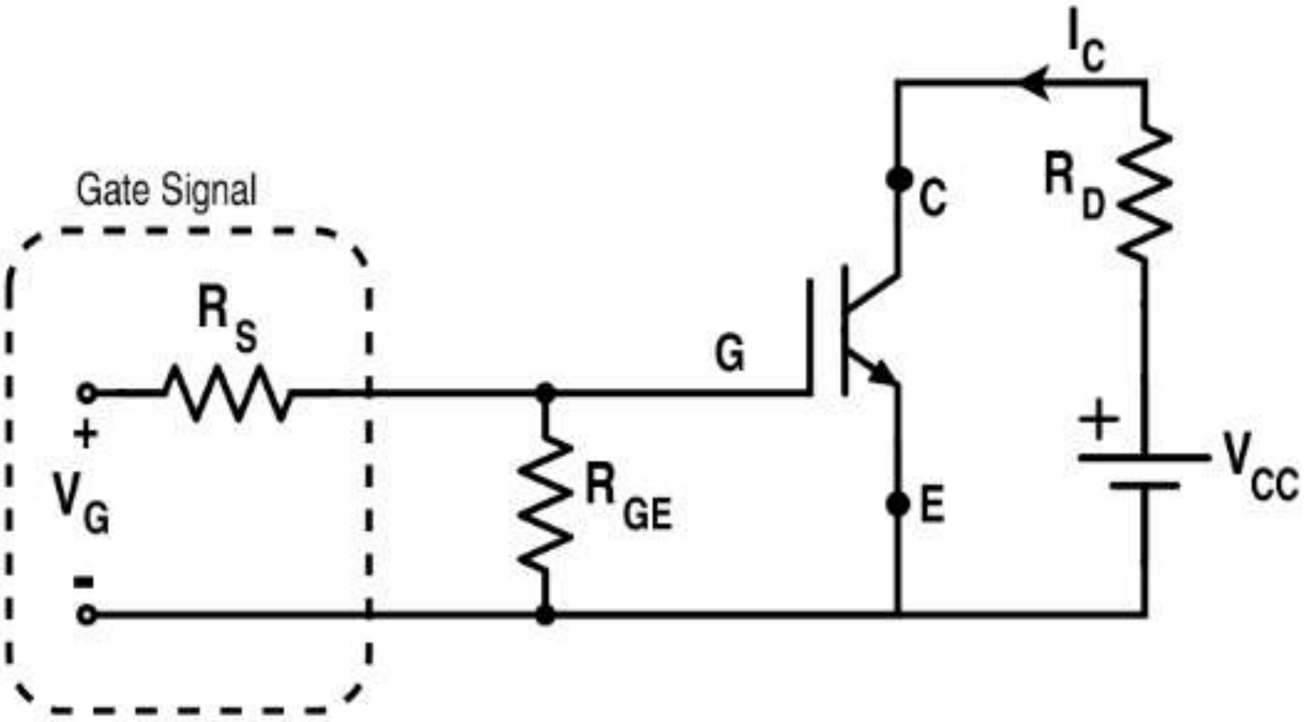
Transfer characteristics of an n-channel enhancement power MOSFET

Insulated-Gate Bipolar Transistor (IGBT)

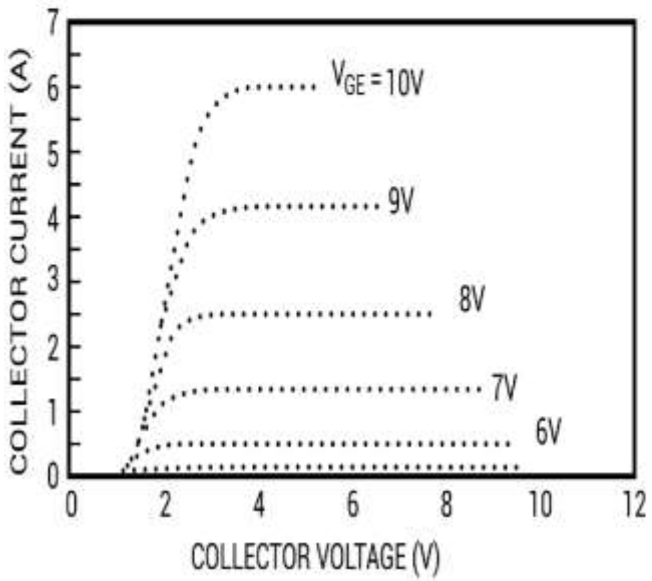
- IGBT combines the physics of both BJT and power MOSFET to gain the advantages of both worlds. It is controlled by the gate voltage. It has the high input impedance like a power MOSFET and has low on-state power loss as in case of BJT. There is no even secondary breakdown and not have long switching time as in case of BJT. It has better conduction characteristics as compared to MOSFET due to bipolar nature.

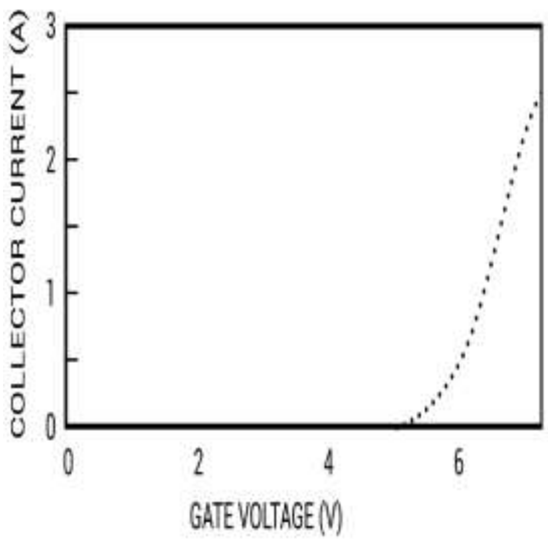


Cross -sectional structural diagram of IGBT



Equivalent diagram of IGBT



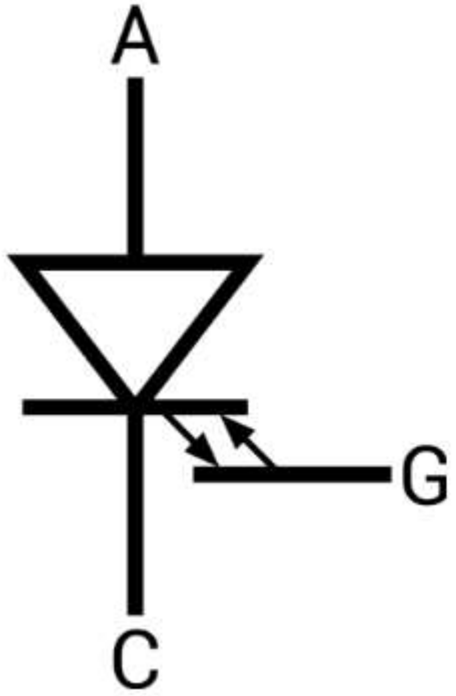


Forward characteristics of IGBT

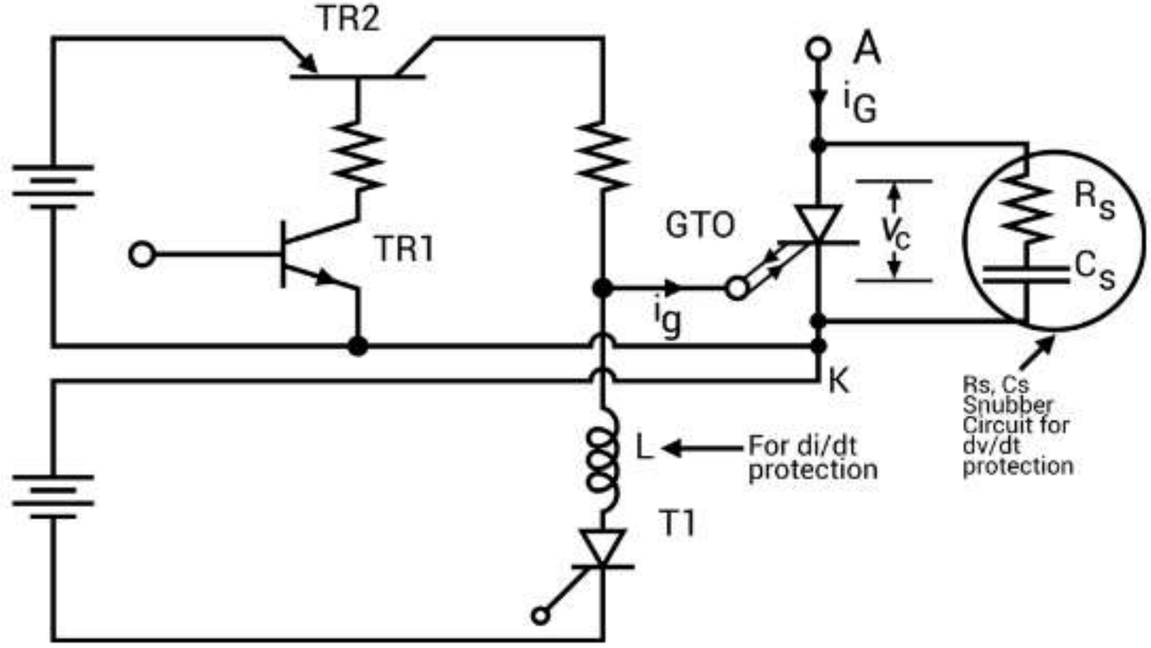
Transfer characteristics of IGBT

GTO (Gate Turn-off Thyristor)

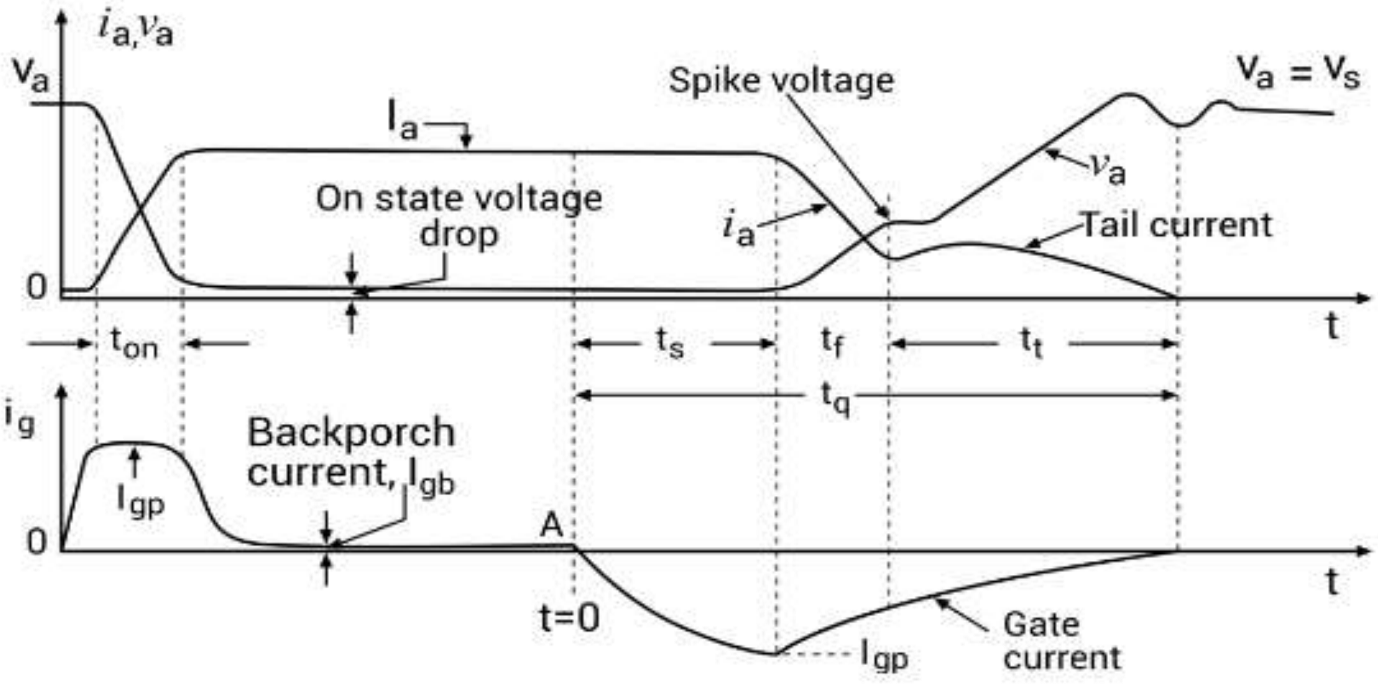
- GTO can be turned on with the positive gate current pulse and turned off with the negative gate current pulse. Its capability to turn off is due to the diversion of PNP collector current by the gate and thus breaking the regenerative feedback effect.
- Actually the design of GTO is made in such a way that the pnp current gain of GTO is reduced. A highly doped n spot in the anode p layer form a shorted emitter effect and ultimately decreases the current gain of GTO for lower current regeneration and also the reverse voltage blocking capability. This reduction in reverse blocking capability can be improved by diffusing gold but this reduces the carrier lifetime. Moreover, it requires a special protection.



Symbol of GTO



Gate Drive Circuit for GTO



Switching characteristics for GTO

SCR Specifications and Ratings:

- Peak Invese Voltage (V_{PIV})

  The peak inverse voltage is defined as the maximum voltage which SCR can safely withstand in its OFF state. The applied voltage should never be exceeded under any circumstances.

- On State Voltage:

  The voltage which appears across the SCR during its ON state is known as its ON state Voltage. The maximum value of voltage which can appear across the SCR during its conducting state is called its maximum on state voltage. Usually it will be 1V to 4V.

- Finger Voltage:

  The minimum voltage, which is required between the anode and cathode of an SCR to trigger it to conduction mode, is called its finger voltage.

- Rate of Rise of Voltage (dV/dt)

  The rate at which the voltage across the device rises (for forward condition) without triggering the device, is known as its rate of rise of voltage.

- Voltage Safety Factor:

  The normal operating voltage of the SCR is kept well below its peak inverse voltage(V_{PIV}) to avoid puncture of SCR due to uncertain conditions. The operating voltage and peak inverse voltage are related by voltage safety factor V_f
  V_f = Peak inverse voltage / (2 x RMS value of input

- Maximum average ON state current (I_{mac}):

  This is the average value of maximum continuous sinusoidal ON state current with conduction angle 180deg, at frequency 40 to 60Hz, which should not be exceeded even with intensive cooling.
- Maximum rms ON-state current: (I_{mrc})

  It is the rms value of the maximum continuous sinusoidal ON state current at the frequency 40 to 60 Hz and conduction angle 180deg, which should not be exceeded even with intensive cooling.
- Maximum surge - ON state Current (I_{msc})

  It is the maximum admissible peak value of a sinusoidal half cycle of tem milliseconds duration at a frequency of 50Hz.

- Latching Current (I_l)

  It is the minimum current, which is required to latch the device from its OFF state to its ON state. In other words, it is the minimum current required to trigger the device.

- Holding Current (I_H)

  It is the minimum current required to hold the SCR conducting. In other words, It is the minimum current, below which the device stops conducting and returns to its OFF state.

- Gate Current:

  The current which is applied to the gate of the device for control purposes is known as gate current.

- Minimum Gate Current:

  The minimum current required at the gate for triggering the device.
- Maximum Gate Current:

  The maximum current which can be applied to device safely. Current higher than this will damage the gate terminal.
- Gate Power Loss:

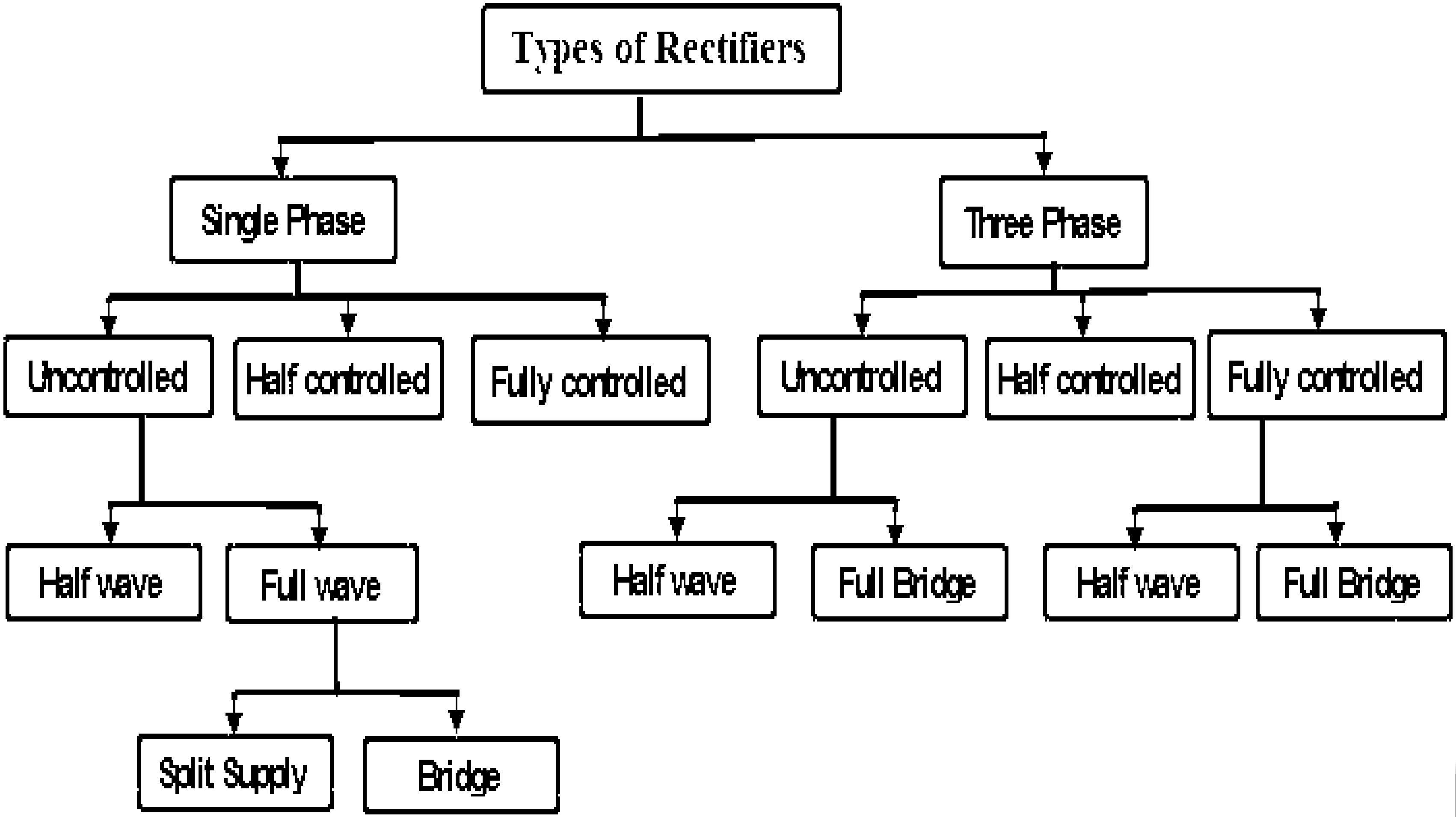
  The mean power loss, which occurs due to flow of gate current between the gate and the main terminals.

UNIT II
SINGLE PHASE AND THREE PHASE CONTROLLED RECTIFIERS

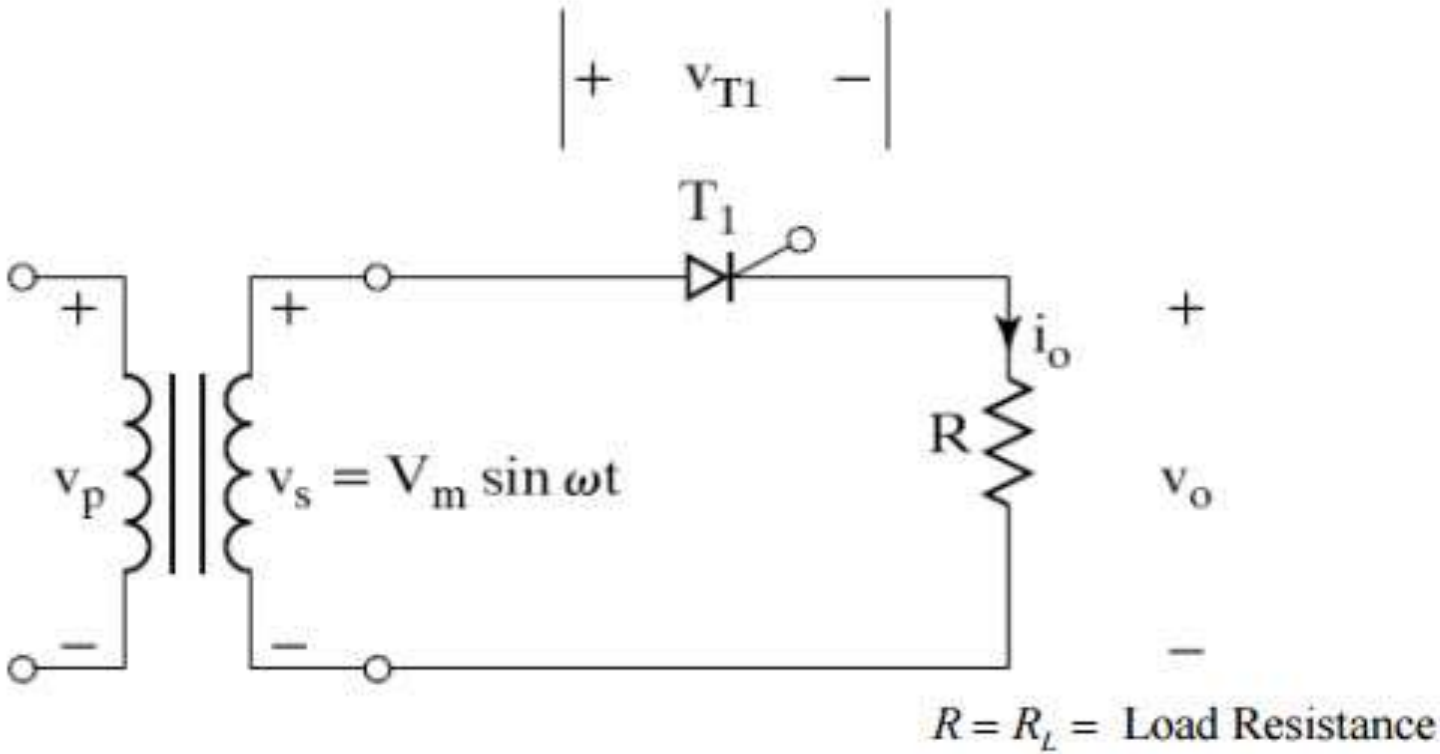
Phase control technique

- The term PCR or Phase controlled rectifier is a one type of rectifier circuit in which the diodes are switched by Thyristors or SCRs (Silicon Controlled Rectifiers). Whereas the diodes offer no control over the o/p voltage, the Thyristors can be used to differ the output voltage by adjusting the firing angle or delay. A phase control Thyristor is activated by applying a short pulse to its gate terminal and it is deactivated due to line communication or natural. In case of heavy inductive load, it is deactivated by firing another Thyristor of the rectifier during the negative half cycle of i/p voltage.

Types of Phase Controlled Rectifier



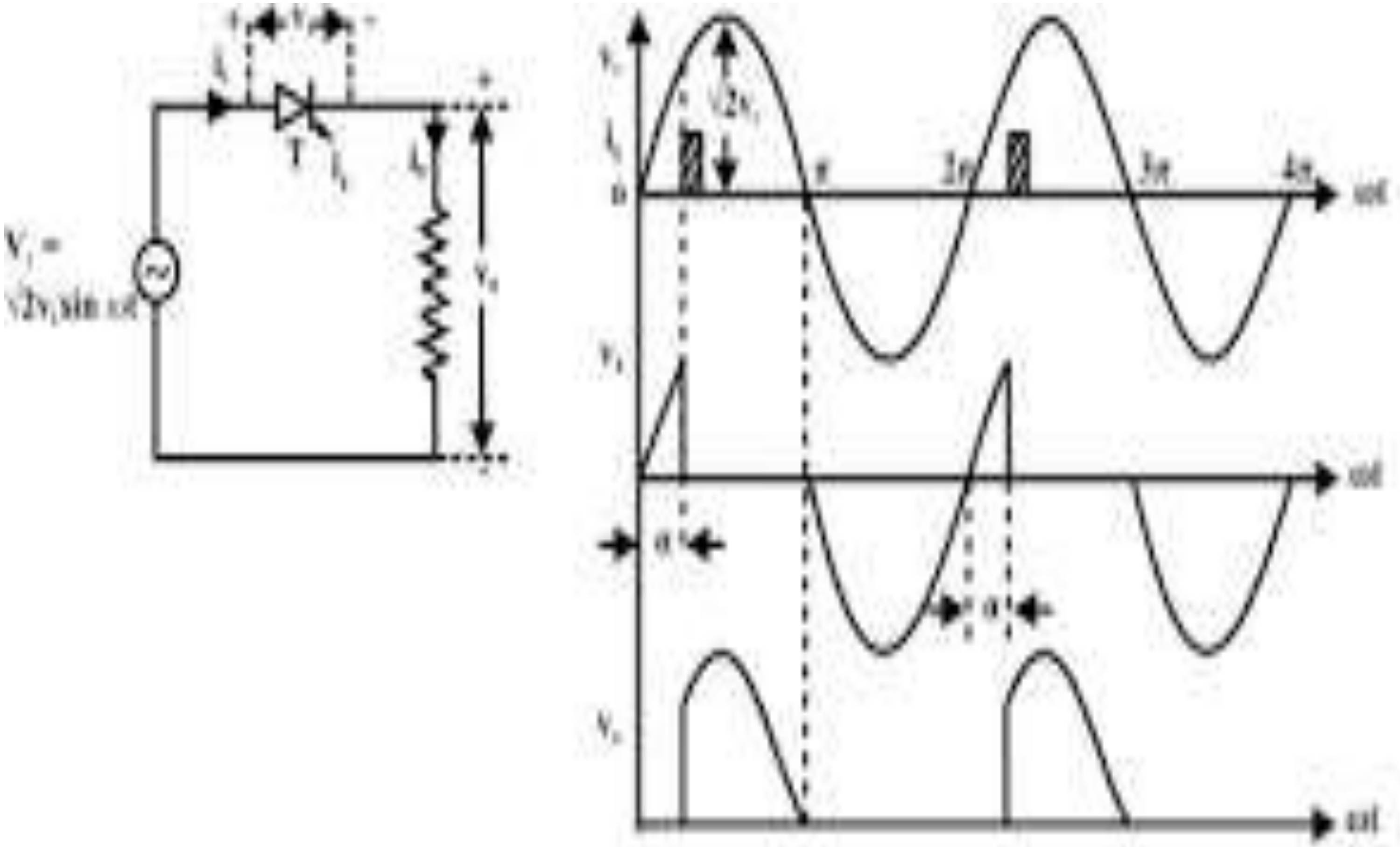
Single phase half wave rectifier circuit



Applications of Phase Controlled Rectifier

- Phase controlled rectifier applications include paper mills, textile mills using DC motor drives and DC motor control in steel mills.
- AC fed traction system using a DC traction motor.
- Electro-metallurgical and Electrochemical processes.
- Reactor controls.
- Magnet power supplies.
- Portable hand instrument drives.
- Flexible speed industrial drives.
- Battery charges.
- High voltage DC transmission.
- UPS (Uninterruptible power supply systems).

Single Phase Half Wave Controlled Rectifier with R load

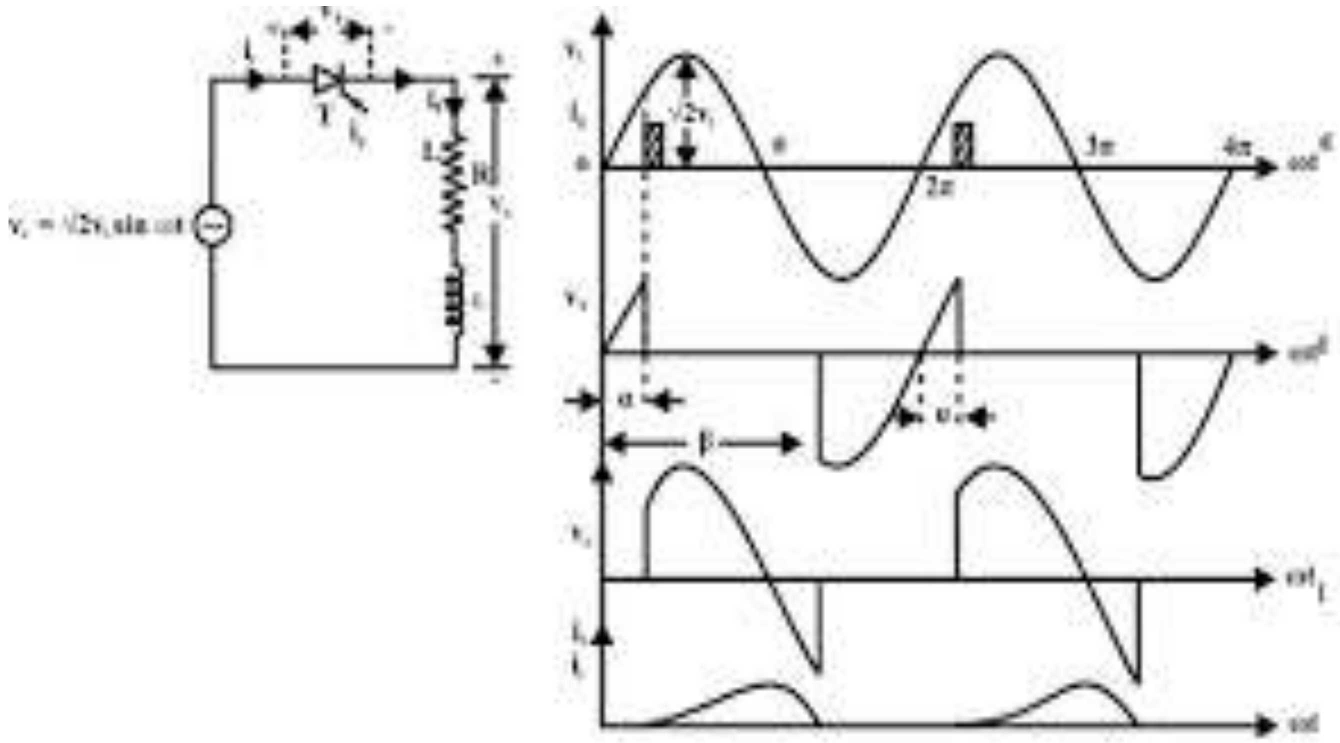


$$\therefore V_0(Avg) = \frac{1}{2\pi}\int_0^{2\pi} V_m \sin(wt)\, dwt$$

$$= \frac{V_m}{2\pi}\left[-\cos wt\right]_\alpha^\pi$$

$$= \frac{V_m}{2\pi}(1+\cos\alpha)$$

Single Phase Half Wave Controlled Rectifier with RL load



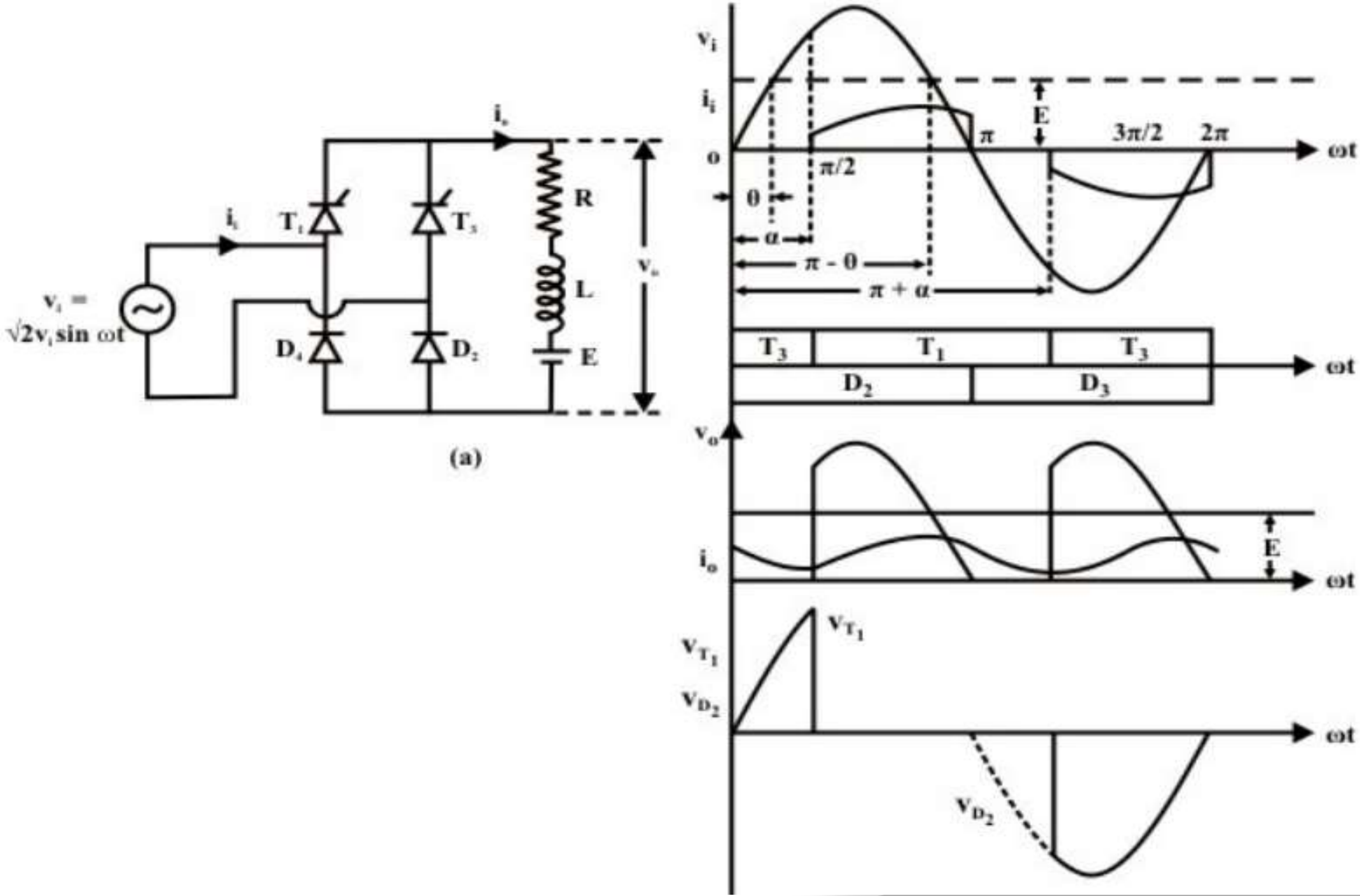
The average output voltage $V_0 = \frac{1}{2\pi}\int_{\alpha}^{\beta} Vmsinwt\ d(wt) = \frac{Vm}{2\pi}(\cos\alpha - \cos\beta)$

$$I_0 = \frac{Vm}{2\pi R}(\cos\alpha - \cos\beta)$$

RMS load voltage $V_{0r} = \left\{\frac{1}{2\pi}\int_{\alpha}^{\beta} Vm^2 sin^2 wt\ d(wt)\right\}^{1/2}$

$$= \frac{Vm}{2\sqrt{\pi}}\left[(\beta - \alpha) - \frac{1}{2}\{sin2\beta - sin2\alpha\}\right]^{1/2}$$

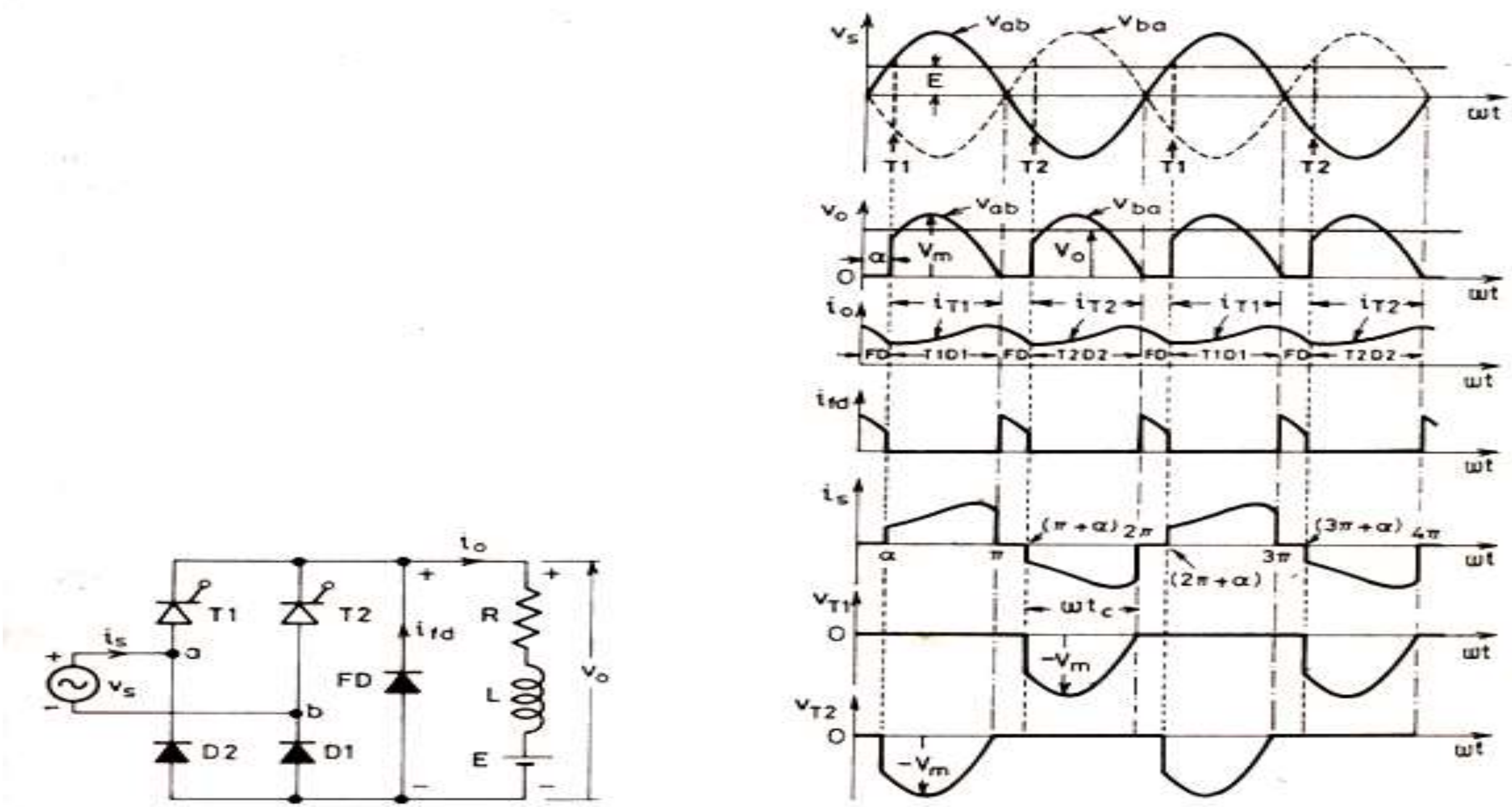
Single phase half controlled converter with RLE load



- The diode D2 and D4 conducts for the positive and negative half cycle of the input voltage waveform respectively. On the other hand T1 starts conduction when it is fired in the positive half cycle of the input voltage waveform and continuous conduction till T3 is fired in the negative half cycle. Fig. shows the circuit diagram and the waveforms of a single phase half controlled converter supplying an R – L – E load.

$$V_{oav} = \frac{1}{\pi}\int_{0}^{\pi} v_{o}\, d\omega t = \frac{1}{\pi}\int_{\alpha}^{\pi} \sqrt{2}V_{i} \sin \omega t \, d\omega t = \frac{\sqrt{2}V_{i}}{\pi}(1+\cos\alpha)$$

$$I_{ov} = \frac{V_{oav} - E}{R} = \frac{\sqrt{2}V_{i}}{\pi R}(1+\cos\alpha - \pi \sin\theta)$$



single phase half controlled converter with RLE load and freewheeling diode

Numerical problems

1. A single phase 230V, 1 Kw heater is connected across 1 phase 230V, 50Hz supply through an SCR. For firing angle delay of 45^0 and 90^0, calculate the power absorbed in the heater element.

Solution: Heater resistance $R = 230^2/1000\ \Omega$

The rms value of voltage is $V_{or} = \frac{Vm}{2\sqrt{\pi}}\left[(\pi - \alpha) + \frac{1}{2}sin2\alpha\right]^{1/2}$

$$= \frac{\sqrt{2}\times 230}{2\sqrt{\pi}}\left[\left(\pi - \frac{\pi}{4}\right) + \frac{1}{2}sin90\right]^{1/2} = 155.071V$$

Power absorbed by the heater element for $\alpha = 45^0$ is

$$\frac{Vor^2}{R} = \left[\frac{155.071}{230}\right]^2 \times 1000 = 454.57W$$

for $\alpha = 90^0$ the rms voltage is

$$V_{or} = \frac{\sqrt{2} X 230}{2\sqrt{\pi}}\left[\left(\pi - \frac{\pi}{2}\right) + \frac{1}{2} sin 180\right]^{1/2} = 115V$$

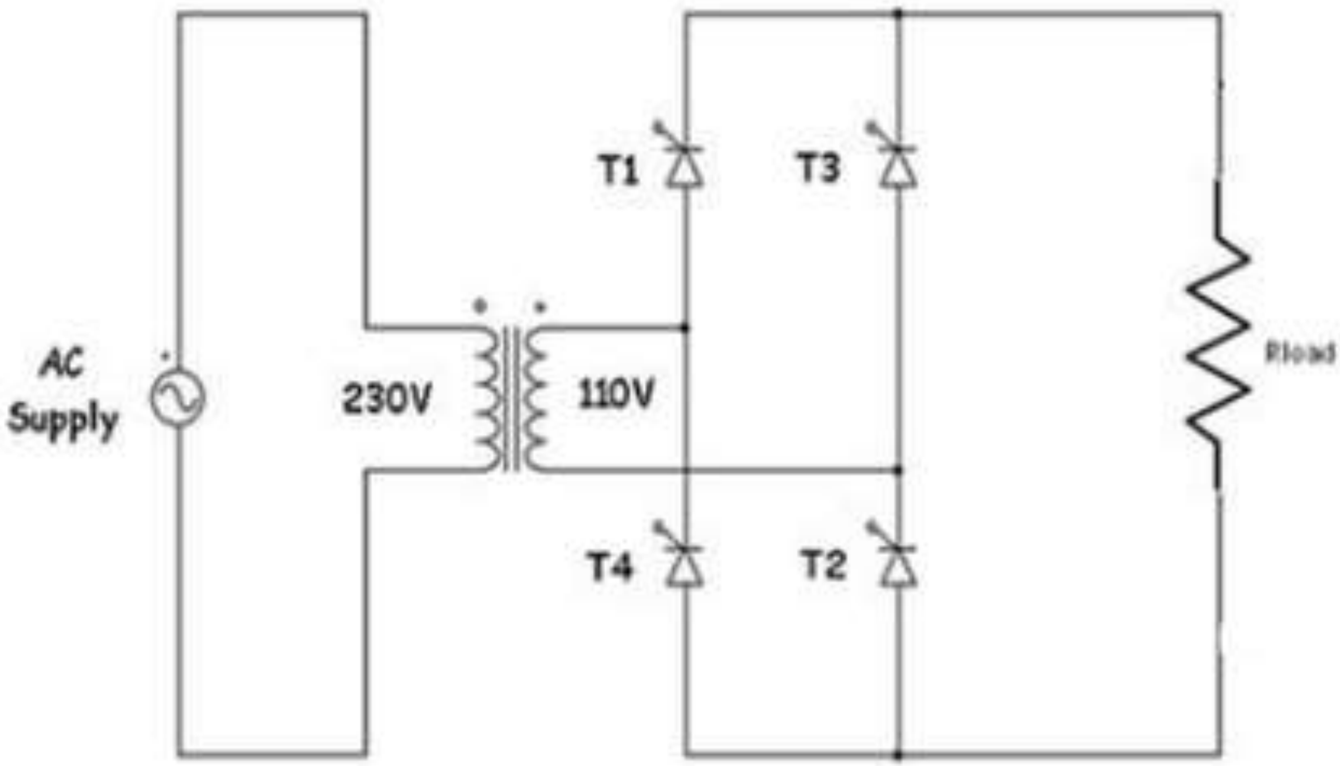
Power absorbed by the heater element for $\alpha = 90^0$ is

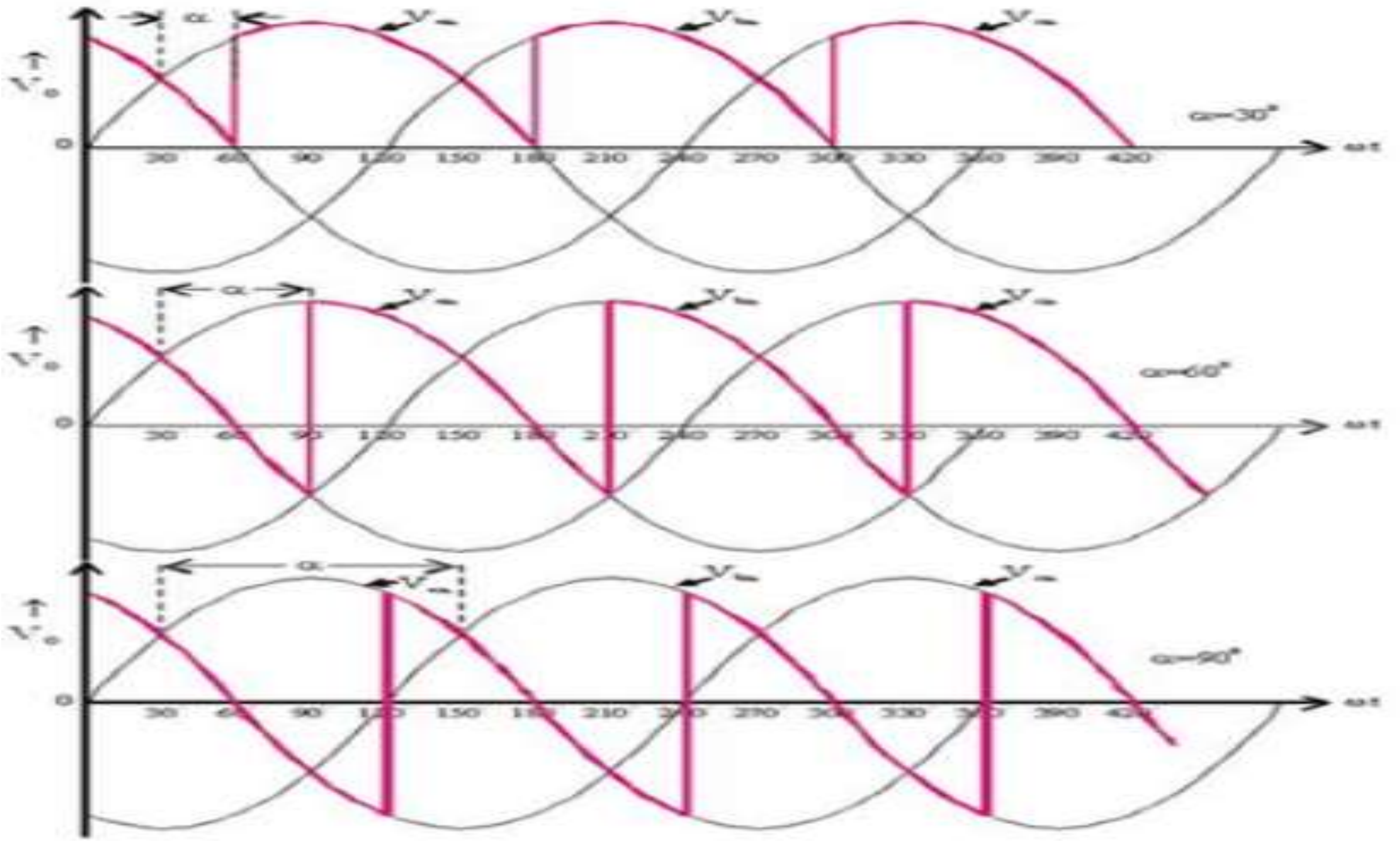
$$\frac{Vor^2}{R} = \left[\frac{115}{230}\right]^2 \times 1000 = 250W$$

2. A resistive load of 10Ω is connected through a half-wave controlled rectifier circuit to 220V, 50 Hz, single phase source. Calculate the power delivered to the load for a firing angle of 60°. Find also the value of input power factor

3. A single phase semi converter delivers to RLE load with R=5Ω, L = 10mH and E = 80V. The source voltage is 230V, 50Hz. For continuous conduction, Find the average value of output current for firing angle = 50^{o}.

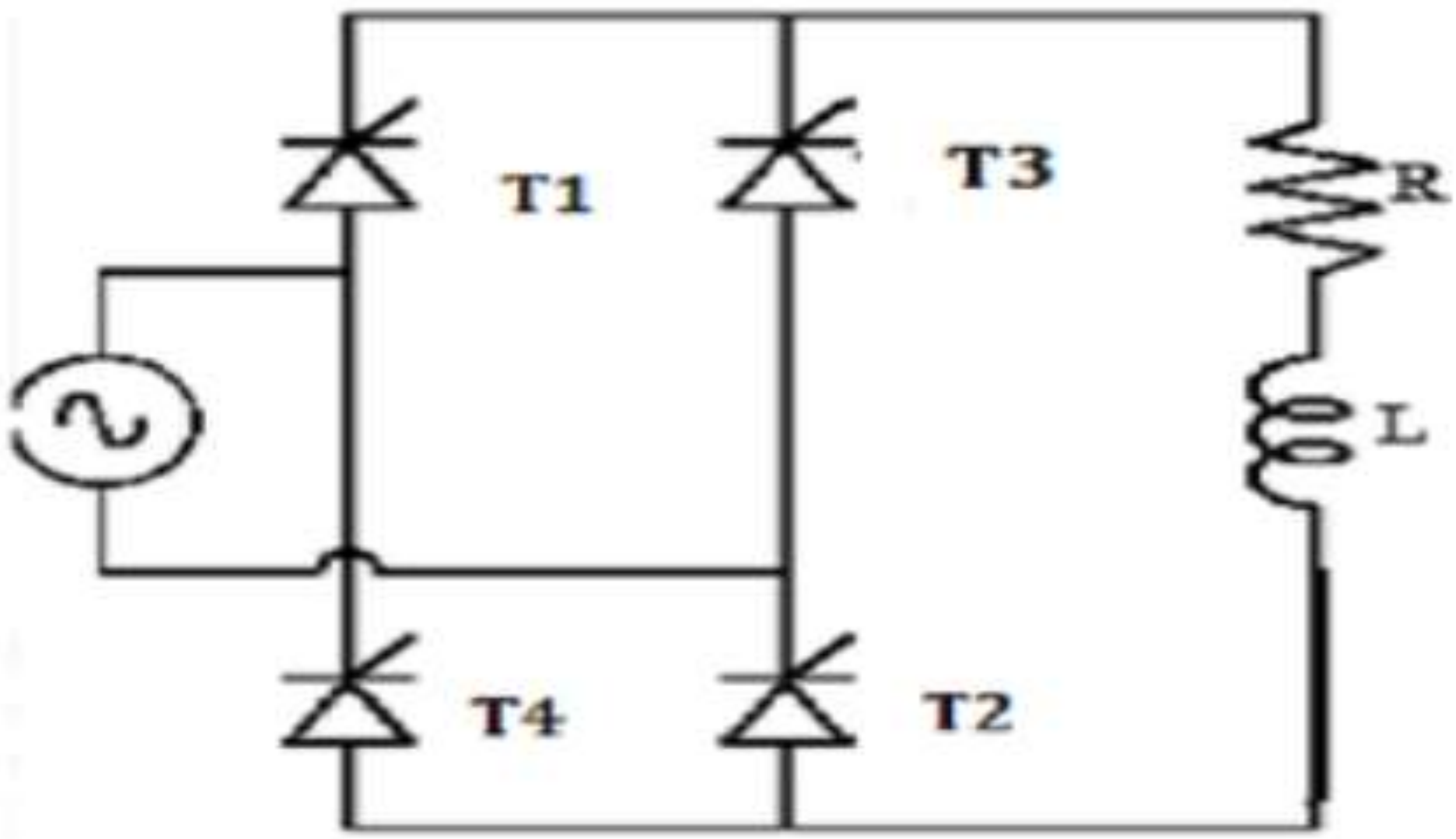
Single phase full wave controlled rectifier

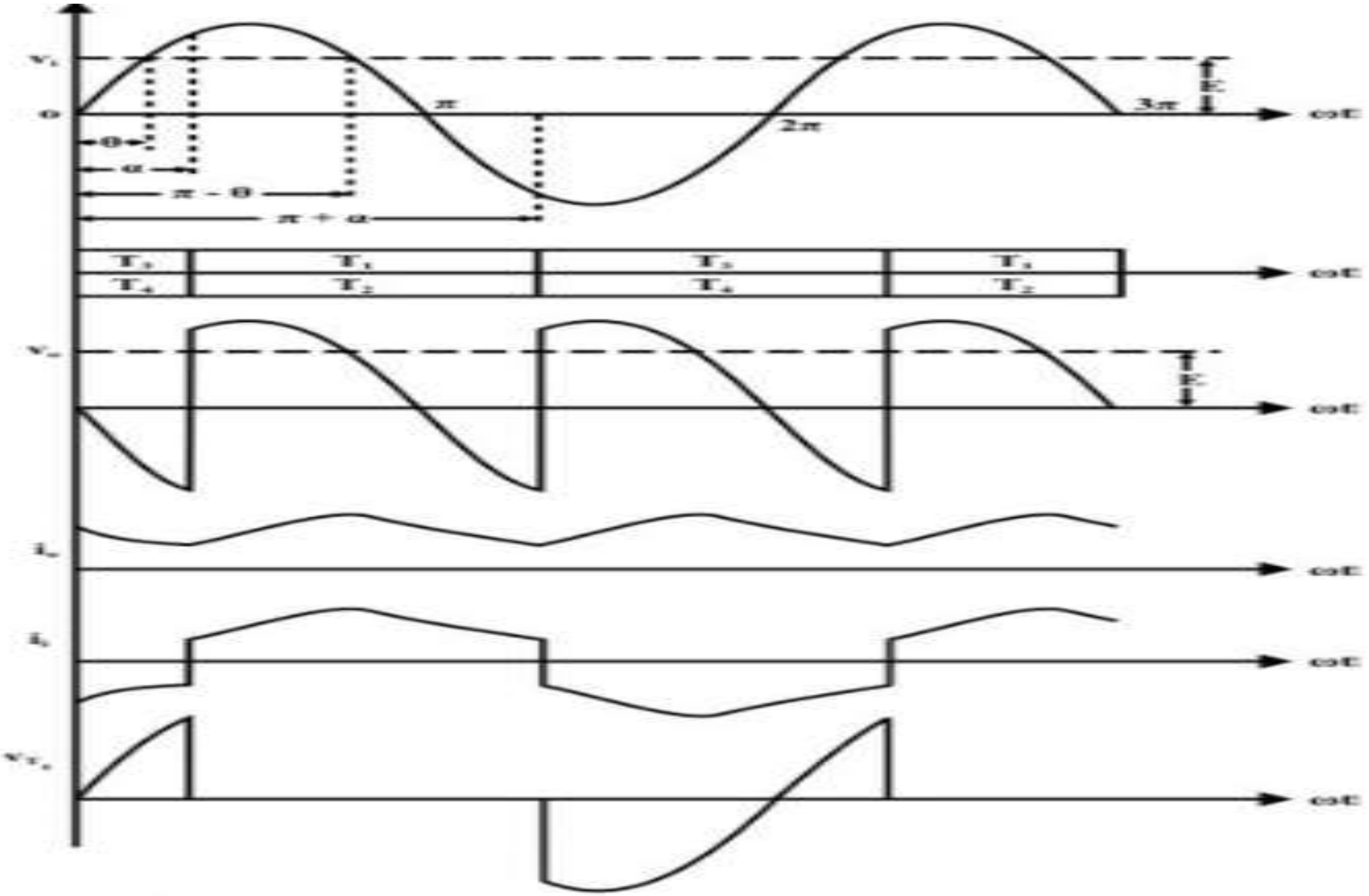




single phase full converter circuit with R load input and output waveforms

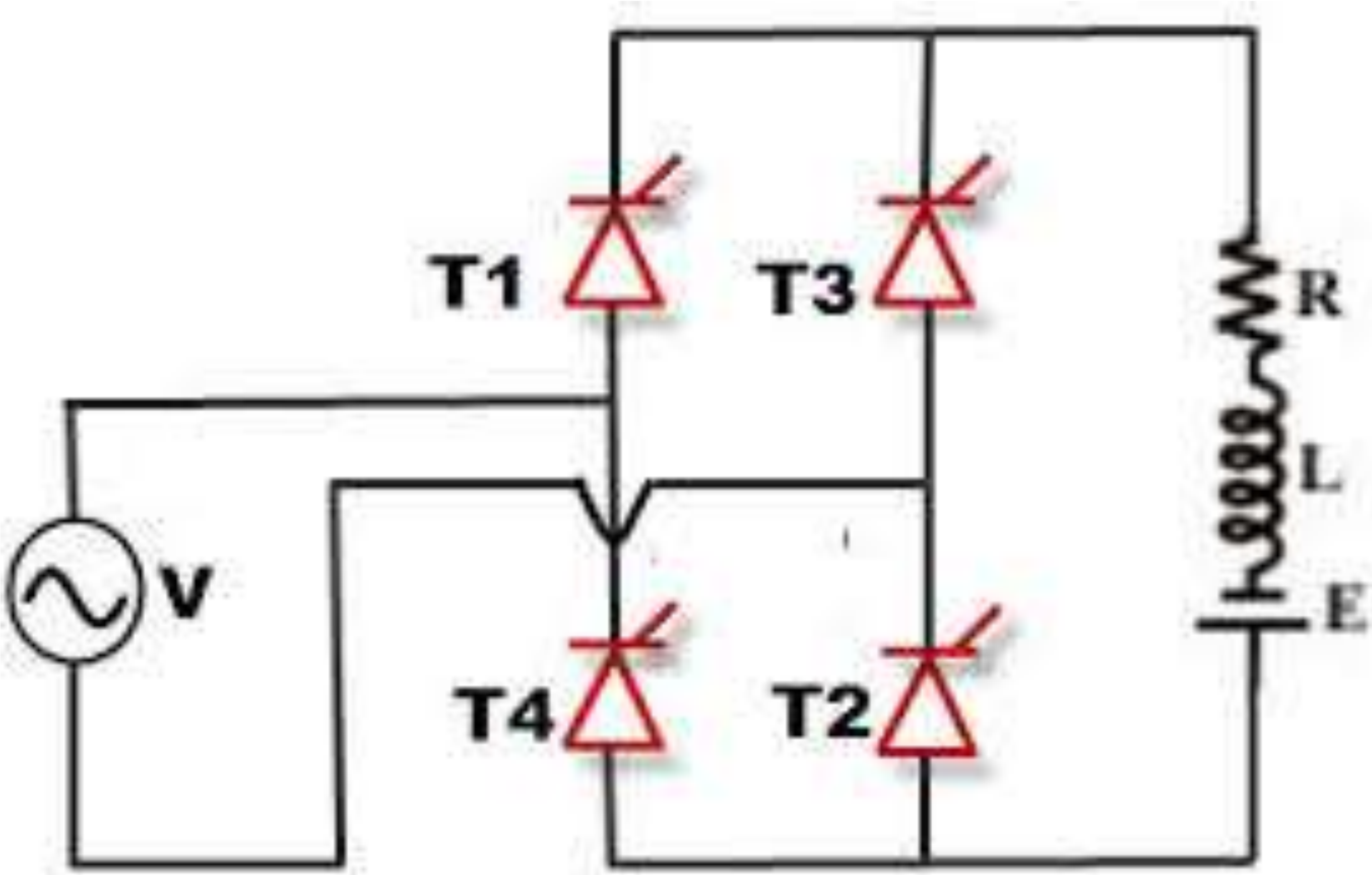
Single Phase Full Wave Controlled Rectifier with RL load



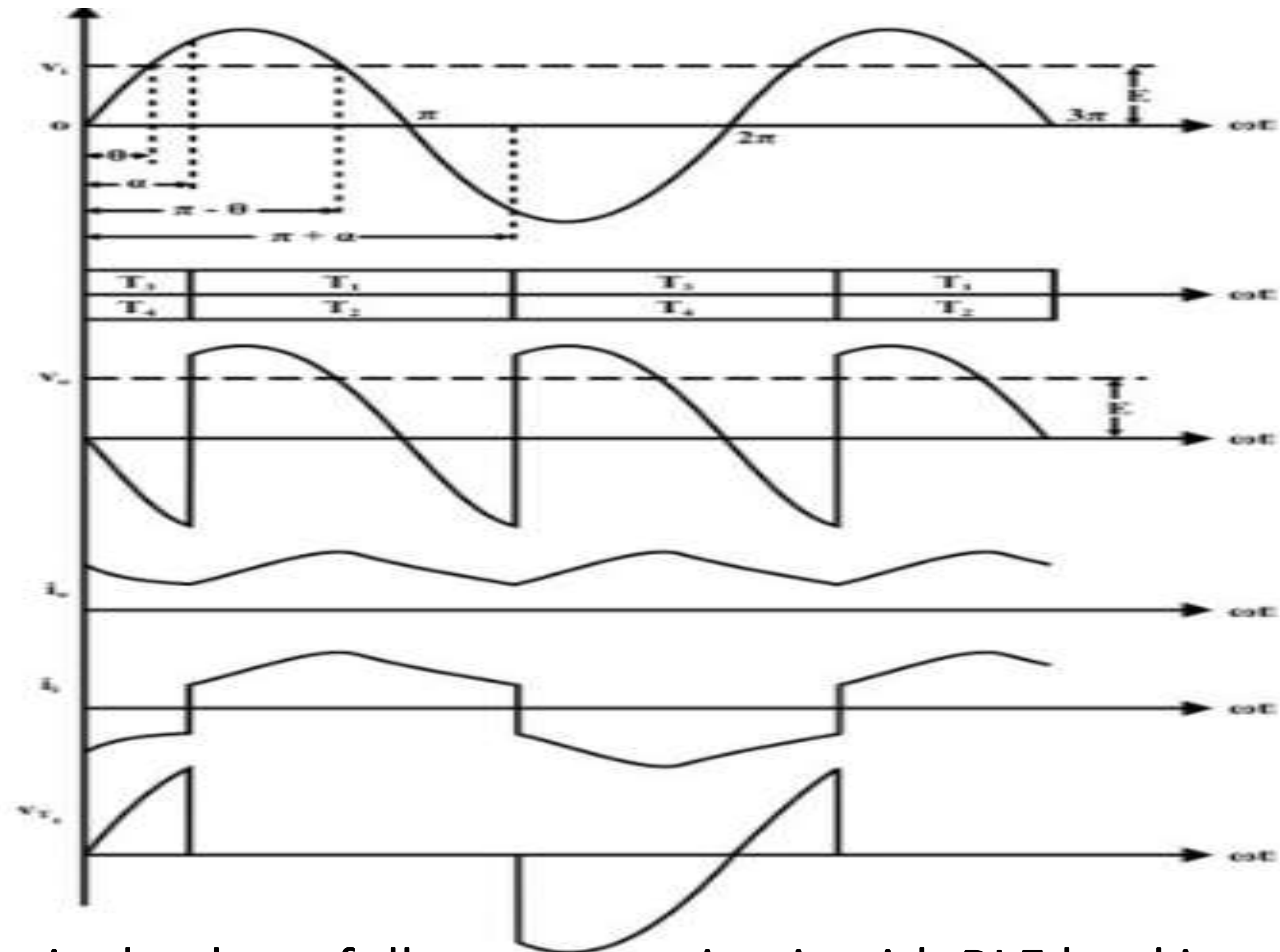


single phase full converter circuit with RL load input and output waveforms

Single phase fully controlled converters with RLE load



- In positive half-cycle of the input, Thyristors T1 and T2 are forward biased while T3 and T4 are reverse biased. Thyristors T1 and T2 are triggered simultaneously at some firing angle in the positive half cycle, and T3 and T4 are triggered in the negative half cycle.
- The load current starts flowing through them when they are in conduction state. The load for this converter can be RL or RLE depending on the application.



single phase full converter circuit with RLE load input and output waveforms

single phase half wave converter

1. Average DC load voltage: (V_{oavg})

$$V_{oavg} = V_0 = \frac{1}{T}\int_0^T Vmsinwt\ d(wt) \text{ where T is time period}$$

$$V_{oavg} = \frac{1}{2\pi}\left[\int_\alpha^\pi Vmsinwt\ d(wt) + \int_\pi^{2\pi+\alpha} 0\ d(wt)\right]$$

$$= \frac{1}{2\pi}\left[\int_\alpha^\pi Vmsinwt\ d(wt)\right]$$

$$= \frac{Vm}{2\pi}[-coswt]_\alpha^\pi$$

$$= \frac{Vm}{2\pi} - [cos\pi - cos\alpha]$$

$$= \frac{Vm}{2\pi}[1 + cos\alpha]$$

If $\alpha = 0$ $V_{oavg\,max} = \frac{Vm}{\pi}$

If $\alpha = 180$ $V_{oavg} = 0$

2. Average DC load current is given as

$$I_{0avg} = \frac{V0avg}{R}$$

$$I_{0avg} = \frac{Vm}{2\pi R}\,[1 + cos\alpha]$$

3. RMS load voltage

$$V_{rms} = \left\{\frac{1}{T}\int_0^T Vm^2 sin^2 wt\, d(wt)\right\}^{1/2}$$

$$V_{rms} = \left\{\frac{1}{2\pi}\int_\alpha^\Pi Vm^2 sin^2 wt\, d(wt)\right\}^{1/2}$$

$$V_{rms} = \frac{Vm}{2\sqrt{\pi}}\left[(\pi - \alpha) + \frac{1}{2}sin2\alpha\right]^{1/2}$$

If $\alpha = 0$ $V_{rms} = \frac{Vm}{2}$

If $\alpha = 180$ $V_{rms} = 0$

The RMS voltage may be varied from 0 to $\frac{Vm}{2}$ by varying α from 180 to 0

4. Power delivered to the resistive load is given

P_L = (RMS load voltage)(RMS load current)

$= V_{rms} X\ I_{rms}$

$$= \frac{Vrms^2}{R} = Irms^2 XR$$

5. Input volt amperes = (RMS source voltage)(RMS line current)

$$= V_s I_{rms}$$

$$= V_s \frac{\sqrt{2}Vs}{R2\sqrt{\pi}}\left[(\pi - \alpha) + \frac{1}{2} sin2\alpha\right]^{1/2}$$

$$= \frac{Vs^2}{\sqrt{2\pi}XR}\left[(\pi - \alpha) + \frac{1}{2} sin2\alpha\right]^{1/2}$$

6. Input power factor: It is defined as the ratio of total mean input power to the total rms input volt amperes

$$\text{Input power factor} = \frac{\frac{\sqrt{2}Vs}{2\sqrt{\pi}}\left[(\pi-\alpha)+\frac{1}{2}sin\,2\alpha\right]^{1/2}}{Vs}$$

$$= \frac{1}{\sqrt{2\pi}}\left[(\pi - \alpha) + \frac{1}{2} sin2\alpha\right]^{1/2}$$

7. Form factor: Form factor is defined as the ratio of RMS voltage to the average DC voltage

$$\text{Form Factor} = \frac{\text{Vrms}}{\text{Vavg}}$$

8. Effective value of the AC component of the output voltage

$$V_{ac} = [Vrms^2 - Vavg^2]^{1/2}$$

9. Ripple factor (R_f)

It is defined as the ratio of AC component to the DC. Where ripple is the amount of AC component present in DC component

$$R_f = \frac{Vac}{Vavg} = \frac{[Vrms^2 - Vavg^2]^{1/2}}{Vavg} = \left[\left(\frac{Vrms}{Vavg}\right)^2 - 1\right]^{1/2} = \sqrt{FF^2 - 1}$$

10. Transformer Utilization Factor (TUF):

It is defined as the ratio of output DC power to the volt ampere rating of the transformer

$$TUF = \frac{Pdc}{\text{VA rating of secondary winding of the transformer}}$$

11. Rectifier efficiency:

It is defined as the ratio of output DC power to the input ac power

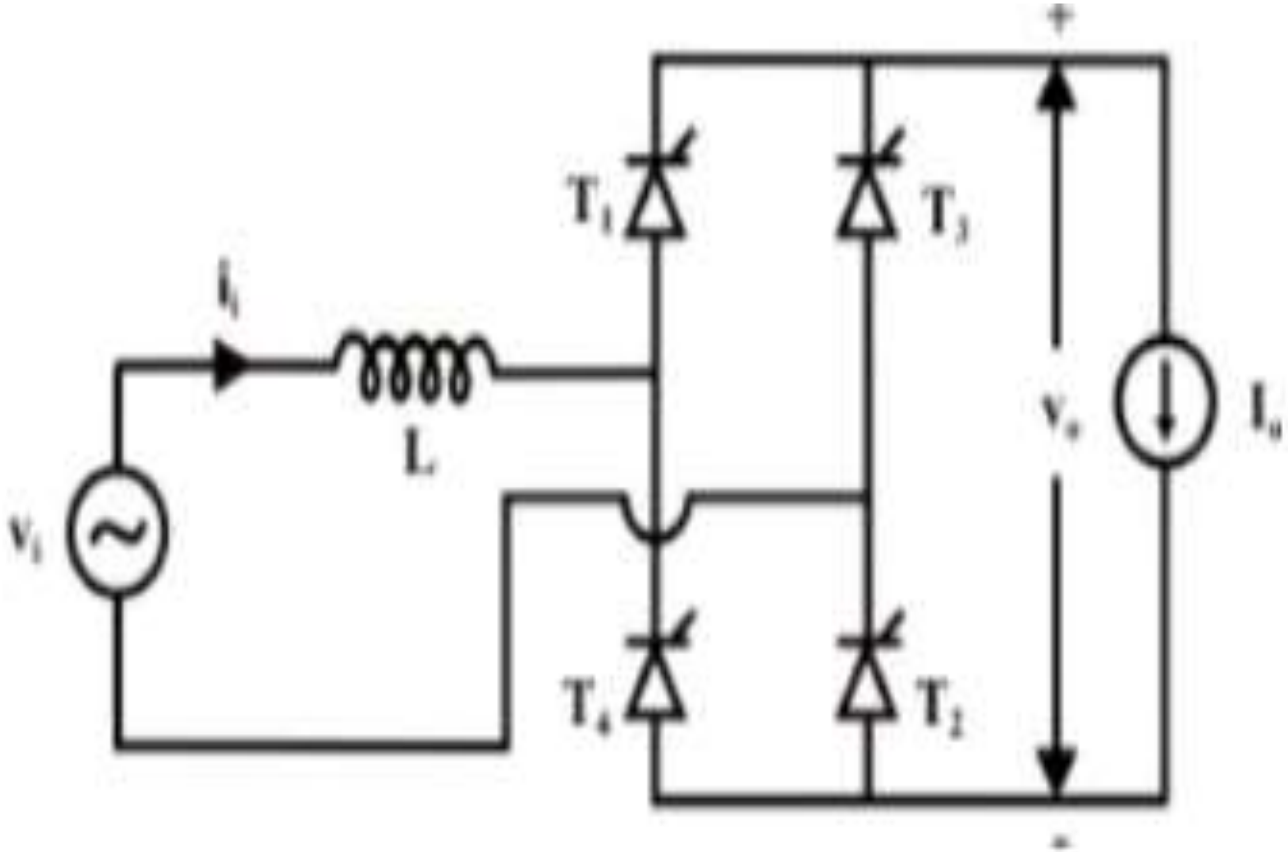
$$\eta = \frac{VavgIavg}{VrmsIrms}$$

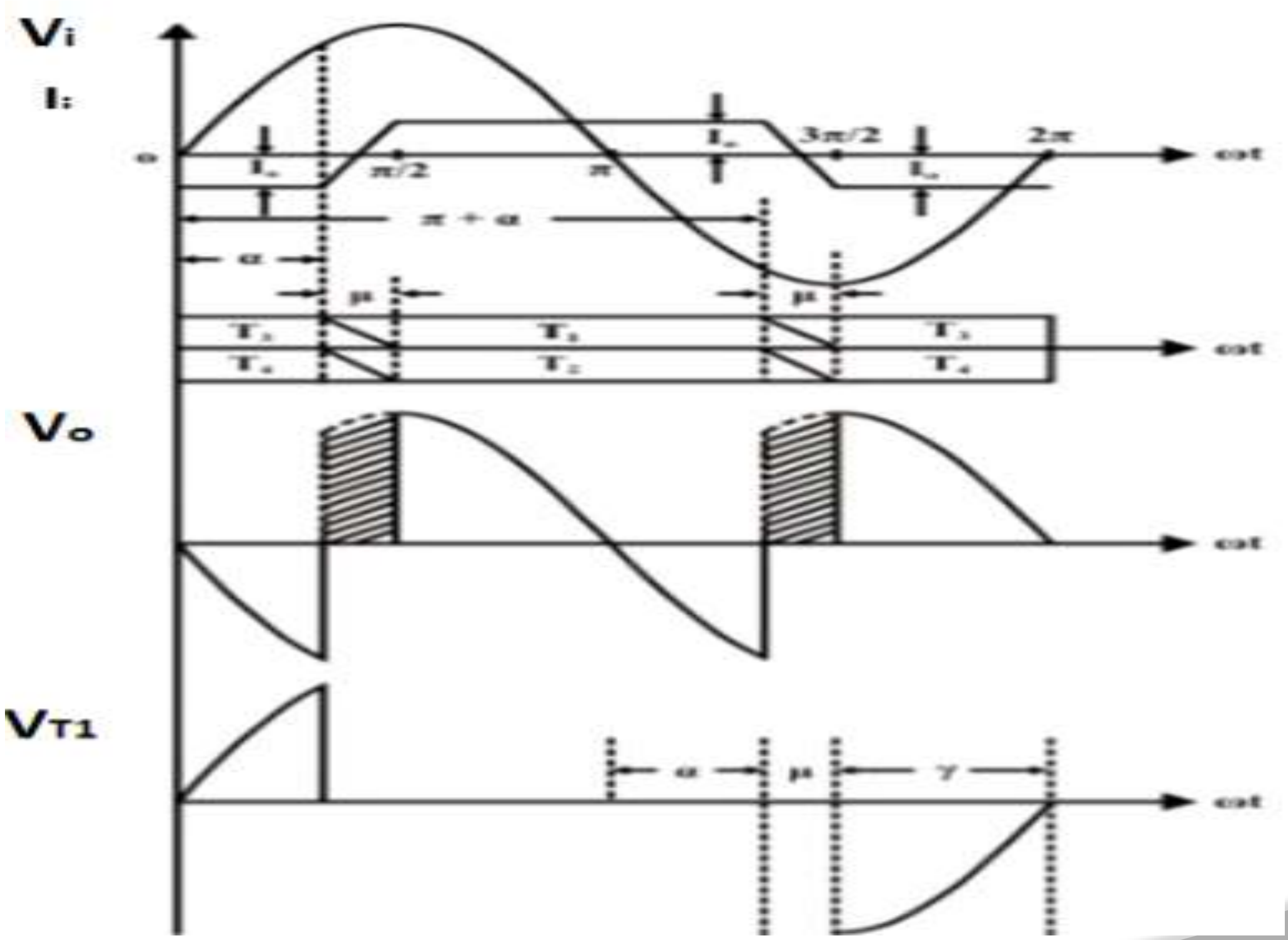
12. Peak inverse voltage (PIV):

It is defined as the maximum voltage that an SCR can be subjected to in the reverse biased condition

In the case of Half wave rectifier it is V_m

Effect of source inductance in single phase rectifier





single phase full converter output waveforms with source inductance

$$L\frac{di_i}{dt} = v_i \;\; for \;\; \alpha \leq \omega t + \mu$$

$$i_i(\omega t = \alpha) = -I_0$$

$$i_i = I - \frac{\sqrt{2}V_i}{\omega L} cos\omega t$$

$$\therefore i_i\big|_{\omega t - \alpha} = I - \frac{\sqrt{2}V_i}{\omega L} cos\alpha = -I_0$$

$$I = \frac{\sqrt{2}V_i}{\omega L}\cos\alpha - I_0$$

$$\therefore \quad i_i = \frac{\sqrt{2}V_i}{\omega L}(\cos\alpha - \cos\omega t) - I_0$$

$$\text{at} \quad \omega t = \alpha + \mu \quad i_i = I_0$$

$$I_0 = \frac{\sqrt{2}V_i}{\omega L}(\cos\alpha - \cos(\alpha + \mu)) - I_0$$

$$\therefore \quad \cos\alpha - \cos(\alpha + \mu) = \frac{\sqrt{2}\omega L}{V_0} I_0$$

$$V_0 = \frac{I}{\pi}\int_{\alpha}^{\alpha+\pi} V_i \, d\omega t$$

or $$V_0 = \frac{I}{\pi}\int_{\alpha+\mu}^{\alpha+\pi} \sqrt{2}v_i \sin \omega t \, d\omega t$$

$$= \frac{\sqrt{2}v_i}{\pi}[\cos(\alpha+\mu) - \cos(\pi+\alpha)$$

$$= \frac{\sqrt{2}v_i}{\pi}[\cos\alpha + \cos(\alpha+\mu)]$$

$$\therefore V_0 = 2\sqrt{2}\frac{v_i}{\pi}\left[\cos\alpha - \cos(\alpha + \mu)\right]$$

$$\therefore V_0 = \frac{2\sqrt{2}}{\pi}v_i\cos\alpha - \frac{2}{\pi}\omega L I_0$$

Numerical problems

1. For the single phase fully controlled bridge is connected to RLE load. The source voltage is 230 V, 50 Hz. The average load current of 10A continuous over the working range. For R= 0.4 Ω and L = 2mH, Compute (a) firing angle for E = 120V (b) firing angle for E = -120V (c) in case output current is constant find the input power factors for both parts a and b

Solution:

a) For E = 120 the full converter is operating as a controlled rectifier

$$\frac{2Vm}{\pi} \cos\alpha = E + I_0 R$$

$$\frac{2\sqrt{2}.230}{\pi} \cos\alpha = 120 + 10X0.4 = 124V$$

$$\alpha = 53.21^0$$

For $\alpha = 53.21^0$ power flows from ac source to DC load.

b) For E = -120 the full converter is operating as a controlled rectifier

$$\frac{2Vm}{\pi}\ cos\alpha = E + I_0 R$$

$$\frac{2\sqrt{2}.230}{\pi}\ cos\alpha = -120 + 10X0.4 = -116V$$

$$\alpha = 124.1^0$$

For $\alpha = 124.1^0$ power flows from DC source to ac load.

c) For constant load current, rms value of load current is

$$I_{or} = I_o = 10A$$

$$V_s\ I_{or}\cos\Phi = EI_o + I_{or}^2 R$$

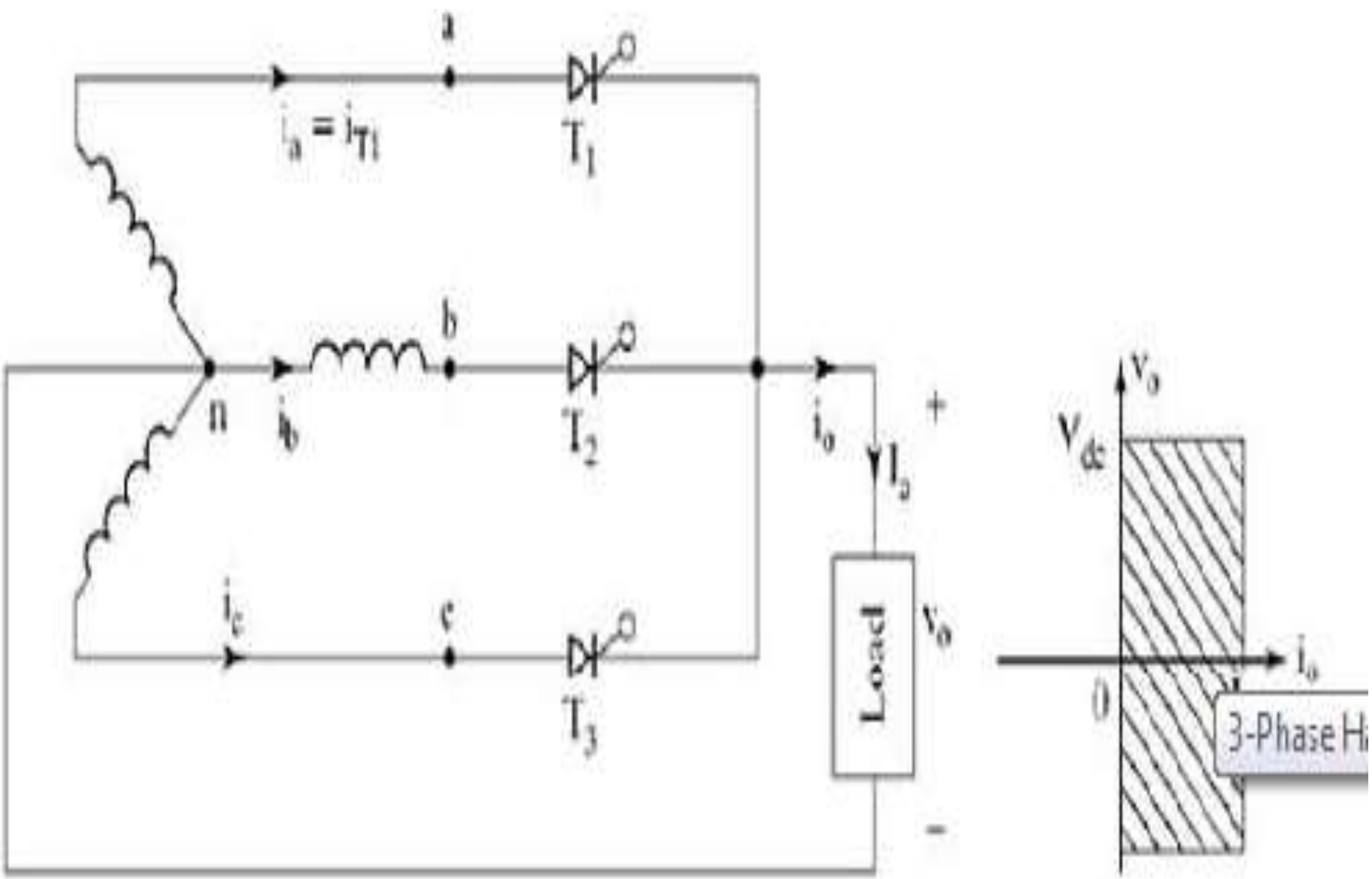
For $\alpha = 53.21^0$ $\cos\Phi = \frac{120 \times 10 + 10^2 \times 0.4}{230 \times 10} = 0.5391$ lag

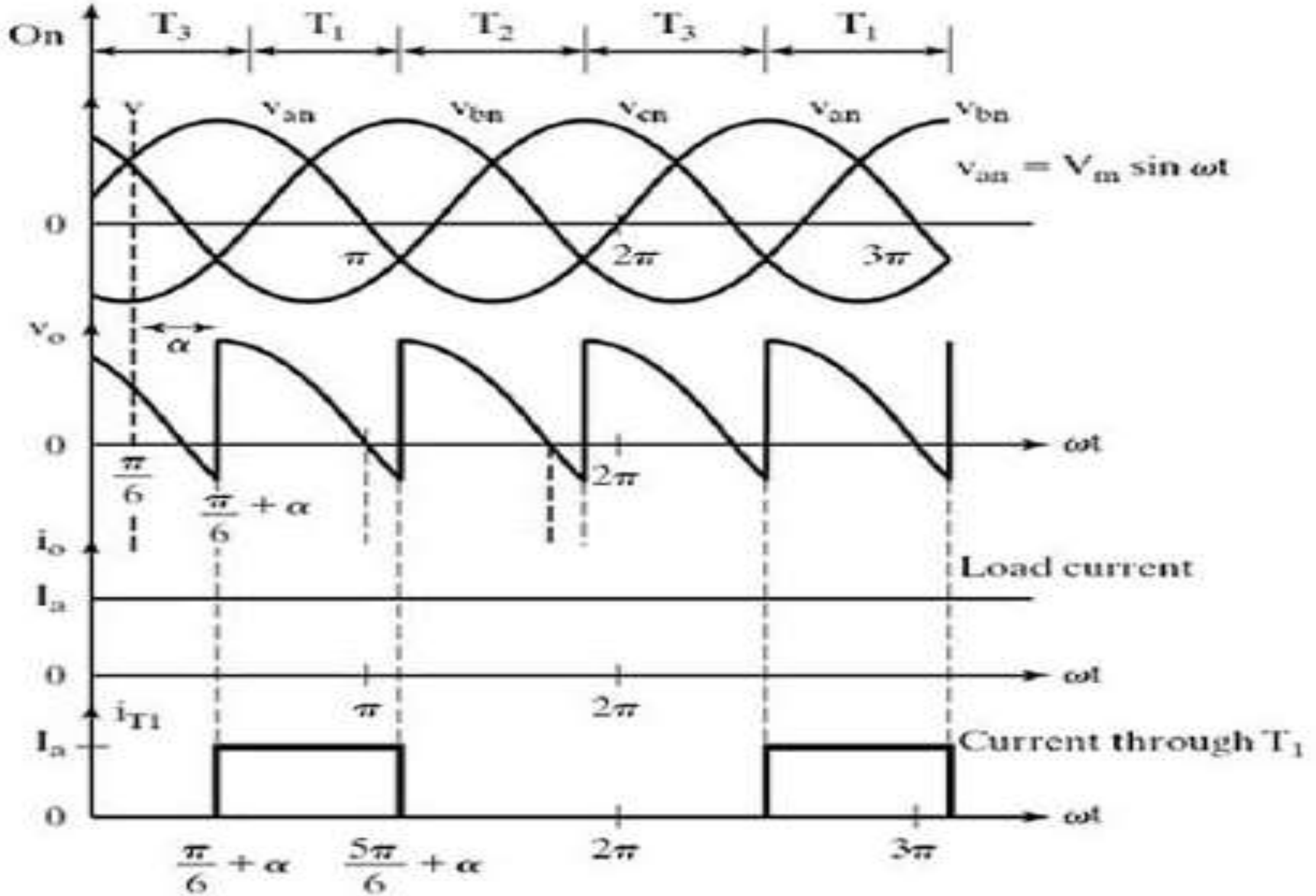
For $\alpha = 124.1^0$ $\cos\Phi = \frac{120 \times 10 - 10^2 \times 0.4}{230 \times 10} = 0.5043$ lag

2. A single phase two pulse converter feeds power to RLE load with R= 6Ω, L= 6mH, E= 60V, AC source voltage is 230V, 50Hz for continuous condition. Find the average value of load current for a firing angle of 50°. In case one of the 4 SCRs gets open circuited. Find the new value of average load current assuming the output current as continuous.

3. For the single phase fully controlled bridge converter having load of 'R', determine the average output voltage, rms output voltage and input power factor if the supply is 230V, 50 Hz, single phase AC and the firing angle is 60 degrees

Operation of three phase half wave rectifier with R and RL loads





Input and output waveforms of three phase half wave rectifier

Three phase supply voltage equations

We define three line neutral voltages (3 phase voltages) as follows

$V_{RN} = V_{an} = V_m \sin wt$ where V_m is the maximum voltage

$V_{YN} = V_{bn} = V_m \sin\left(wt - \frac{2\pi}{3}\right)$

$V_{BN} = V_{cn} = V_m \sin\left(wt - \frac{4\pi}{3}\right)$

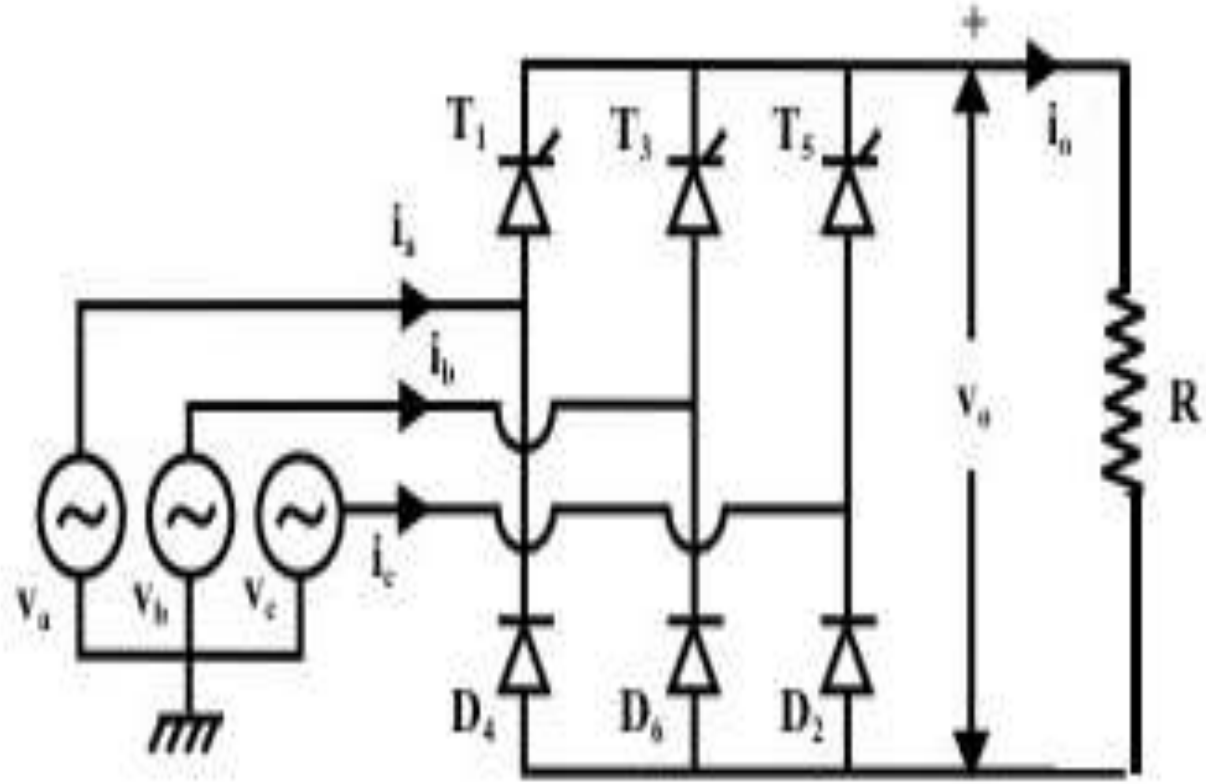
$$V_{avg} = \frac{3}{2\pi} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} Vm \sin wt \; d(wt)$$

$$= \frac{3Vm}{2\pi}\left[(-\cos\alpha)_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha}\right]$$

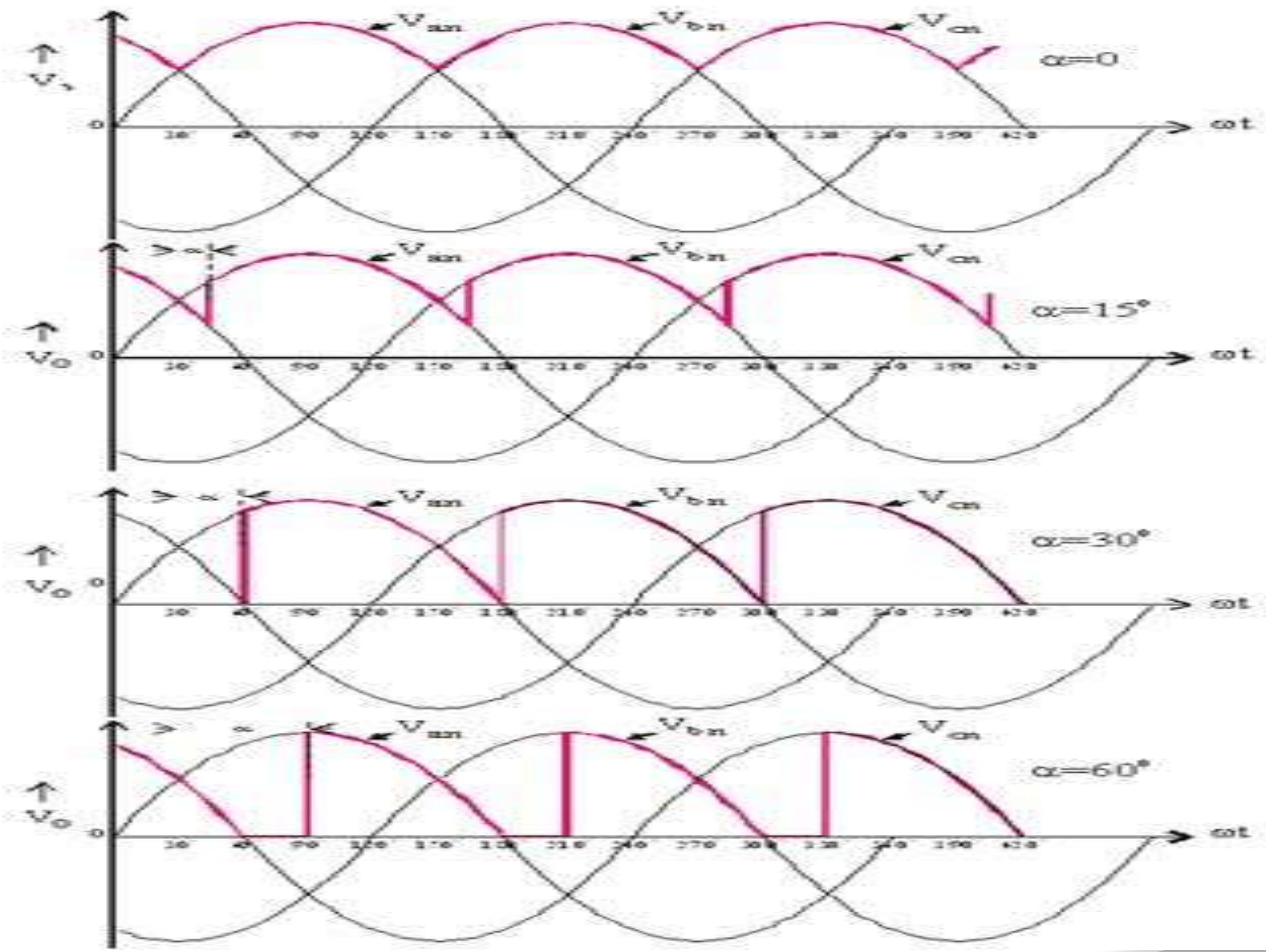
$$= \frac{3\sqrt{3}Vm}{2\pi} \cos\alpha$$

$$= \frac{3Vml}{2\pi} \cos\alpha$$

Operation of three phase half controlled rectifier with R and RL loads



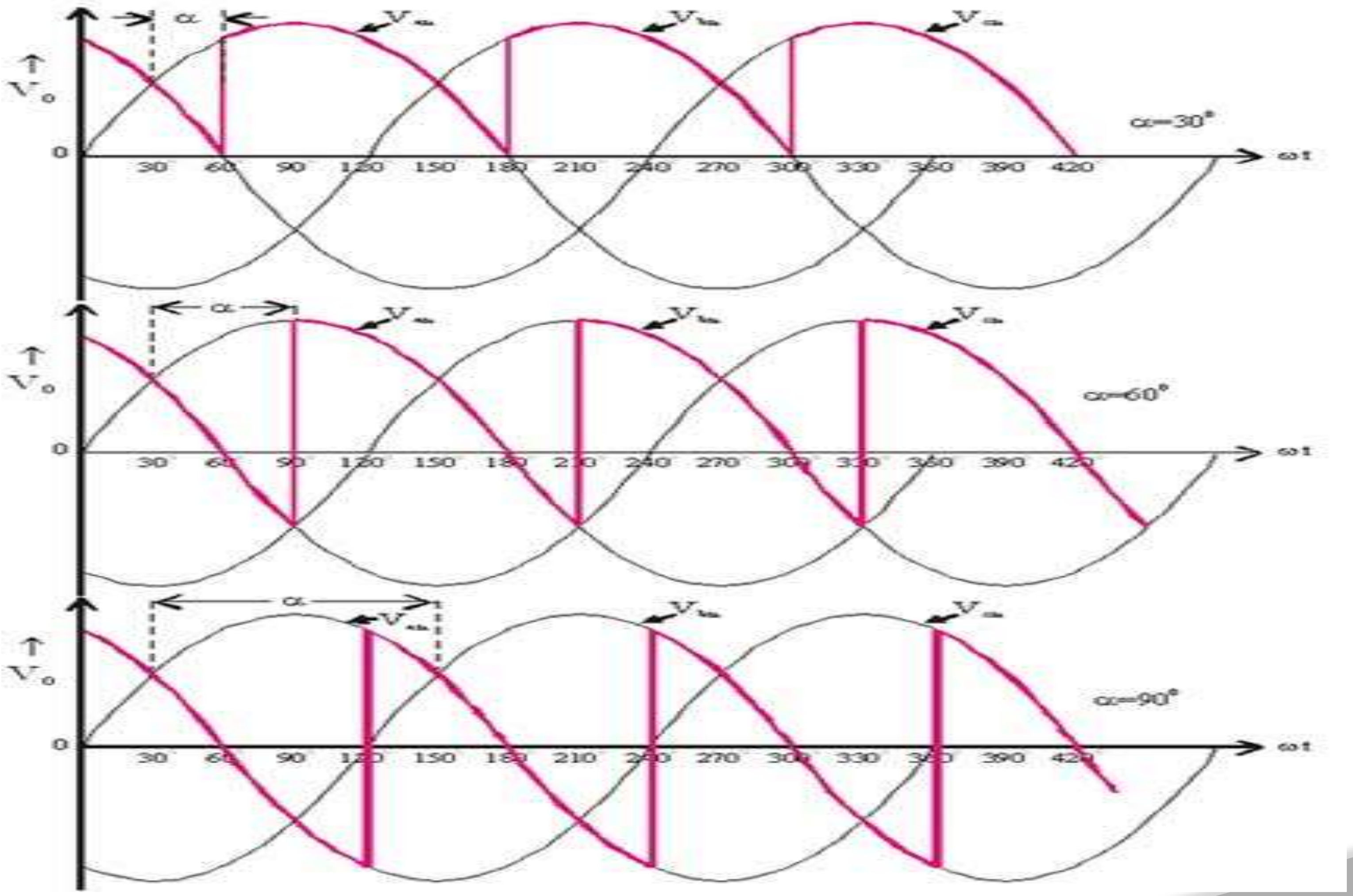
circuit diagram three phase half controlled rectifier



Input and output waveforms of three phase half controlled rectifier with R load

$$V_{avg} = \frac{3}{2\pi}\int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}} Vml\sin wt \, d(wt) + \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}+\alpha} Vml\sin wt \, d(wt)$$

$$= \frac{3Vml}{2\pi}(1 + \cos\alpha)$$



Input and output waveforms of three phase half controlled rectifier with RL load

Numerical Problems

1. A three phase semi converter feeds power to a resistive load of 10Ω. For a firing angle delay of 30^0 the load takes 5 Kw. Find the magnitude of per phase input supply voltage.

Solution:

$$V_{or} = \left[\frac{3}{2\pi}\left[\int_{-\left(\frac{\pi}{6}-\alpha\right)}^{\frac{\pi}{6}} Vml^2 \sin^2 wt\, d(wt) + \int_{-\frac{\pi}{6}}^{\frac{\pi}{6}+\alpha} Vml^2 \sin^2 wt\, d(wt)\right]\right]^{1/2}$$

$$V_{or}^2 = \frac{3Vml^2}{4\pi}\left[\left|wt + \frac{\sin 2wt}{2}\right|_{-\left(\frac{\pi}{6}-\alpha\right)}^{-\frac{\pi}{6}} + \left|wt + \frac{\sin 2wt}{2}\right|_{-\left(\frac{\pi}{6}\right)}^{\frac{\pi}{6}+\alpha}\right]$$

$$V_{or} = \frac{Vml}{2}\sqrt{\frac{3}{\pi}}\left[\frac{2\pi}{3} + \frac{\sqrt{3}}{2}(1 + \cos 2\alpha)\right]^{1/2}$$

For $\alpha = 30^0$

$$P = V^2/R$$

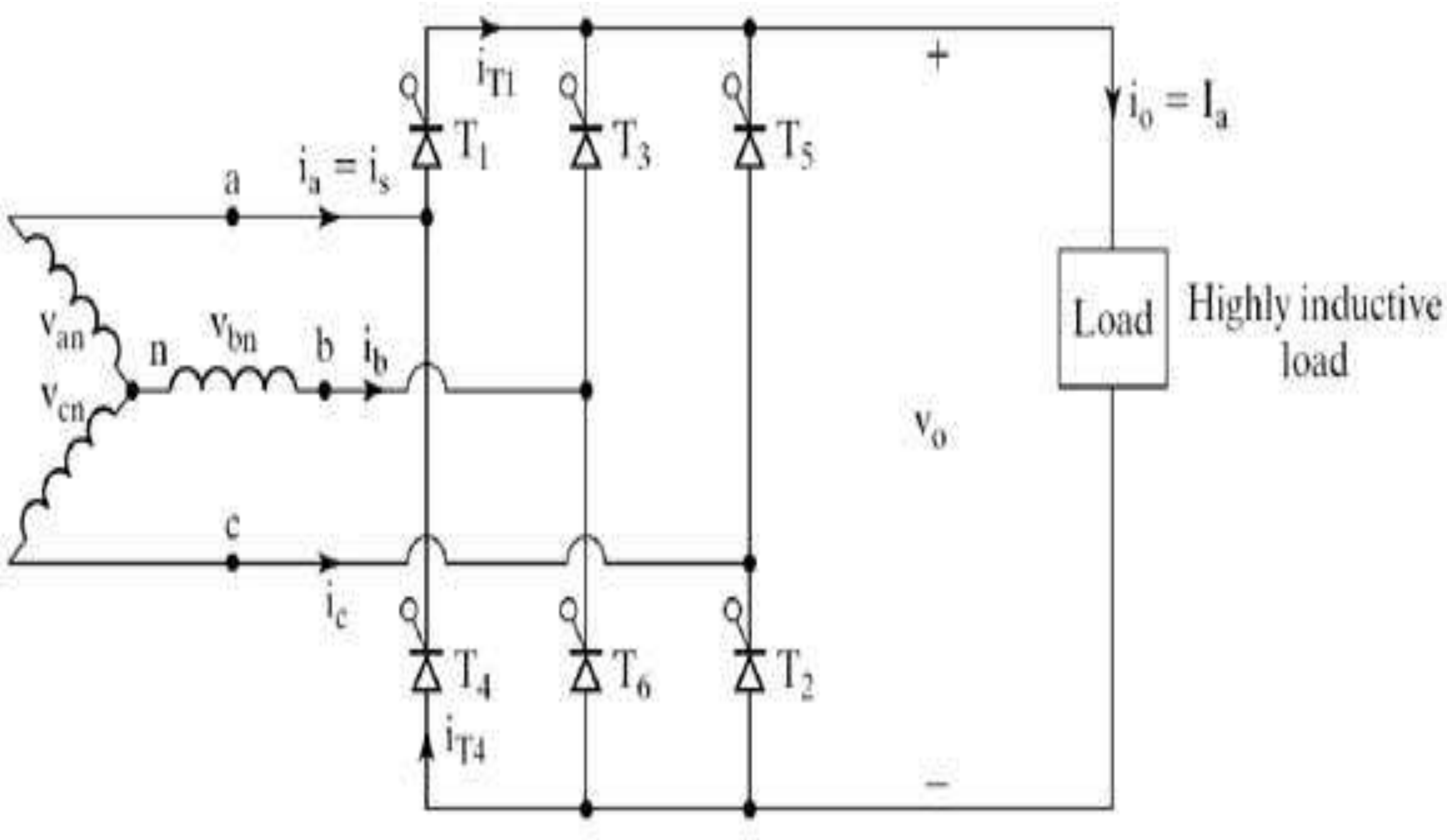
$$5000 \text{x} 10 = \frac{2Vs^2}{4}\frac{3}{\pi}\left[\frac{2\pi}{3} + \frac{\sqrt{3}}{2}(1 + \cos 60)\right]$$

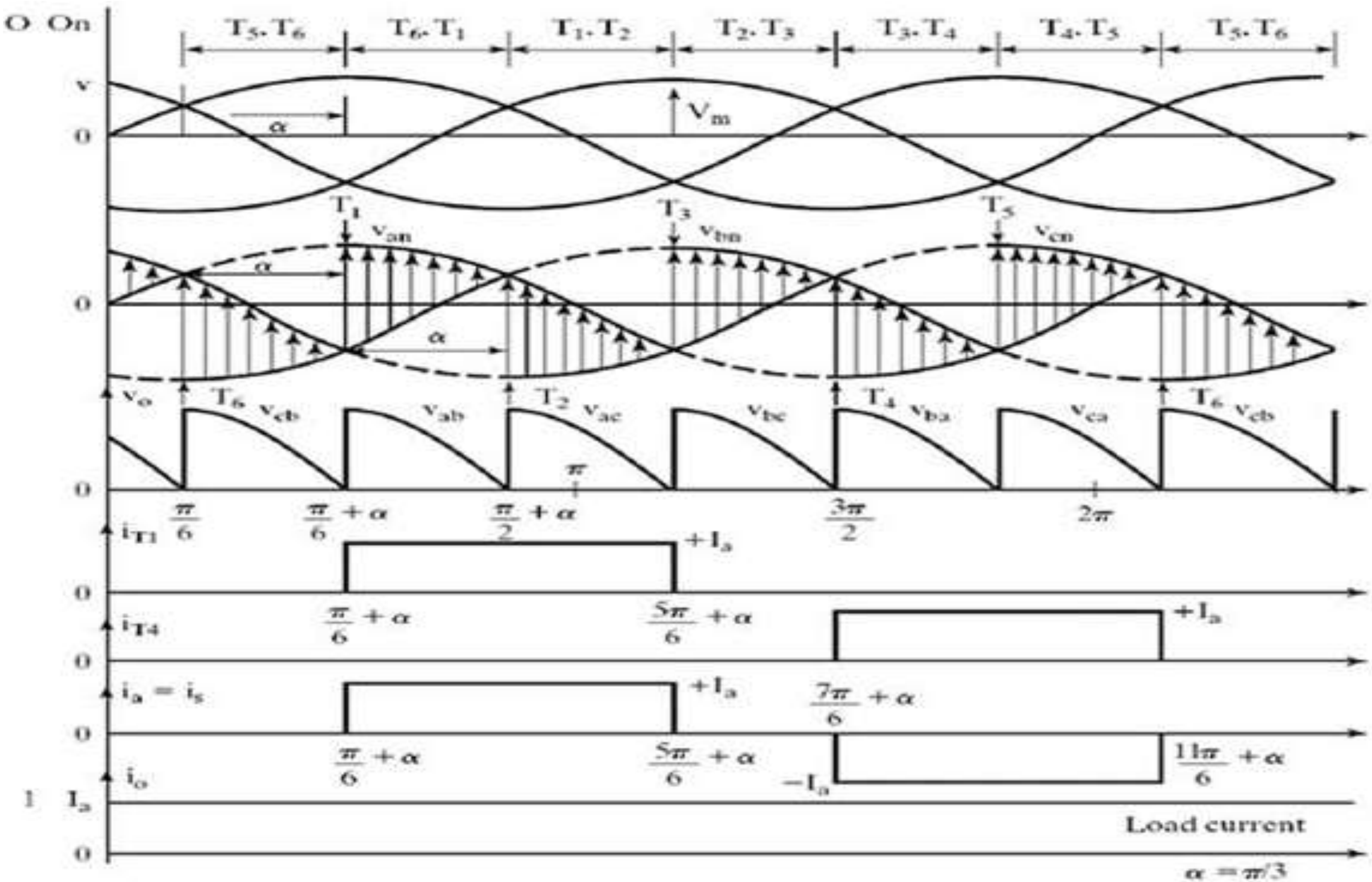
$V_s = 175.67V$ and $V_{ph} = 101.43V$

2. A three-phase half-wave controlled rectifier has a supply of 200V/phase. Determine the average load voltage for firing angle of 0^o, $30^o$and 60^o assuming a thyristor volt drop of 1.5V and continuous load current

3 A three phase half wave converter is supplying a load with a continuous constant current of 50A over a firing angle from 0^o to 60^0. What will be the power dissipated by the load at these limiting values of firing angle. The supply voltage is 415V (line).

Three phase fully controlled rectifier with R and RL loads





Input and output waveforms of three phase fully controlled rectifier

$V_{RN} = V_{an} = V_m \sin wt$ where V_m is the maximum voltage

$$V_{YN} = V_{bn} = V_m \sin \left(wt - \frac{2\pi}{3}\right)$$

$$V_{BN} = V_{cn} = V_m \sin \left(wt - \frac{4\pi}{3}\right)$$

The corresponding line to line voltages are

$$V_{RY} = V_{ab} = V_{an} - V_{bn} = \sqrt{3}\, Vm \sin\left(wt + \frac{\pi}{6}\right)$$

$$V_{YB} = V_{bc} = V_{bn} - V_{cn} = \sqrt{3}\, Vm \sin\left(wt - \frac{\pi}{2}\right)$$

$$V_{BR} = V_{ca} = V_{cn} - V_{an} = \sqrt{3}\, Vm \sin\left(wt + \frac{\pi}{2}\right)$$

$$V_{avg} = \frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} V_o d(wt)$$

$$V_o = V_{ab} = \sqrt{3}\, Vm \sin\left(wt + \frac{\pi}{6}\right)$$

$$V_{avg} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3}\, Vm \sin\left(wt + \frac{\pi}{6}\right) d(wt)$$

$$= \frac{3\sqrt{3}Vm}{\pi} \cos\alpha$$

$$= \frac{3Vml}{\pi} \cos\alpha$$

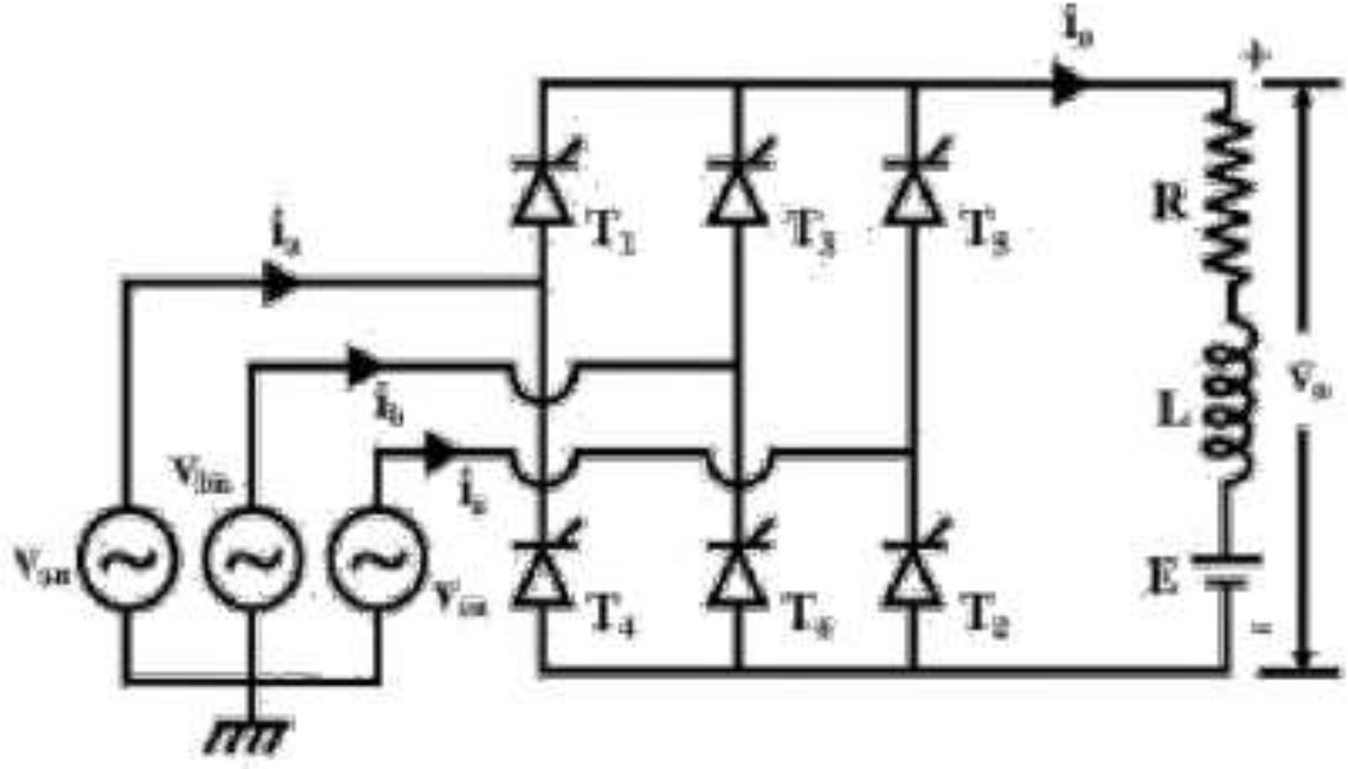
$$V_{orms} = \left[\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} Vo^2\, d(wt)\right]^{1/2}$$

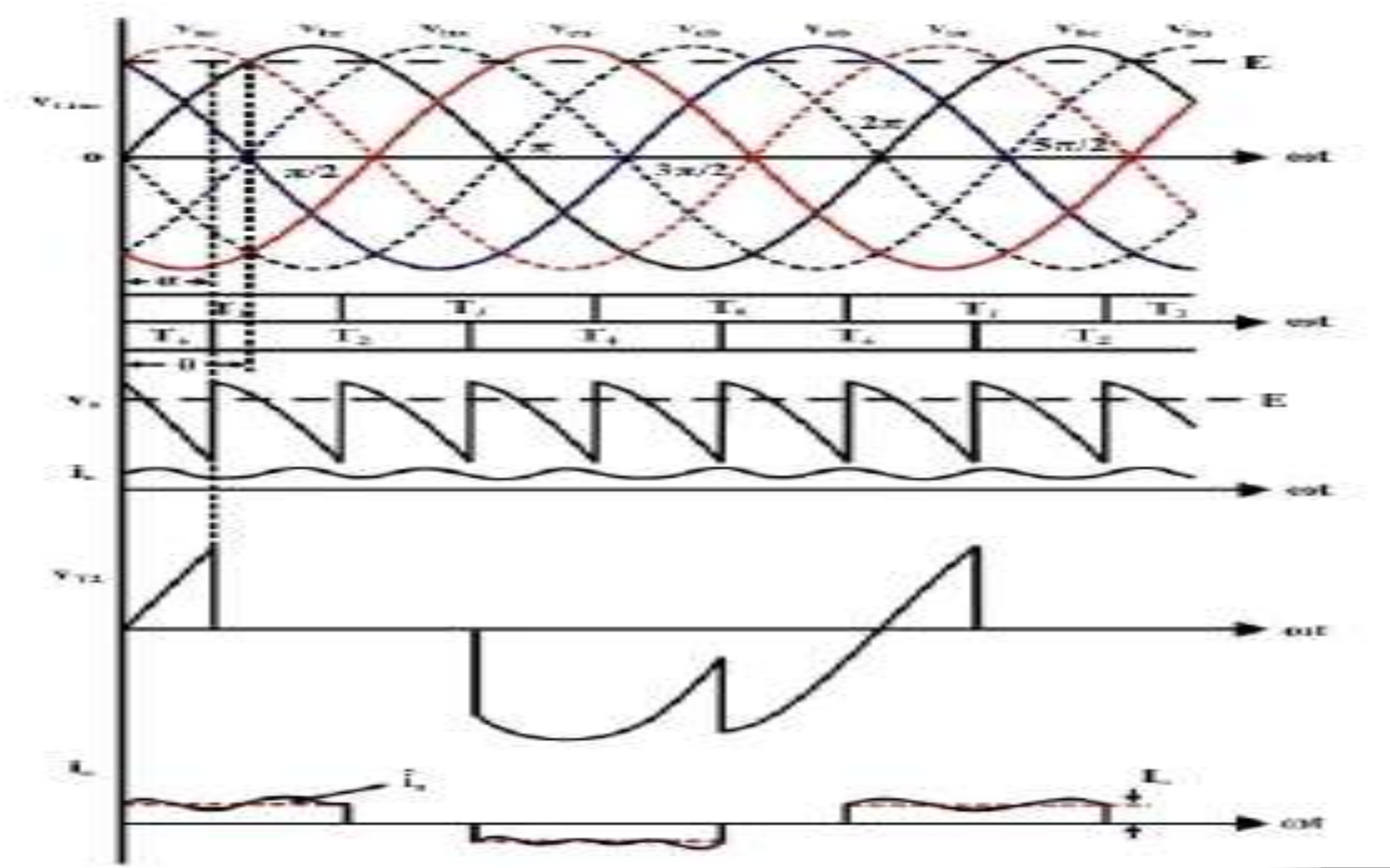
$$= \left[\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} Vab^2\, d(wt)\right]^{1/2}$$

$$= \left[\frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} 3\, Vm^2 \sin^2\left(wt + \frac{\pi}{6}\right) d(wt)\right]^{1/2}$$

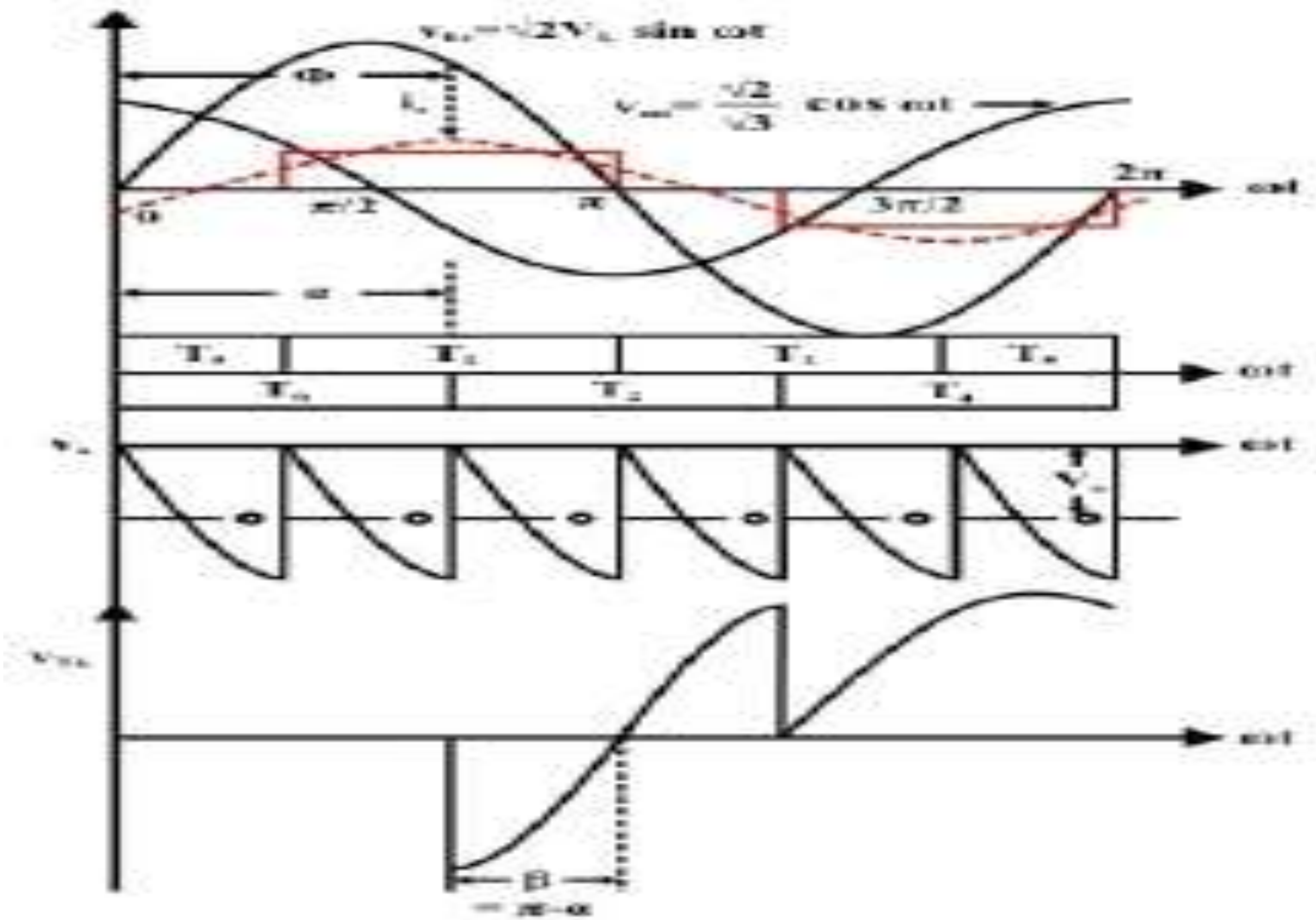
$$= \sqrt{3}Vm\left(\frac{1}{2} + \frac{3\sqrt{3}}{4\pi}cos2\alpha\right)^{1/2}$$

Three phase half wave rectifier with RLE loads



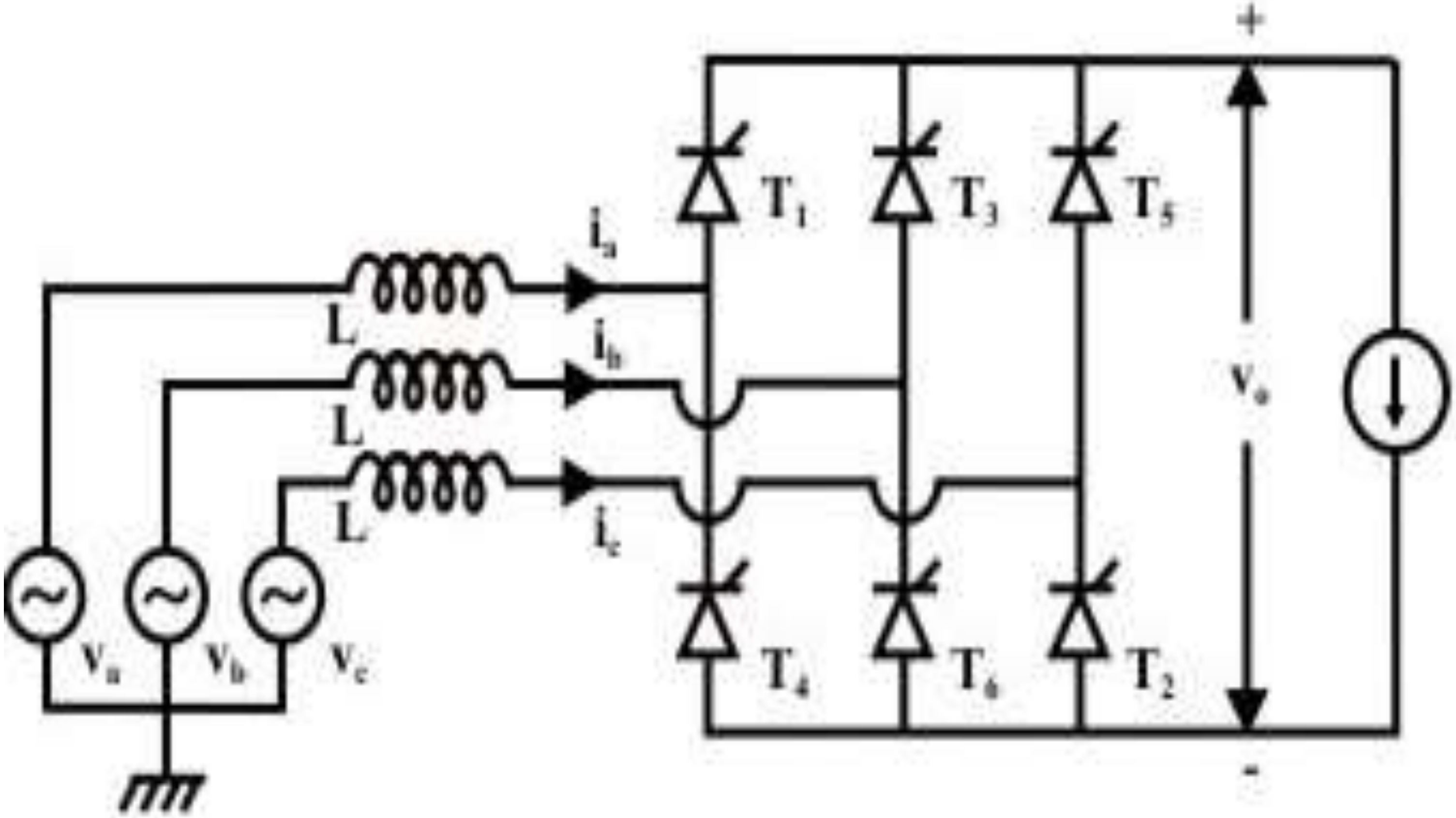


Input and output waveforms of three phase fully controlled rectifier in rectifier mode

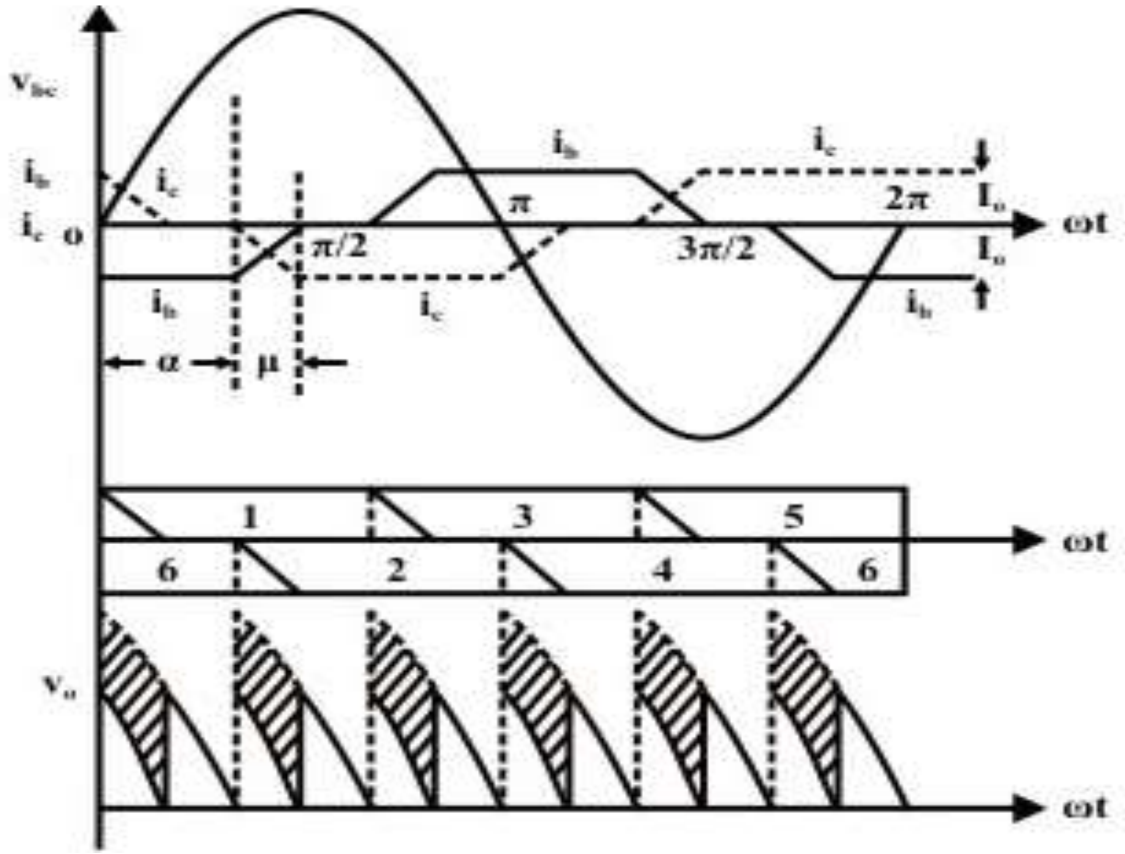


Input and output waveforms of three phase fully controlled rectifier in inversion mode

Effect of source inductance in three phase rectifiers



circuit diagram for three phase rectifier with source inductance



waveforms for three phase rectifier with source inductance

Therefore, in the interval $\alpha < \omega t \le \alpha + \mu$

$$v_b = L\frac{di_b}{dt} - L\frac{di_c}{dt} + v_c$$

or, $$v_{bc} = L\frac{d}{dt}(i_b - i_c)$$

but $i_b + i_c + I_o = 0$ $\therefore$ $\frac{di_b}{dt} = -\frac{di_c}{dt}$

$\therefore$ $$2L\frac{d}{dt}i_b = v_{bc} = \sqrt{2}V_L \sin\omega t$$

$\therefore$ $$i_b = C - \frac{\sqrt{2}V_L}{2\omega L}\cos\omega t$$

at $\omega t = \alpha$, $i_b = -I_0$ $\therefore$ $C = \frac{\sqrt{2}V_L}{2\omega L}\cos\alpha - I_0$

$\therefore$ $$i_b = \frac{\sqrt{2}V_L}{2\omega L}(\cos\alpha - \cos\omega t) - I_0$$

at $\omega t = \alpha + \mu$, $i_b = 0$

$\therefore$ $$\frac{\sqrt{2}V_L}{2\omega L}(\cos\alpha - \cos(\alpha + \mu)) = I_0$$

Or, $$\cos\alpha - \cos(\alpha + \mu) = \frac{\sqrt{2}\omega L}{V_L}I_0$$

for $\mu \le 60°$. It can be shown that for this condition to be satisfied

$$I_0 \le \frac{V_L}{\sqrt{2}\omega L} \cos\left(\alpha - \frac{\pi}{3}\right)$$

To calculate the dc voltage

For $\alpha \le \omega t \le \alpha + \mu$

$$v_0 = v_a - v_b + L\frac{di_b}{d_t} = \frac{3}{2}v_a$$

for $\alpha + \mu \le \omega t \le \alpha + \frac{\pi}{3}$ $\qquad v_0 = v_{ac}$

$$\therefore \qquad V_0 = \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\mu} \frac{3}{2} v_a \, d\omega t + \int_{\alpha+\mu}^{\alpha+\frac{\pi}{3}} v_{ac} \, d\omega t\right]$$

$$= \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\mu}\left(v_{ac} + \frac{3}{2}v_{a} - v_{ac}\right) + \int_{\alpha+\mu}^{\alpha+\frac{\pi}{3}} v_{ac}\, d\omega t\right]$$

$$= \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\frac{\pi}{3}} v_{ac}\, d\omega t + \int_{\alpha}^{\alpha+\mu}\left(\frac{v_{a}}{2} + v_{c}\right) d\omega t\right]$$

$$= \frac{3\sqrt{2}}{\pi} V_L \cos\alpha - \frac{3}{2\pi}\int_{\alpha}^{\alpha+\mu} v_{bc}\, d\omega t$$

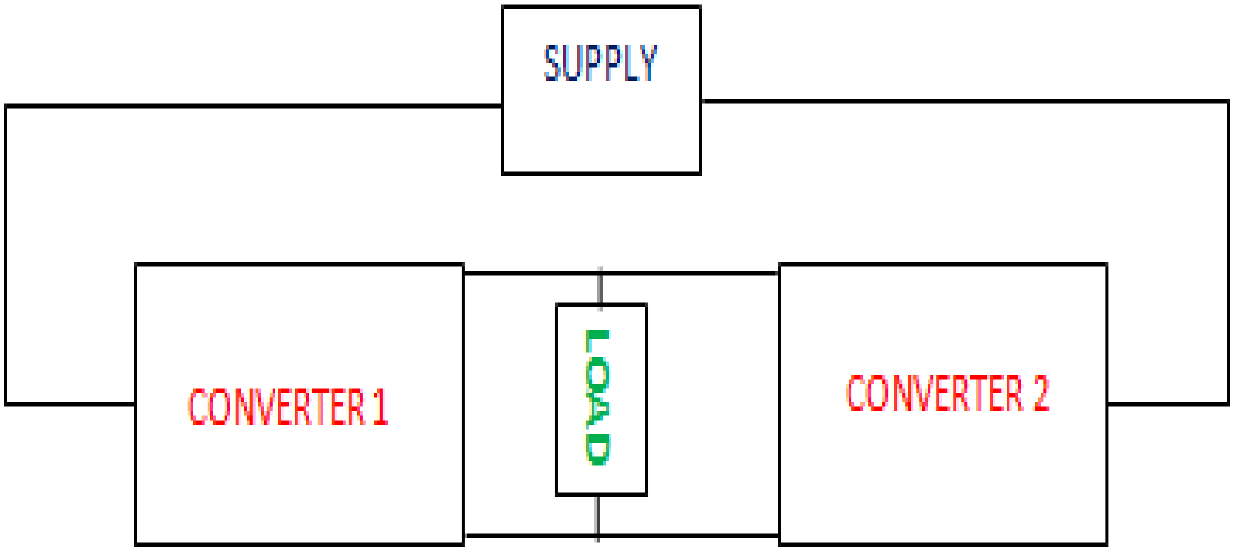
or $$V_o = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha - \frac{3\sqrt{2}V_L}{2\pi}\int_{\alpha}^{\alpha+\mu} \sin\omega t\, d\omega t$$

$$= \frac{3\sqrt{2}}{\pi} V_L \cos\alpha - \frac{3\sqrt{2}V_L}{2\pi}[\cos\alpha - \cos(\alpha + \mu)]$$

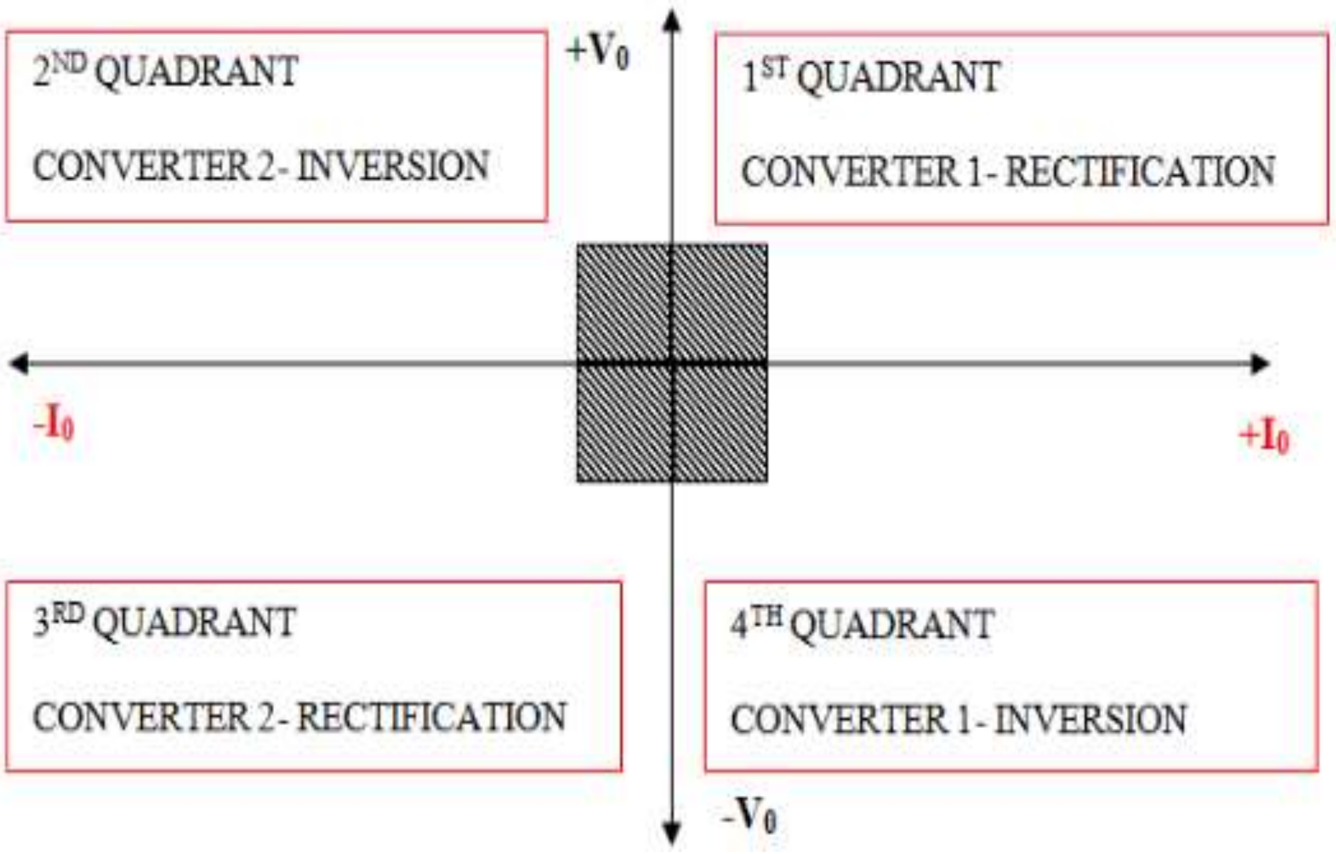
$$V_o = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha - \frac{3}{\pi}\omega L\, I_o$$

Dual converters

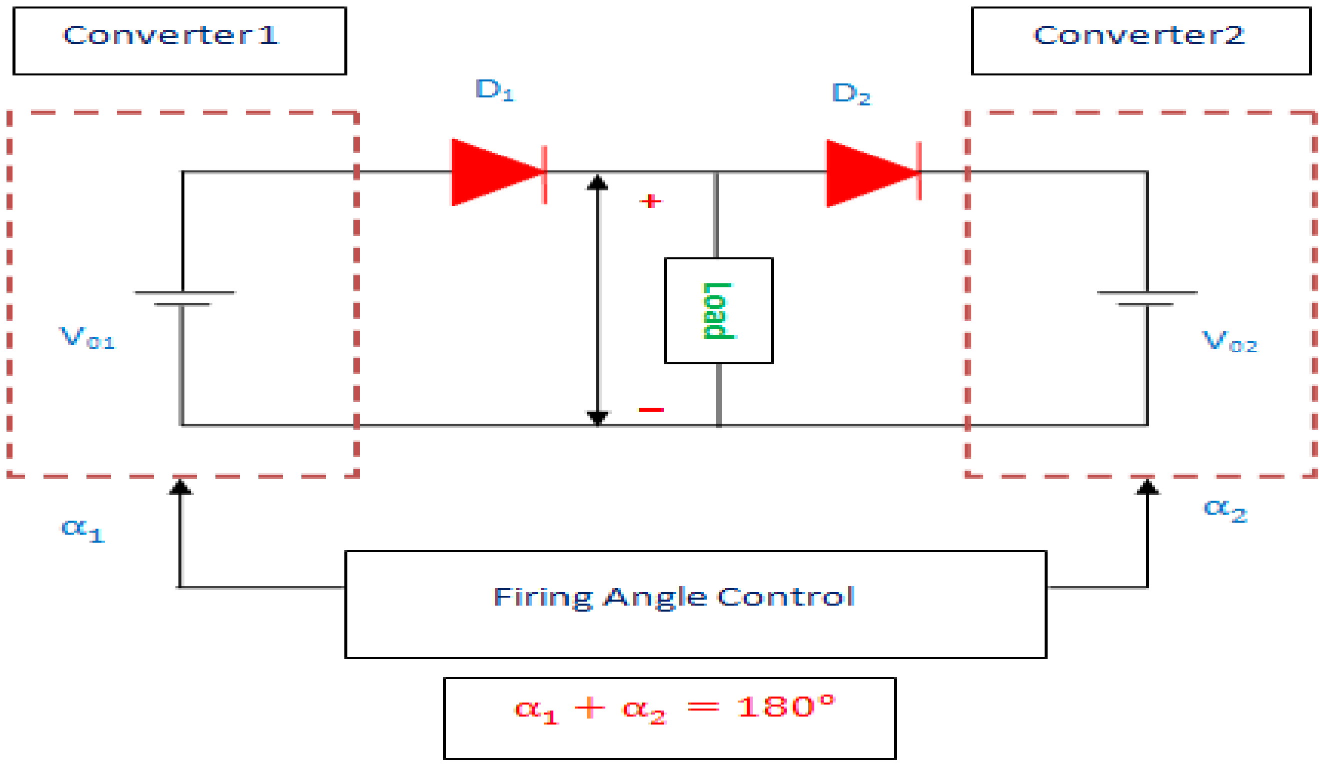
- Dual converter, the name itself says two converters. It is really an electronic converter or circuit which comprises of two converters. One will perform as rectifier and the other will perform as inverter. Therefore, we can say that double processes will occur at a moment. Here, two full converters are arranged in anti-parallel pattern and linked to the same dc load. These converters can provide four quadrant operations.



Block diagram of dual converter

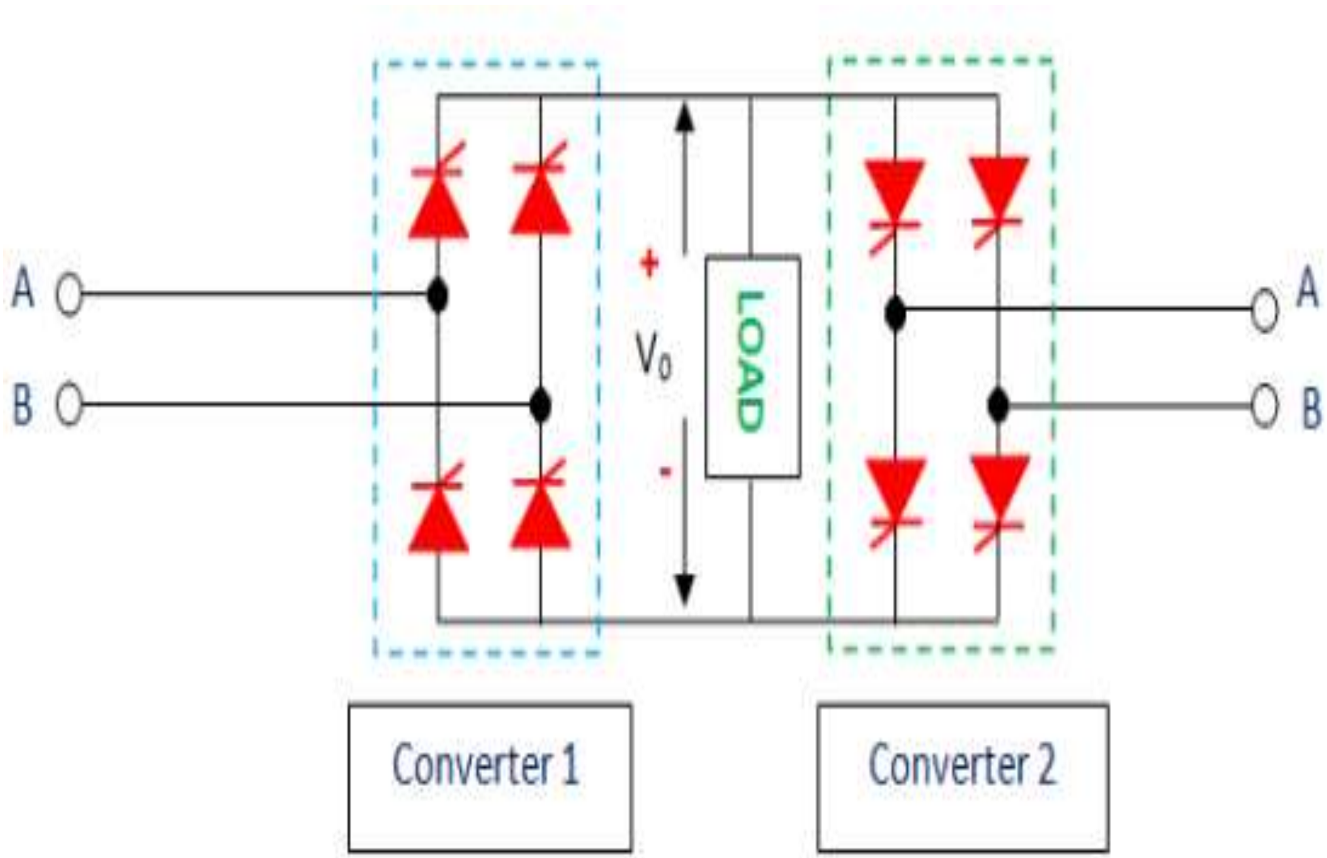


Four quadrant operations of dual converter



Ideal dual converter

Single Phase Dual Converter



Single phase Dual converter

Average output voltage of Single-phase converter= $\dfrac{2V_m Cos\ \alpha}{\pi}$

Average output voltage of Three-phase converter = $\dfrac{3V_{ml} Cos\ \alpha}{\pi}$

For converter 1, the average output voltage, $V_{01} = V_{max} Cos\alpha_1$

For converter 2, the average output voltage, $V_{02} = V_{max} Cos\alpha_2$

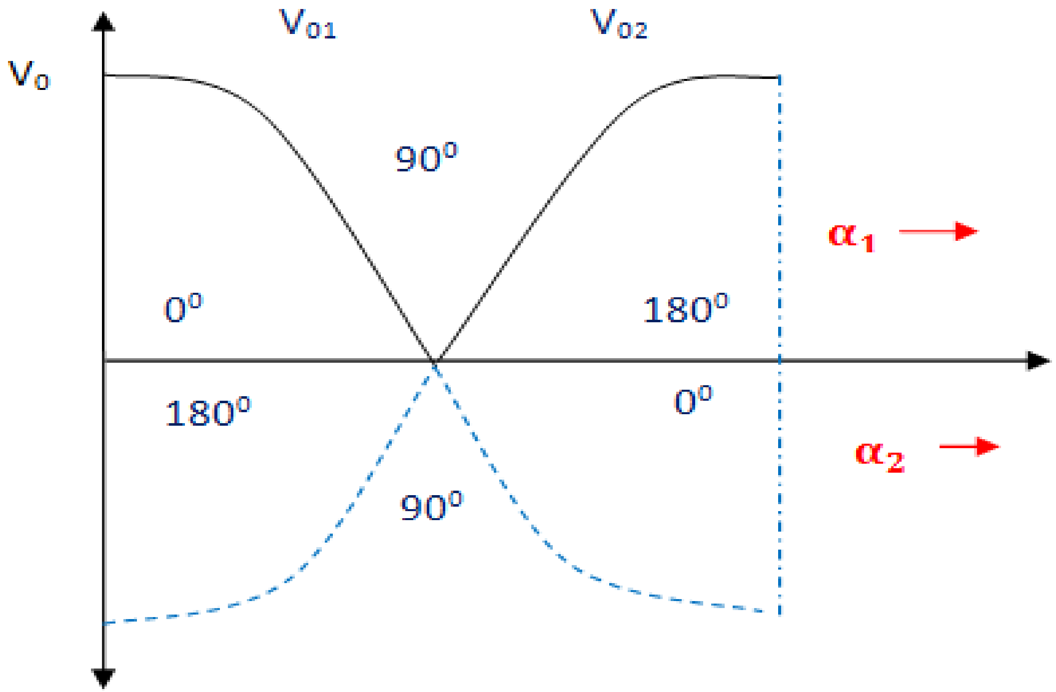
$$V_0 = V_{01} = -V_{02}$$

$$V_{max} Cos\alpha_1 = -V_{max} Cos\alpha_2$$

$$Cos\alpha_1 = Cos(180^o - \alpha_2) \; or \; Cos\alpha_2 = Cos(180^o + \alpha_2)$$

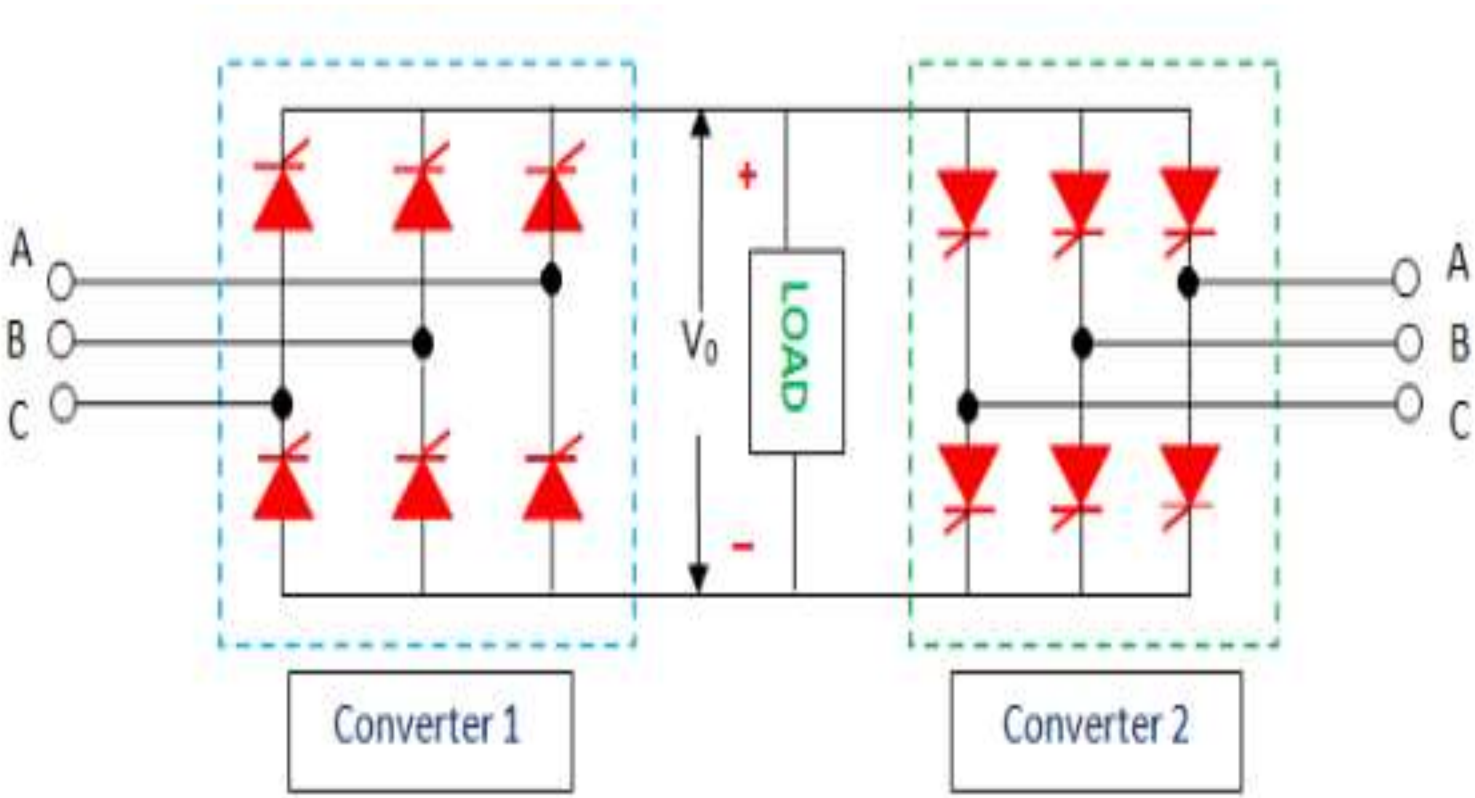
Output voltage, $\alpha_1 + \alpha_2 = 180^o \; And \; \alpha_1 - \alpha_2 = 180^o$

The firing angle can never be greater than 180°. So, $\alpha_1 + \alpha_2 = 180^o$



output voltage variation with firing angle

Three Phase Dual Converter



Three phase dual converter

Application of Dual Converter

- Direction and Speed control of DC motors.
- Applicable wherever the reversible DC is required.
- Industrial variable speed DC drives.

UNIT III
AC VOLTAGE CONTROLLERS AND CYCLOCONVERTERS

AC voltage controllers

- AC voltage controllers (ac line voltage controllers) are employed to vary the RMS value of the alternating voltage applied to a load circuit by introducing Thyristors between the load and a constant voltage ac source. The RMS value of alternating voltage applied to a load circuit is controlled by controlling the triggering angle of the Thyristors in the AC Voltage Controller circuits.

  Control strategies: There are two different types of thyristor control used in practice to control the ac power flow

- On-Off control
- Phase control

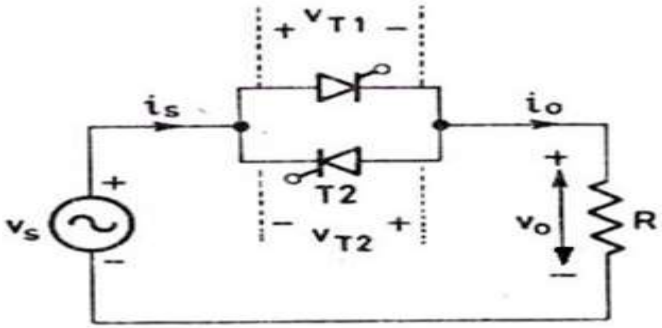
Phase control

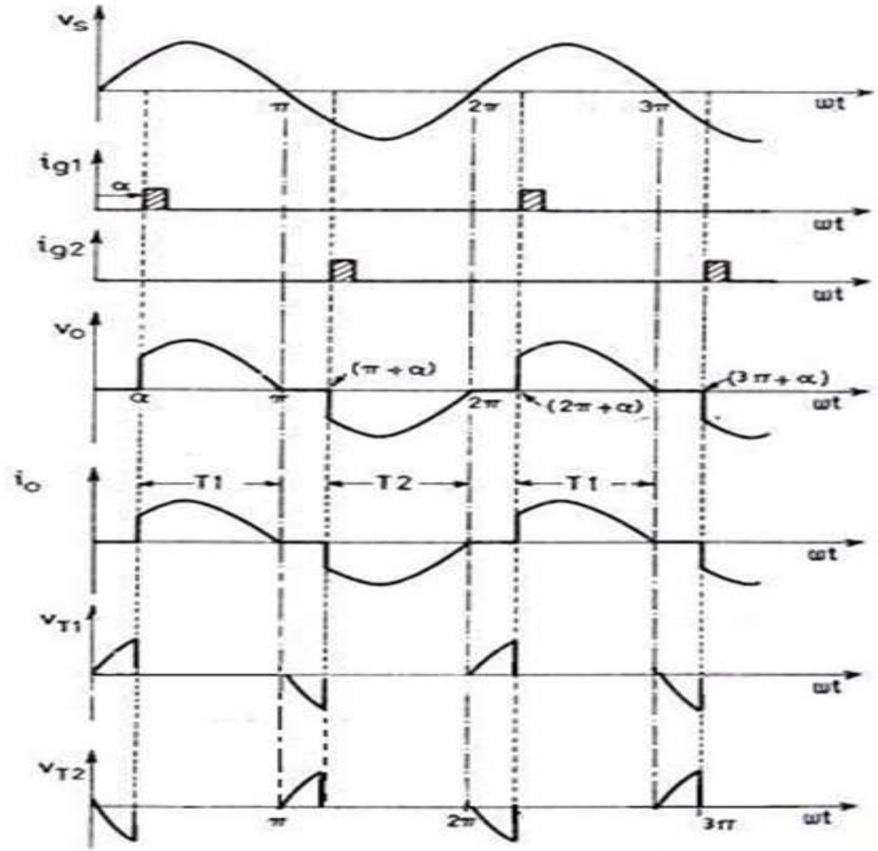
- In phase control the Thyristors are used as switches to connect the load circuit to the input ac supply, for a part of every input cycle. That is the ac supply voltage is chopped using Thyristors during a part of each input cycle.
- The thyristor switch is turned on for a part of every half cycle, so that input supply voltage appears across the load and then turned off during the remaining part of input half cycle to disconnect the ac supply from the load.

Applications of ac voltage controllers

- Lighting / Illumination control in ac power circuits.
- Induction heating.
- Industrial heating & Domestic heating.
- Transformers tap changing (on load transformer tap changing).
- Speed control of induction motors (single phase and poly phase ac induction motor control).
- AC magnet controls.

Single phase AC voltage controller with R load





Circuit diagram and output waveforms of AC voltage controller with R load

- AC to AC voltage converters operates on the AC mains essentially to regulate the output voltage. Portions of the supply sinusoid appear at the load while the semiconductor switches block the remaining portions. Several topologies have emerged along with voltage regulation methods, most of which are linked to the development of the semiconductor devices.

$$V_{rms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi} 2V^2 \sin^2 \omega t \quad d\omega t}$$

$$= V\sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}}$$

$$power \quad factor = \frac{average \quad power}{apparent \quad voltamperes} = \frac{P}{VI_L}$$

$$= \frac{VI_{L1}\cos\phi_1}{VI_L}$$

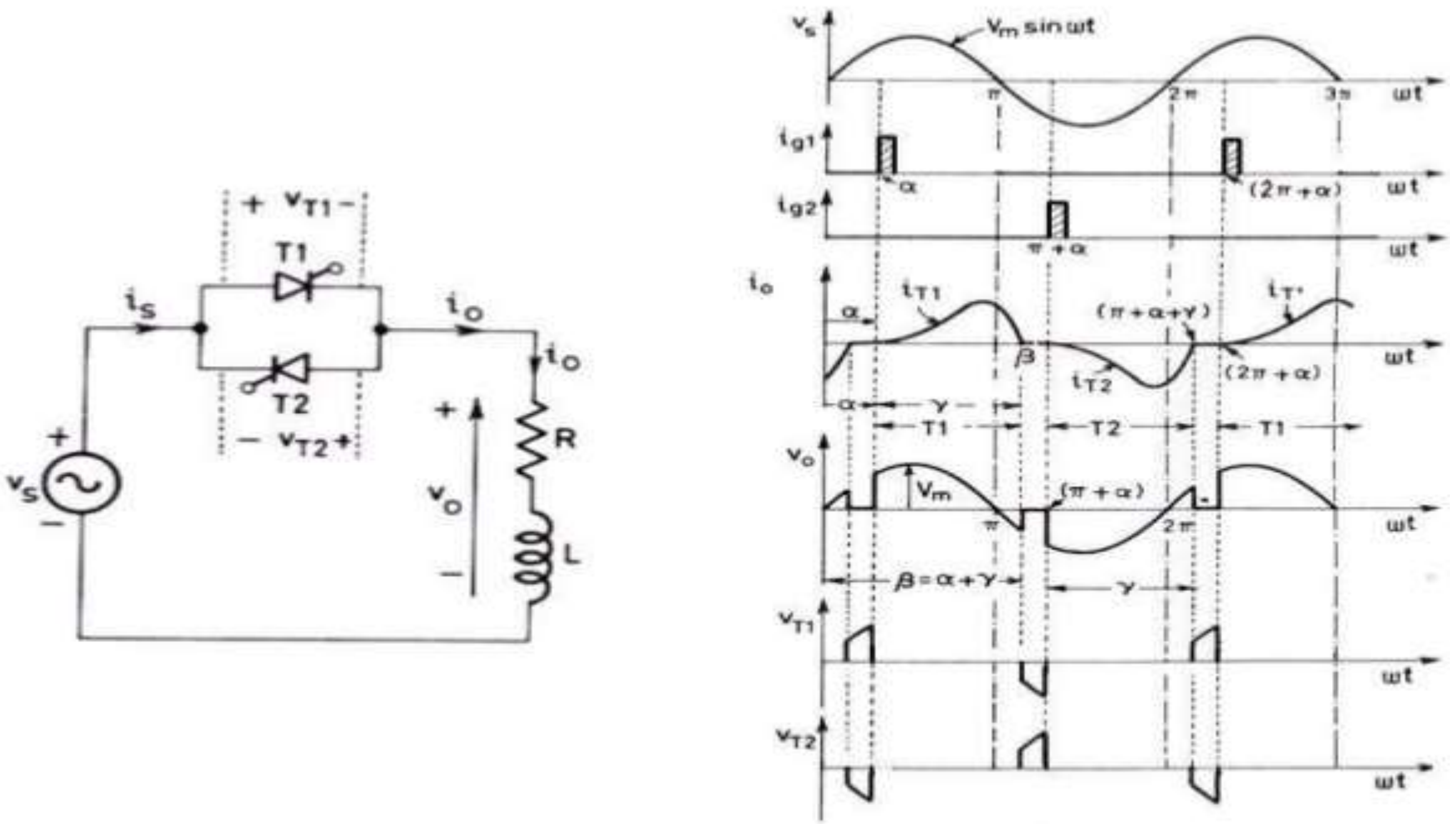
$$distortion \quad factor = \frac{I_{L1}}{I_L}$$

The Average Power, P drawn by the resistive load is

$$P = \frac{1}{2\pi}\int_0^{2\pi} vi_L \quad d\omega t \quad = \frac{1}{\pi}\int_{\alpha}^{\pi} \frac{2V^2}{R}\sin^2 \omega t \quad dwt$$

$$= \frac{2V^2}{R\pi}\left[\pi - \frac{\alpha}{2} + \frac{\sin 2\alpha}{2}\right]$$

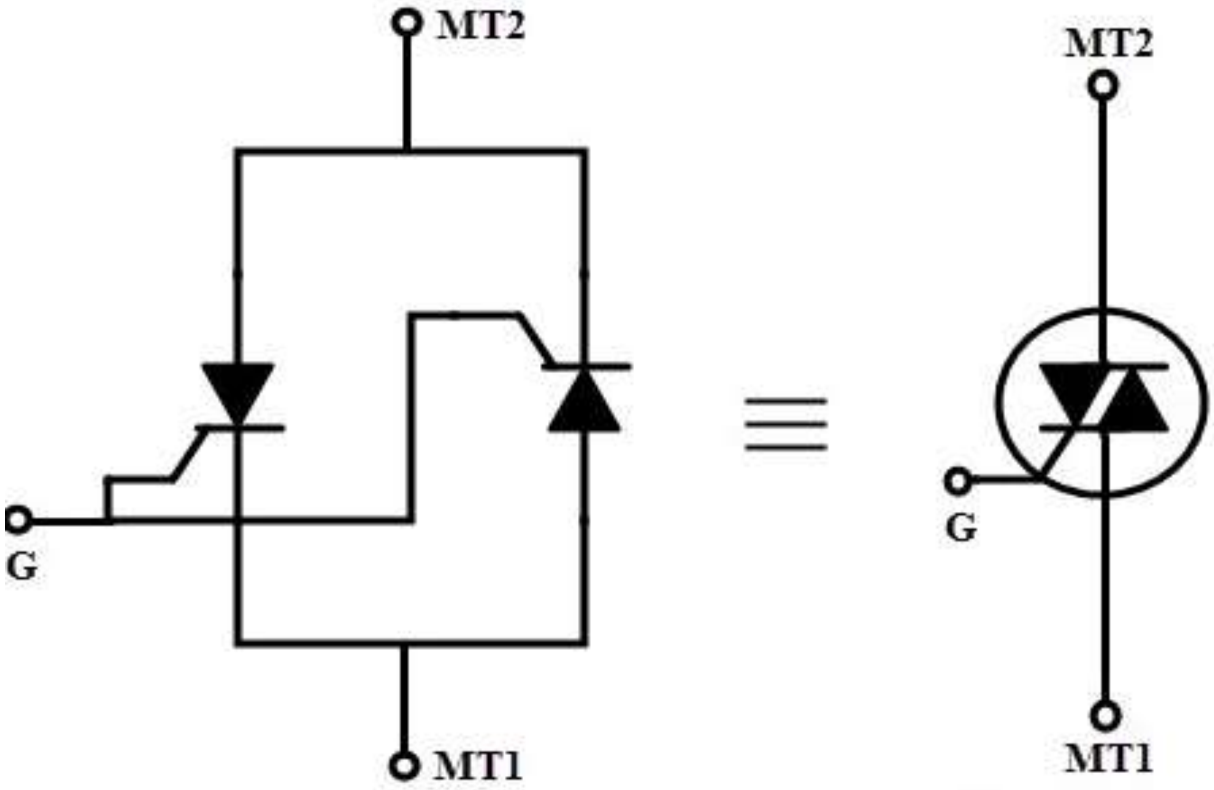
Single phase AC voltage controller with RL load



Circuit diagram and output waveforms of AC voltage controller with RL load

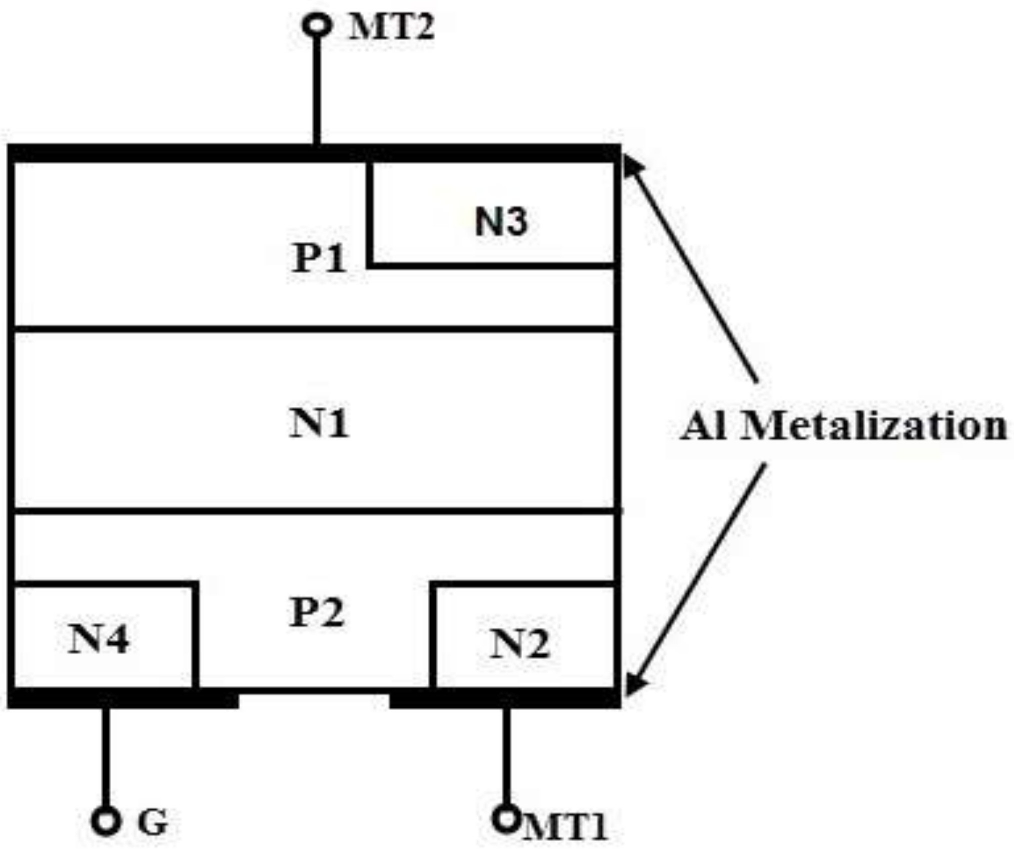
- With inductive loads the operation of the PAC is illustrated in above figure. The current builds up from zero in each cycle. It quenches not at the zero crossing of the applied voltage as with the resistive load but after that instant. The supply voltage thus continues to be impressed on the load till the load current returns to zero. A single-pulse trigger for the TRIAC) or the anti parallel SCR has no effect on the devices if it (or the anti-parallel device) is already in conduction in the reverse direction.

Modes of operation of TRIAC

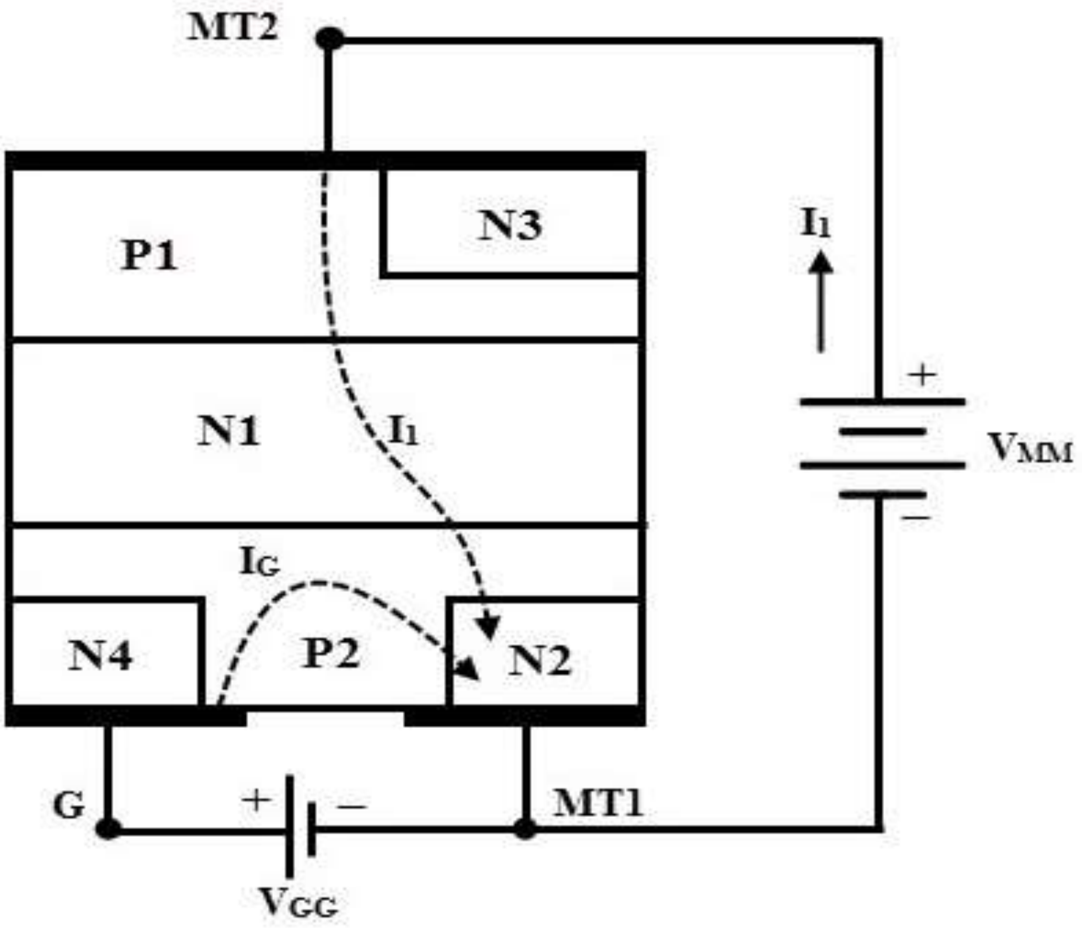


Two thyristor analogy and circuit symbol of TRIAC

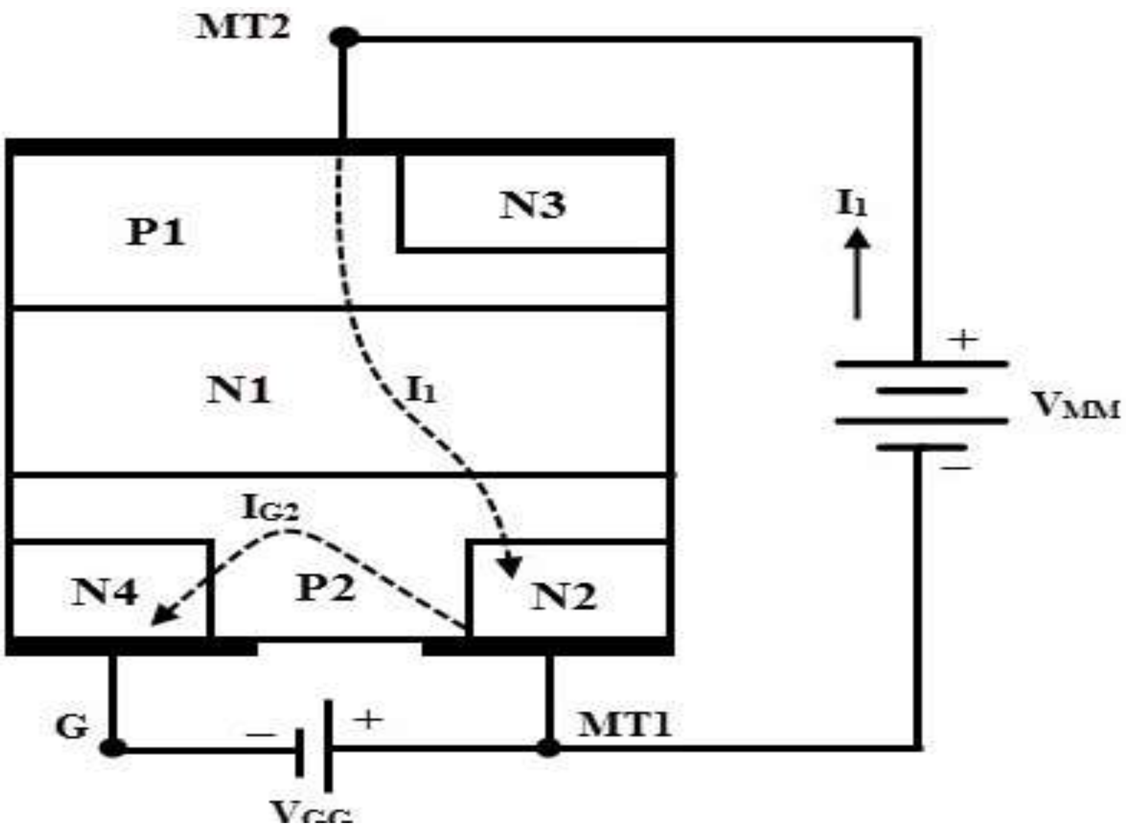
- The triac is an important member of the thyristor family of devices. It is a bidirectional device that can pass the current in both forward and reverse biased conditions and hence it is an AC control device. The triac is equivalent to two back to back SCRs connected with one gate terminal as shown in figure. The triac is an abbreviation for a TRIode AC switch. TRI means that the device consisting of three terminals and AC means that it controls the AC power or it can conduct in both directions of alternating current.



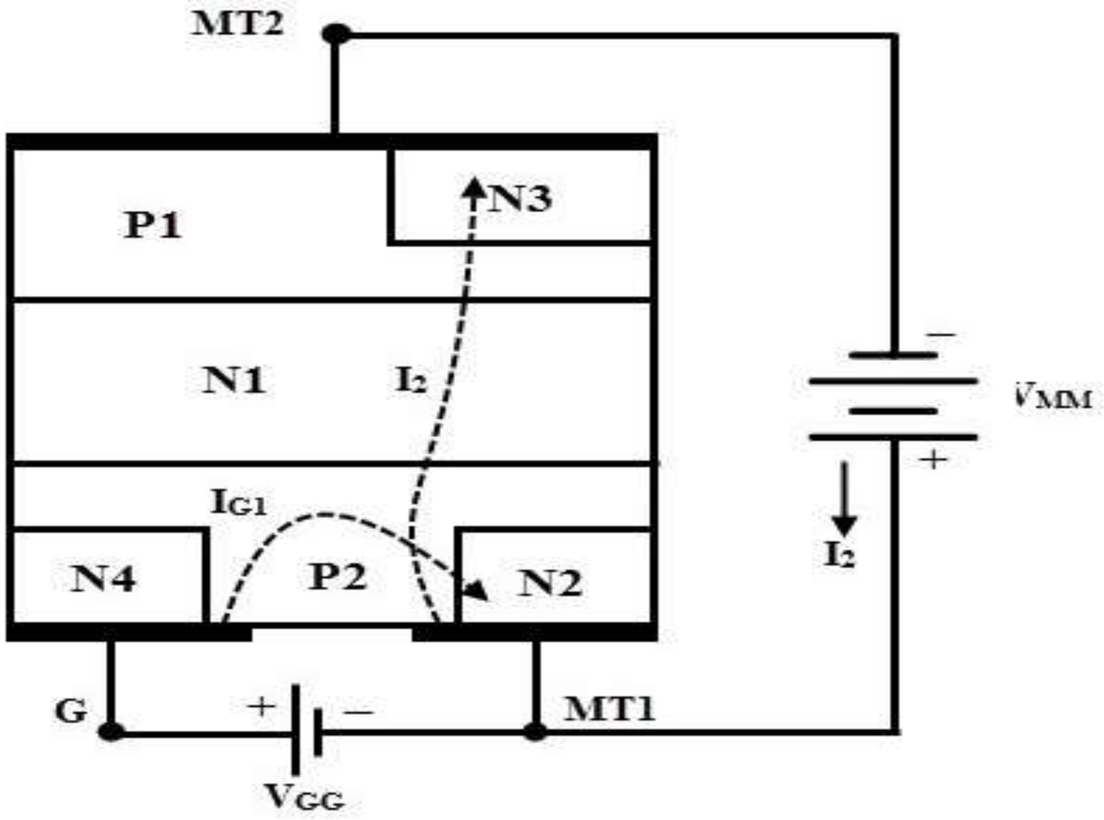
construction of TRIAC



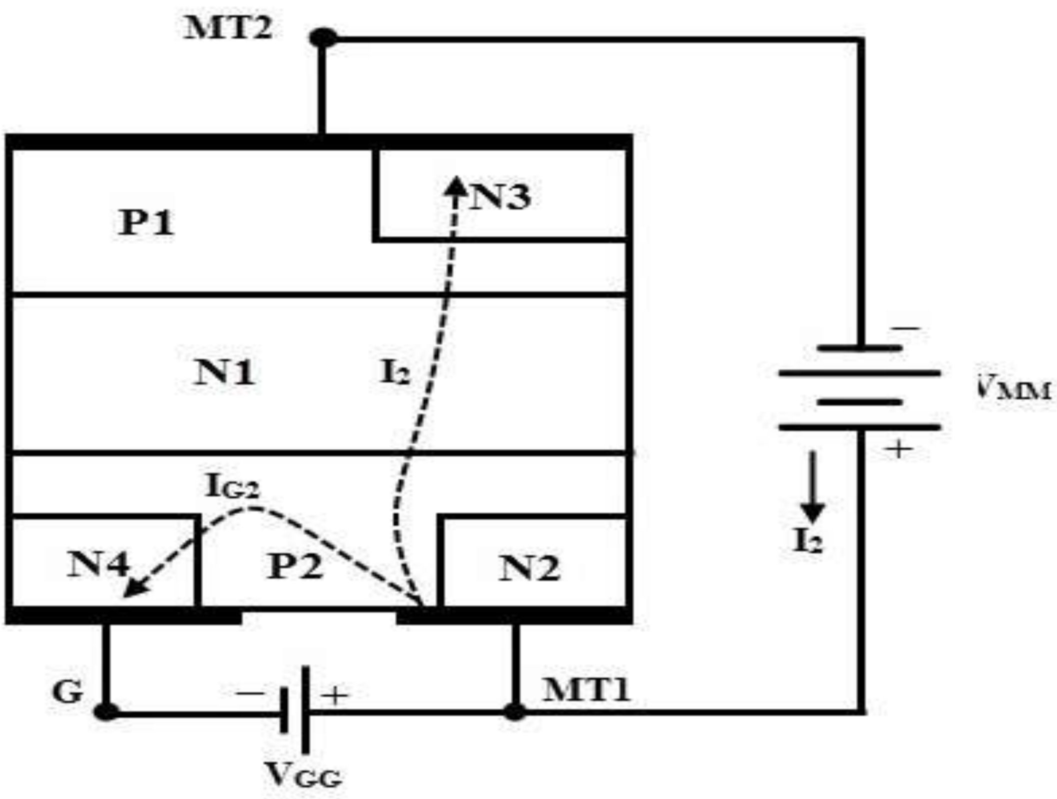
Mode 1 operation of TRIAC



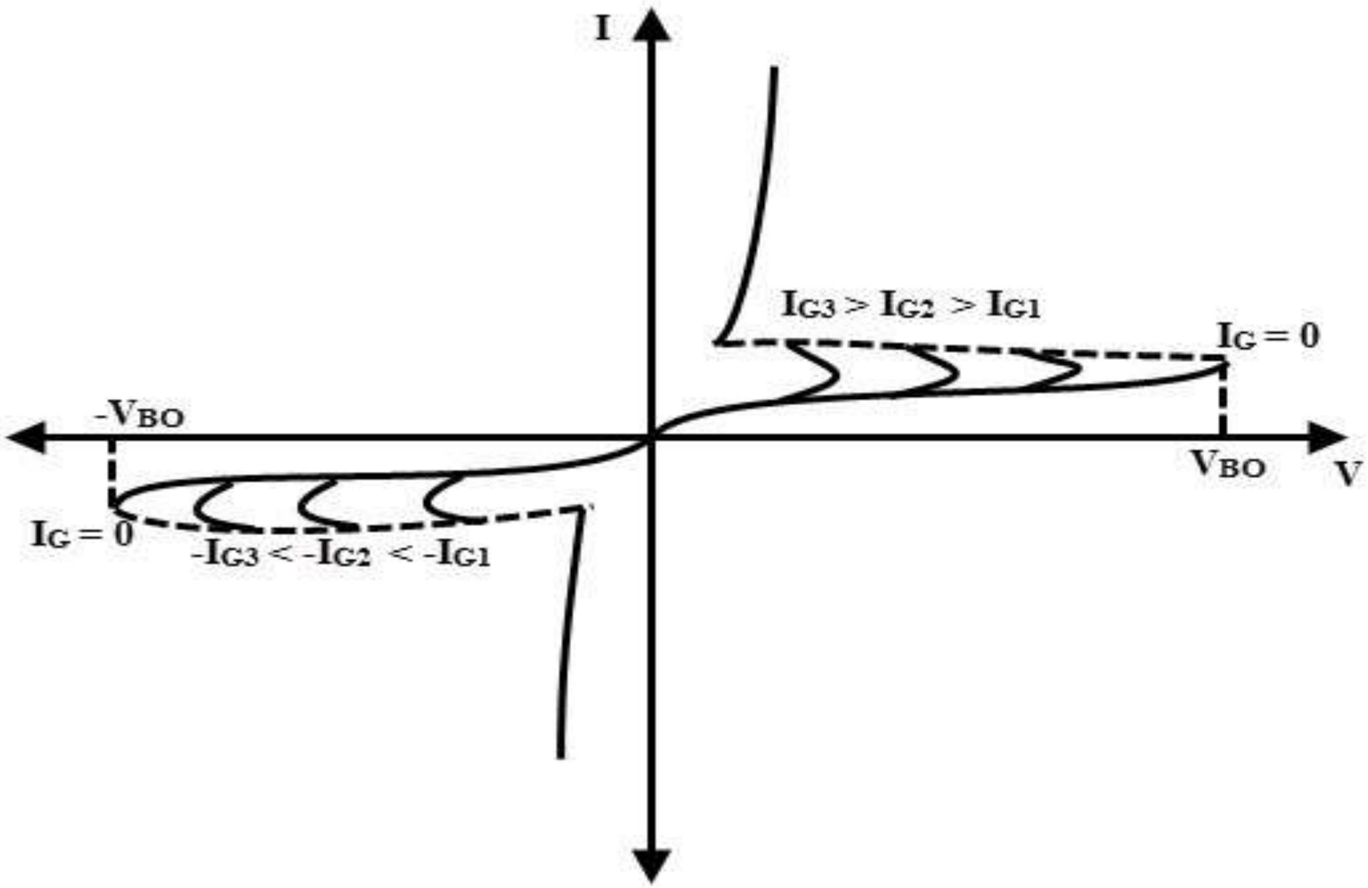
Mode 2 operation of TRIAC



Mode 3 operation of TRIAC



Mode 4 operation of TRIAC



V-I characteristics of TRIAC

Numerical Problems

1. A single phase voltage controller is employed for controlling the power flow from 230V, 50Hz source into a load circuit consisting of R=3 Ω and L=4 Ω. Calculate

(i) the range of firing angle

(ii) the maximum value of rms load current

(iii) the maximum power and power factor

(iv) The maximum values of average and rms thyristor currents.

Solution:

i. For controlling the load the minimum value of firing angle α = load phase angle

$$\varphi = tan^{-1}\frac{wL}{R} = tan^{-1}\frac{4}{3} = 53.13\,^{\circ}$$

The maximum possible value of α is 180^0

So the firing angle control range is $53.13\,^{\circ} \leq \alpha \leq 180^{\circ}$

ii. The maximum value of rms value of load current occurs when $\alpha = \Phi = 53.13^0$

But at this value of firing angle, the power circuit of ac voltage controller behaves as if load is directly connected to ac source. Therefore maximum value of rms load current is

$$I_0 = \frac{230}{\sqrt{R^2+(wL)^2}} = \frac{230}{\sqrt{3^2+4^2}} = 46A$$

iii. Maximum power = $I_0^2 xR = 46^2 x3 = 6348W$

Power factor $= \frac{Io^2 xR}{VsIo} = \frac{46x3}{230} = 0.6$

iv. Average thyristor current is maximum when $\alpha = \Phi$ and conduction angle $\gamma = \Pi$

$$I_{TAVG} = \frac{1}{2\pi}\int_{\alpha}^{\alpha+\pi} \frac{Vm}{z} \sin(wt - \varphi)\, d(wt)$$

$$= \frac{Vm}{\pi z} = \frac{\sqrt{2} \times 230}{\pi \times \sqrt{3^2+4^2}} = 20.707A$$

Similarly maximum value of thyristor current is

$$I_{Trms} = \left\{\frac{1}{2\pi}\int_{\alpha}^{\alpha+\pi} \frac{Vm^2}{z^2} sin^2(wt - \alpha)\, d(wt)\right\}^{1/2}$$

$$= \frac{Vm}{2z} = \frac{\sqrt{2} \times 230}{2 \times \sqrt{3^2+4^2}} = 32.527A$$

2. An ac voltage controller uses a TRIAC for phase angle control of a resistive load of 100Ω. Calculate the value of delay angle for having an rms load voltage of 220 volts. Also calculate the rms value of TRIAC current. Assume the rms supply voltage to be 230V.

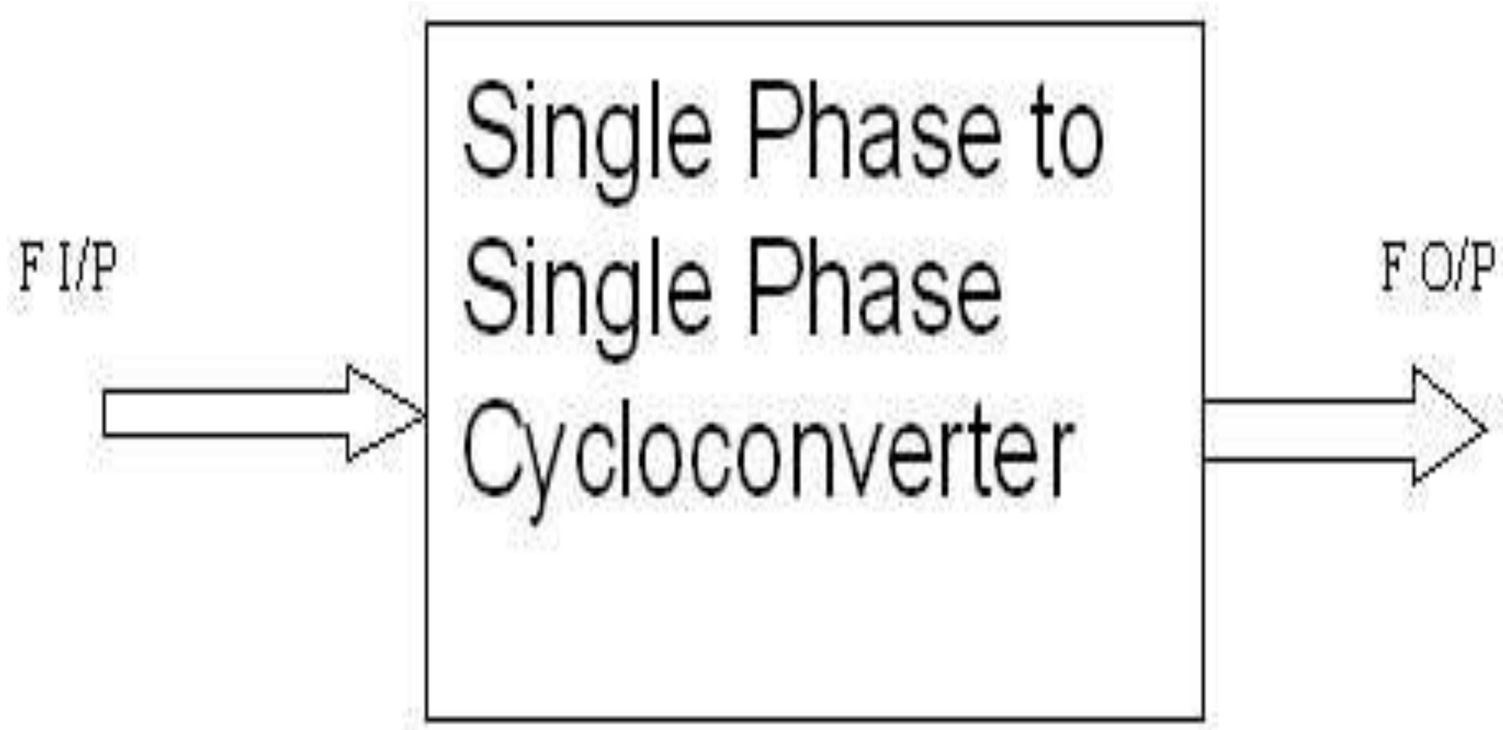
3. The ac voltage controller uses on-off control for heating a resistive load of R = 4 ohms and the input voltage is Vs = 208V, 60Hz. If the desired output power is P_O = 3KW, determine the

- duty cycle δ
- input power factor

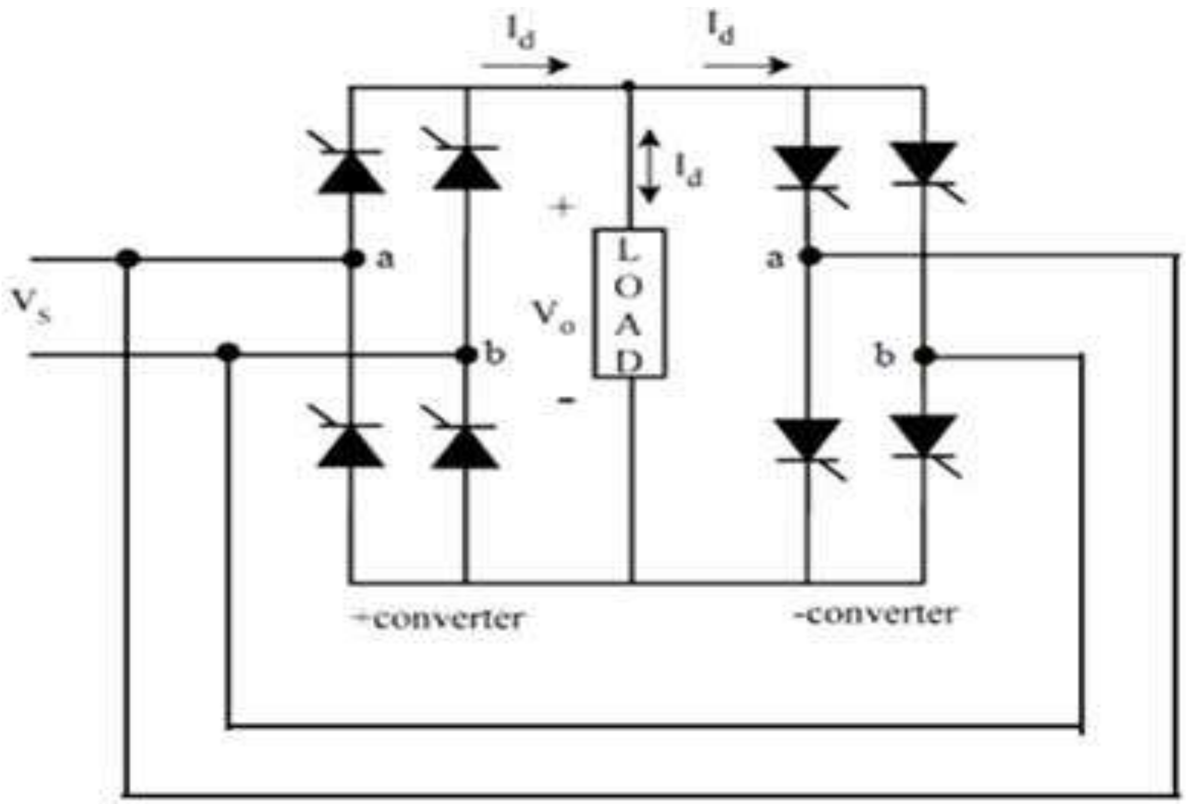
Sketch waveforms for the duty cycle obtained in (a)

Cyclo converters

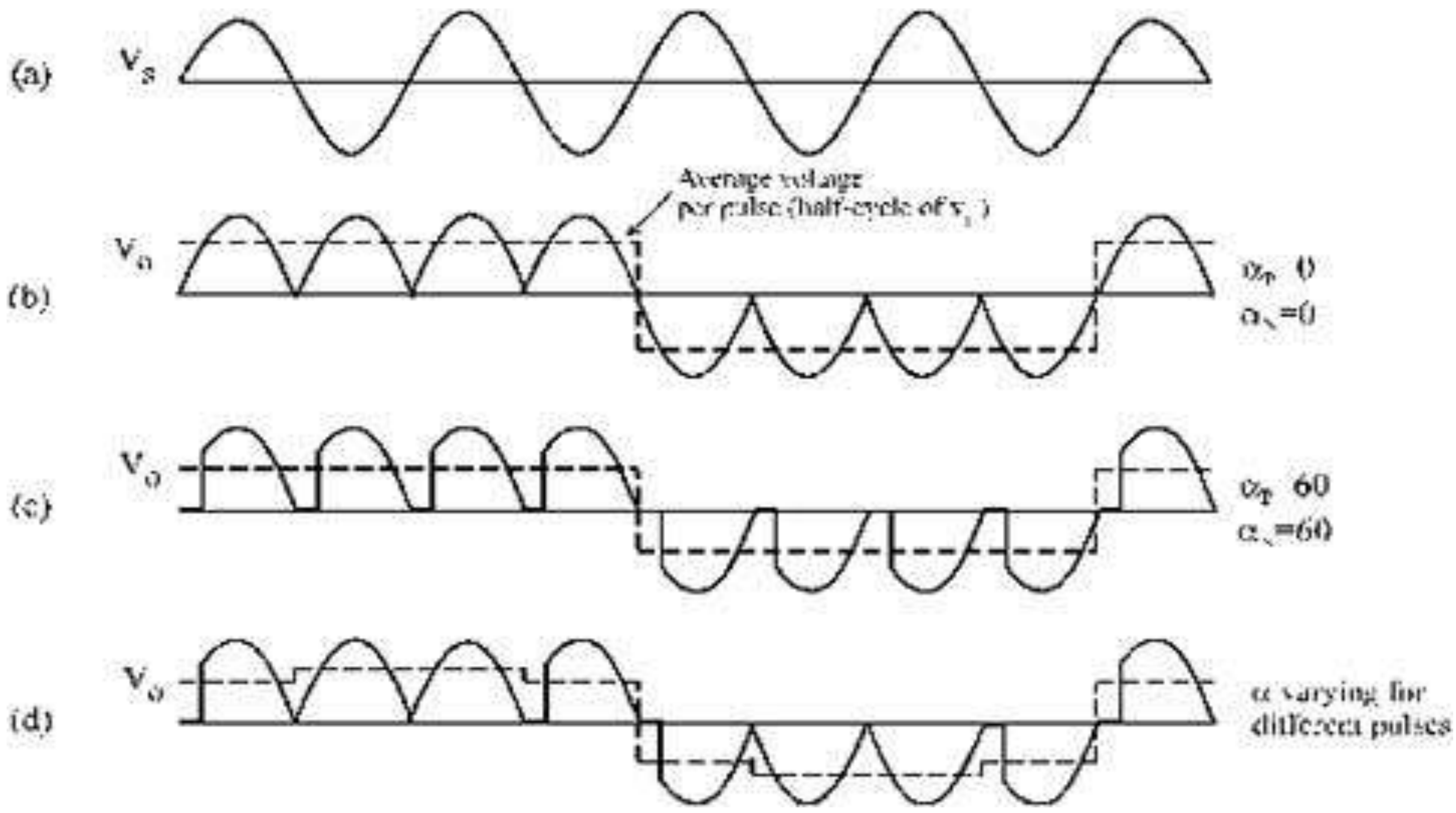
- The Cycloconverter has four thyristors divided into a positive and negative bank of two thyristors each. When positive current flows in the load, the output voltage is controlled by phase control of the two positive bank thyristors whilst the negative bank thyristors are kept off and vice versa when negative current flows in the load. An idealized output waveform for a sinusoidal load current and a 45 degrees load phase angle is shown in Figure



Block diagram of cycloconverters



circuit diagram of cycloconverter



Input and output waveforms of cycloconverter

Single phase midpoint Cyclo converters

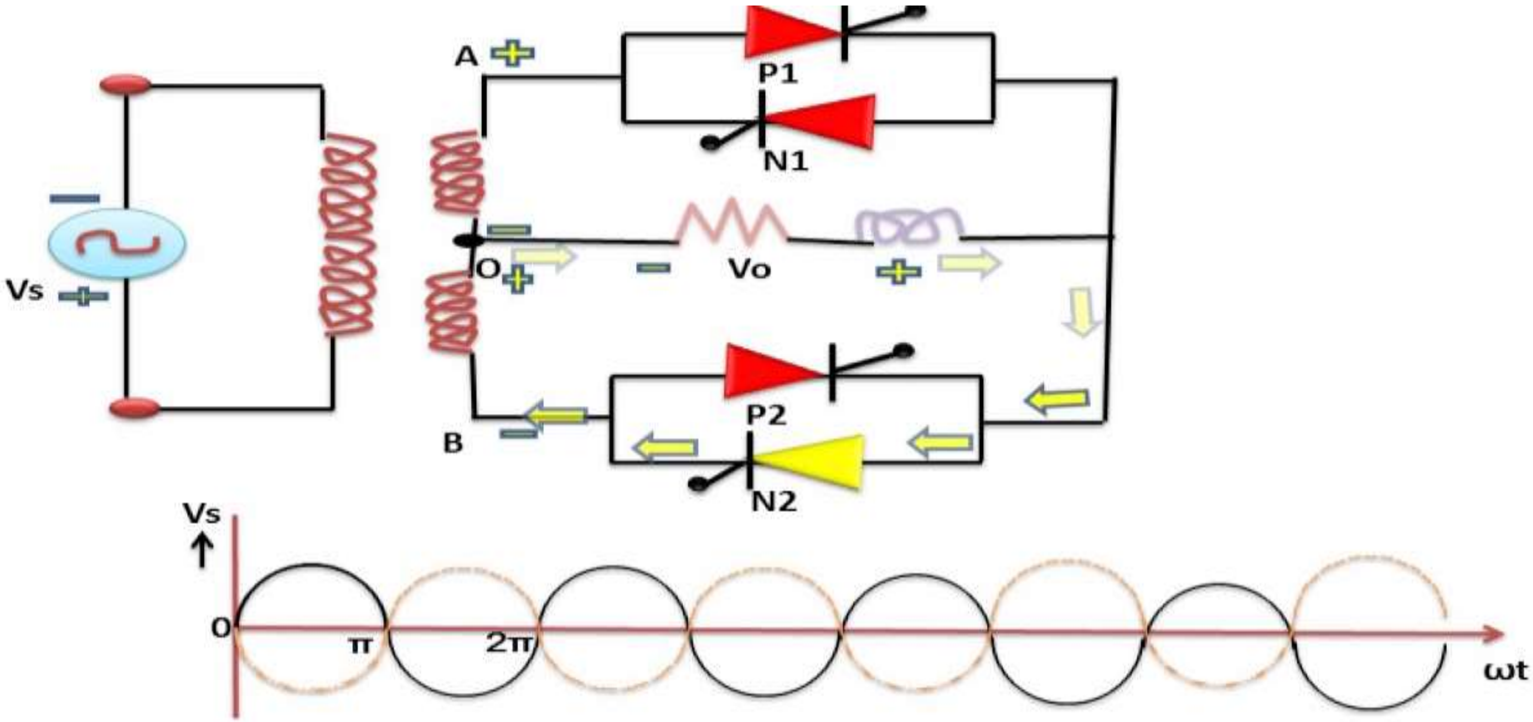
Basically, these are divided into two main types, and are given below

Step-down cyclo-converter

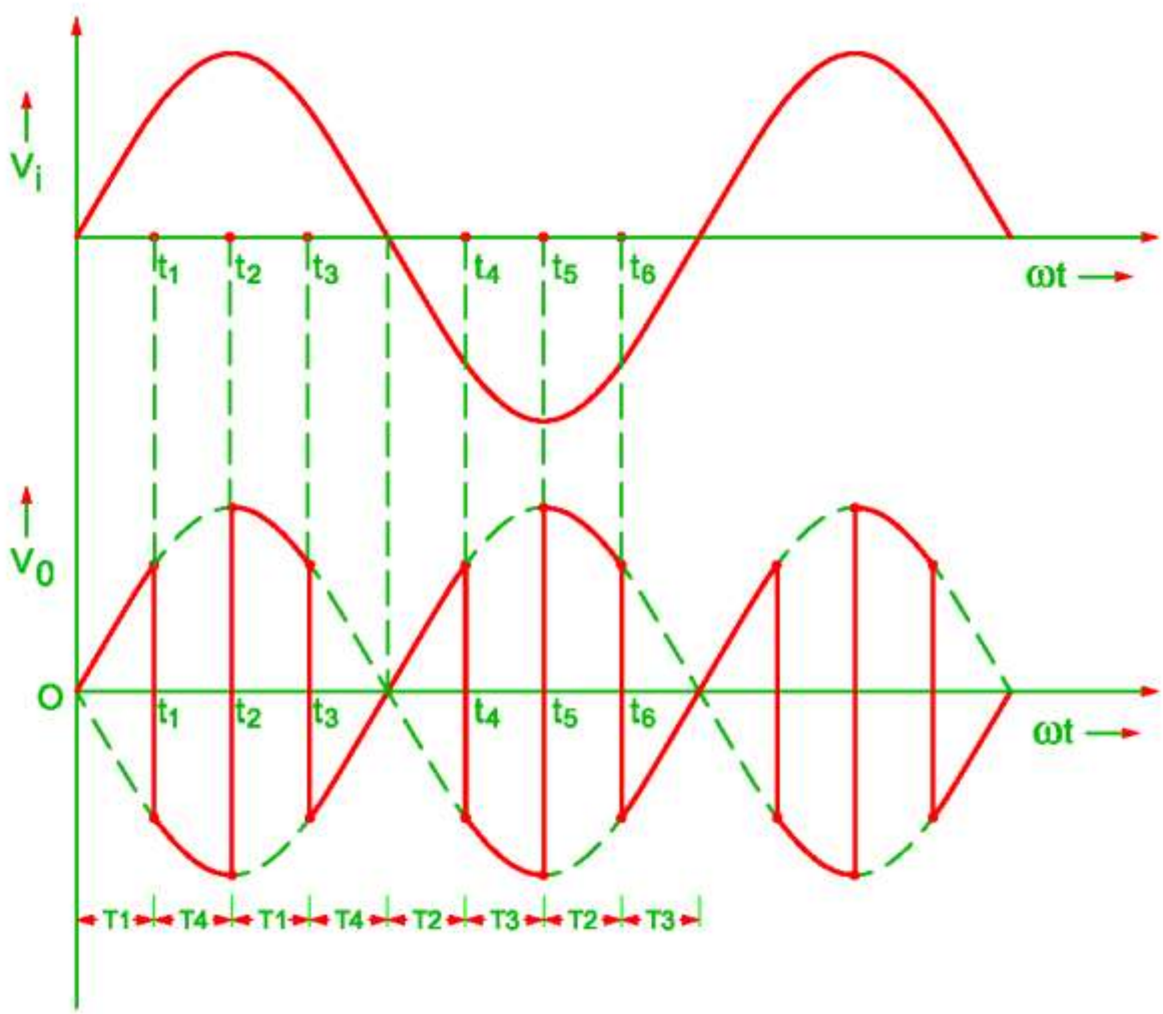
- It acts like a step-down transformer that provides the output frequency less than that of input, $f_o < f_i$.

Step-up cyclo-converter

- It provides the output frequency more than that of input, $f_o > f_i$.



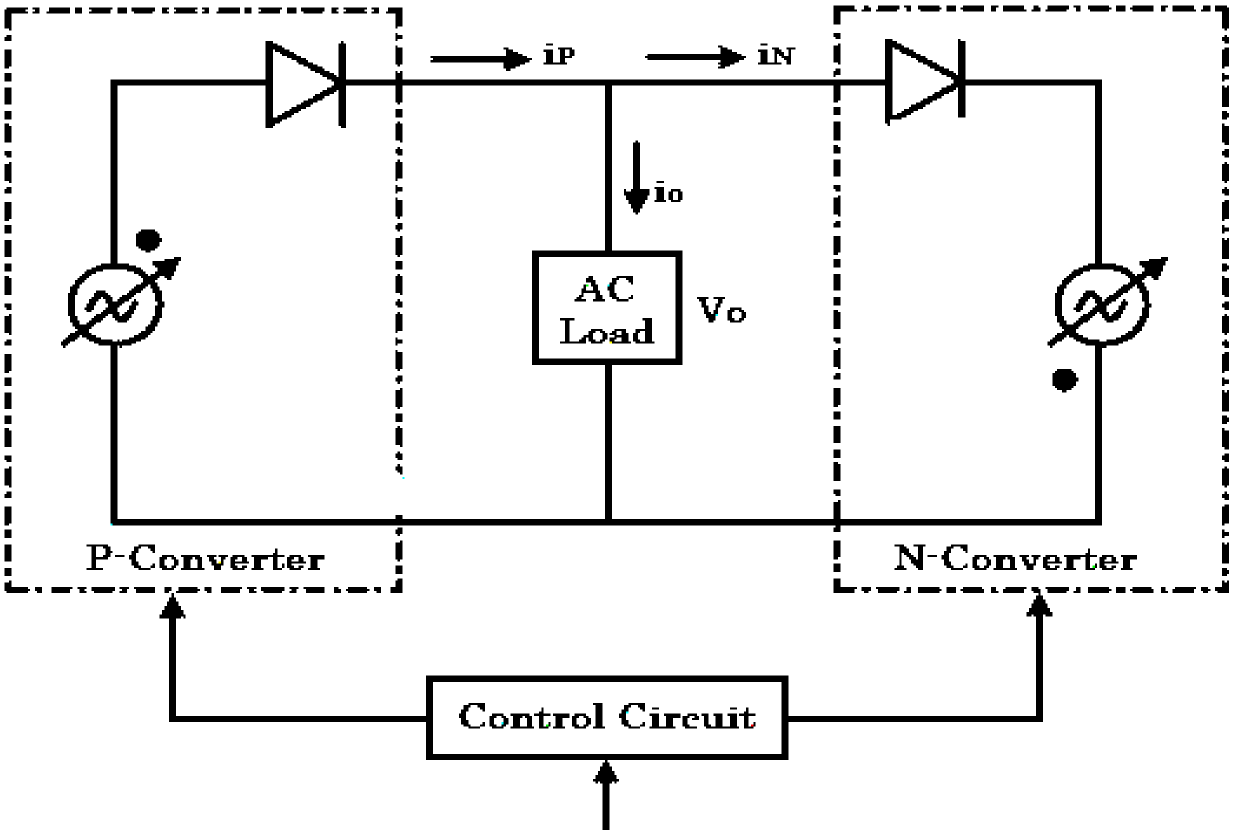
circuit diagram of midpoint cycloconverter



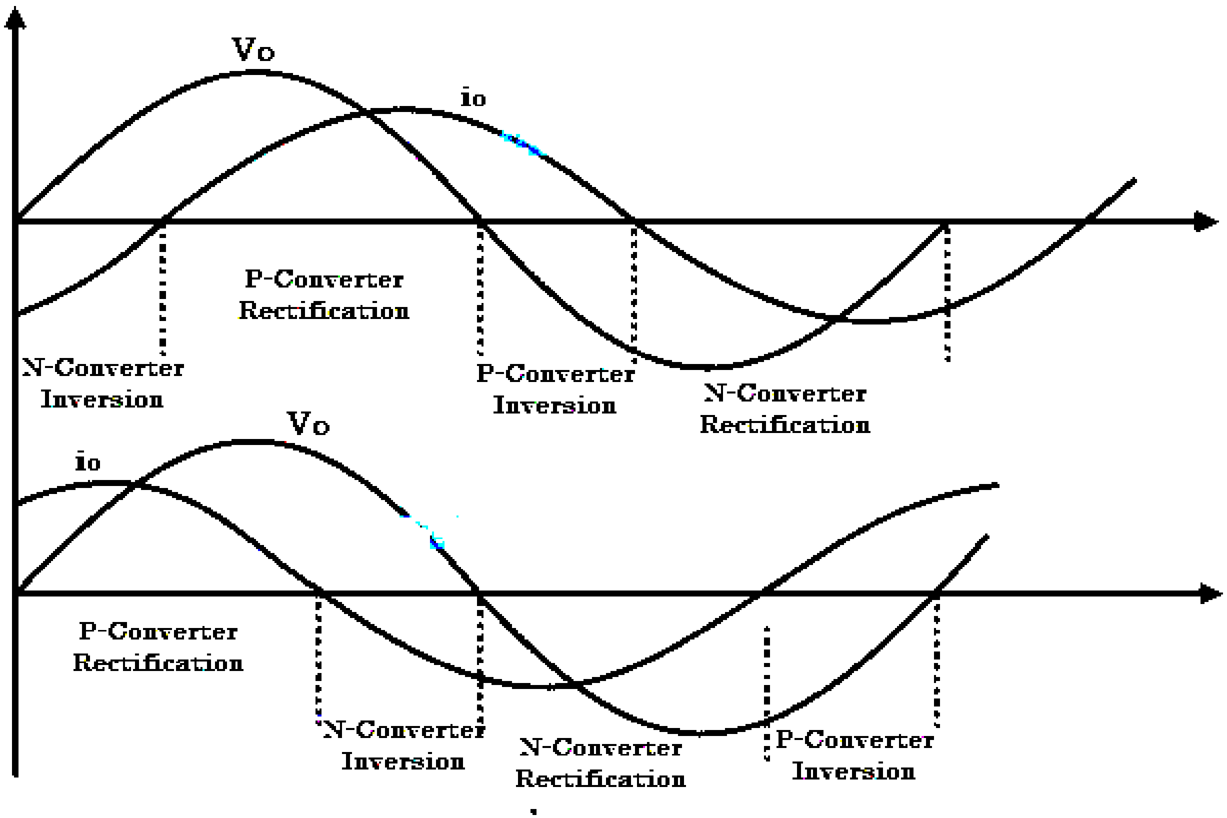
Input and output waveforms of midpoint cycloconverter

Bridge configuration of single phase Cyclo converter

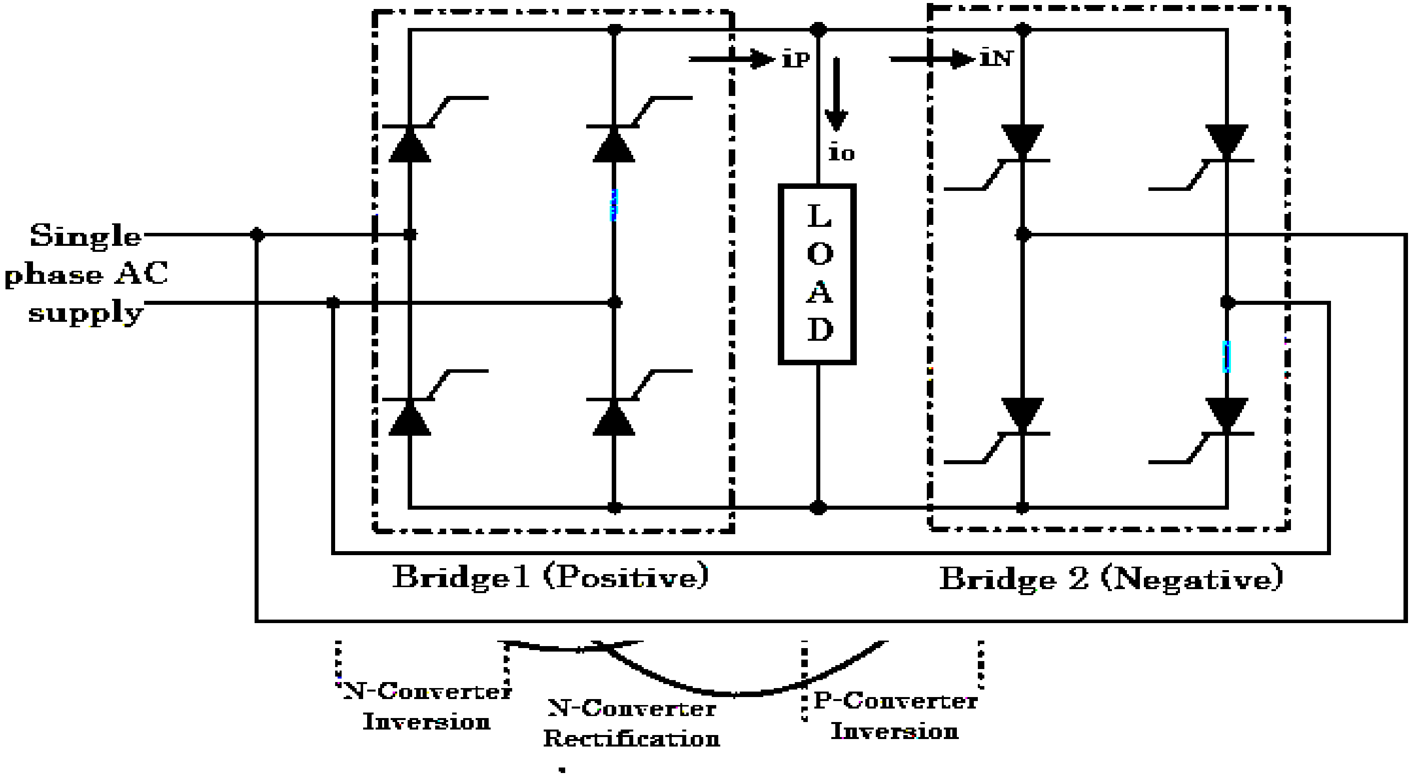
- The equivalent circuit of a cyclo-converter is shown in figure below. Here each two quadrant phase controlled converter is represented by a voltage source of desired frequency and consider that the output power is generated by the alternating current and voltage at desired frequency.
- The diodes connected in series with each voltage source represent the unidirectional conduction of each two quadrant converter. If the output voltage ripples of each converter are neglected, then it becomes ideal and represents the desired output voltage.



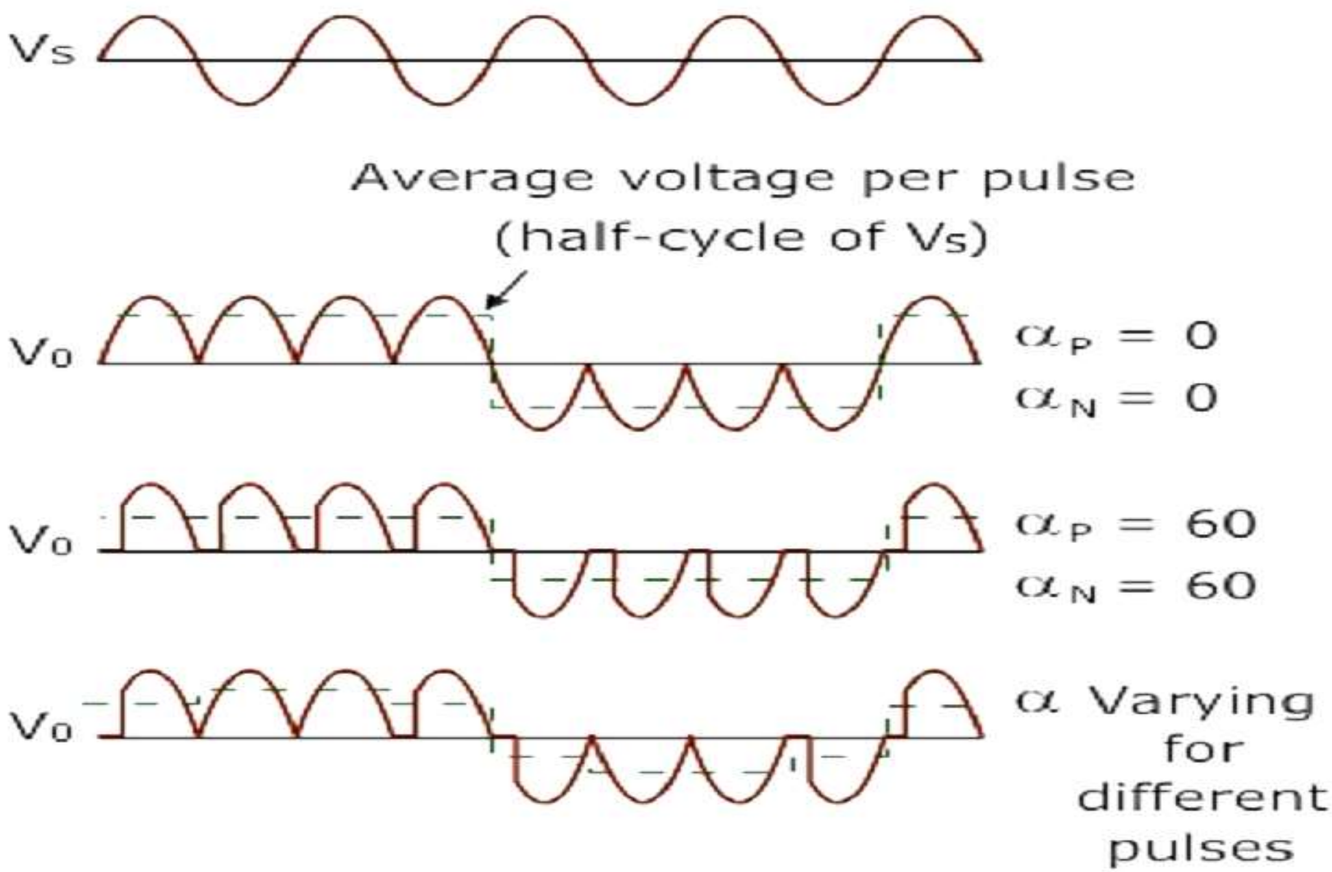
Block diagram of bridge type cycloconverter



cycloconverter waveforms



Circuit diagram of bridge type cycloconverter



Input and output waveforms of bridge type cycloconverter

Numerical Problems

1. A single-phase to single-phase cycloconverter is supplying and inductive load comprising of a Resistance of 5Ω and an inductance of 40 mH from a 230 V, 50 Hz single-phase supply It is Required to provide an output frequency which is 1/3 of the input frequency. If the converters are Operated as semi converter such that and firing delay angle is120°. Neglecting the Harmonic content of load voltage, determine:

   (a) rms value of output voltage.

   (b) rms current of each thyristor and

   (c) input power factor.

$$E = 230\text{ V}, f_1 = 50\text{ Hz}, \alpha_p = \frac{2\pi}{3}$$

$$f_0 = 50/2 = 16.2/3\text{ Hz}, R = 5\Omega, L = 40\text{ mH.}$$

$$\omega_0 = 2\pi \times 50/3 = 104.72\text{ rad/s.}$$

$$X_L = \omega_0 L = 104.72 \times 40 \times 10^{-3} = 4.188\ \Omega$$

$$Z_L = \sqrt{5^2 + (4.188)^2} = 6.52\ \Omega.$$

$$\theta = \tan^{-1}(\omega_o L/R) \cong 40°.$$

(a) For $O \le \alpha \le \pi$, *rms* value of output voltage,

$$E_o = E \cdot \left[\frac{1}{\pi}\left(\pi - \alpha_p + \frac{\sin 2\alpha_p}{2}\right)\right]^{1/2}$$

$$= 230 \cdot \left[\frac{1}{\pi}\left\{\left(\pi - \frac{2\pi}{3}\right) + \frac{\sin 240}{2}\right\}\right]^{1/2}$$

$$= 101.6\text{ V}$$

(b) RMS value of load current, $I_o = \dfrac{E_o}{Z_L}$

$$= \frac{101.6}{4.188} = 24.26 \text{ A.}$$

The *rms* current through each converter group is

$$I_P = I_N = \frac{I_o}{\sqrt{2}} = 17.1542 \text{ A.}$$

and the *rms* current through each thyristor

$$I_{Trms} = \frac{I_p}{\sqrt{2}} = \frac{17.1542}{\sqrt{2}} = 12.13 \text{ A.}$$

(c) *rms* input current, $I_i = I_o = 24.26$ A.

The volt-amp rating $= E \,.\, I_i = 230 \times 24.26 = 5580$ VA

The output power, $P_o = E_o \,.\, I_o .\cos\theta = 101.6 \times 24.26 \times \cos 40°$

$$= 1888.1 \text{ watts.}$$

$$\therefore \quad \text{Power factor} = \frac{P_o}{E \cdot I_i} = \frac{1888}{5580}$$

$$= 0.3384 \text{ (lagging)}$$

Now,

$$\text{P.F.} = \frac{m_f}{\sqrt{2}} \,.\cos\phi$$

$$m_f = \cos(180 - \alpha_p) = \cos 60° = 0.5$$

$$\cos\phi = \cos 40 = 0.766.$$

Hence,

$$P_f = \frac{0.5}{\sqrt{2}} \,.\cos 40 = 0.27$$

2. In a standard A single-phase bridge-type cyclo-converter has input voltage of 230V, 50Hz and load of R=10Ω. Output frequency is one-third of input frequency. For a firing angle delay of 30^o, Calculate (i) rms value of output voltage (ii) rms current of each converter (iii) rms current of each thyristor (iv) input power factor.

3. A single-phase to single-phase mid-point cyclo-converter is delivering power to a resistive load. The supply transformer has turns ratio of 1: 1: 1. The frequency ratio is fo/fs = 1/5. The firing angle delay α for all the four SCRs are the same. Sketch the time variations of the following waveforms for α = 0° and α = 30°(a) Supply voltage (b) Output current and (c) Supply current. Indicate the conduction of various thyristors also.

UNIT IV
DC – DC CONVERTERS

Introduction to Choppers

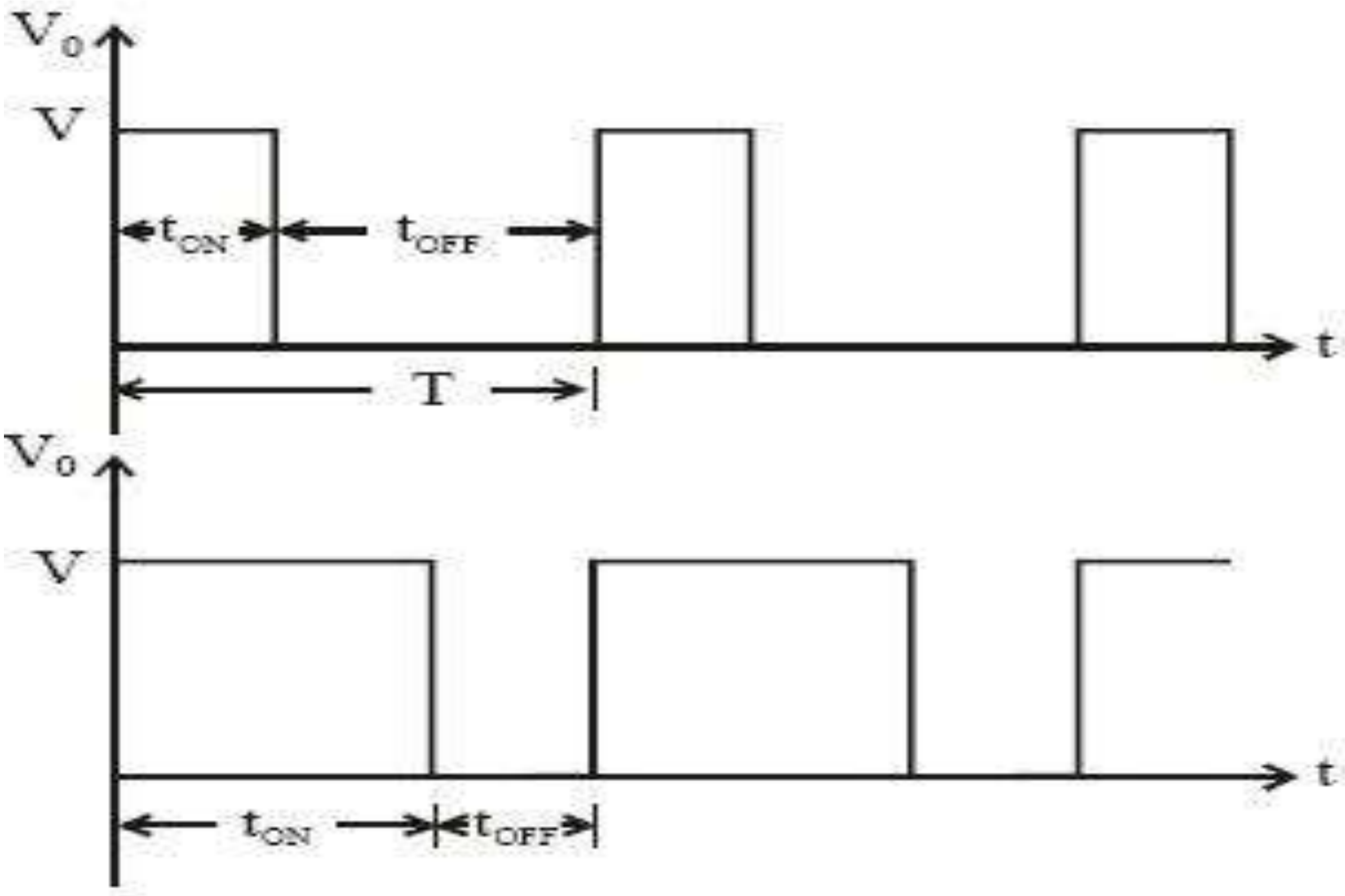
- A chopper uses high speed to connect and disconnect from a source load. A fixed DC voltage is applied intermittently to the source load by continuously triggering the power switch ON/OFF. The period of time for which the power switch stays ON or OFF is referred to as the chopper's ON and OFF state times, respectively.
- Choppers are mostly applied in electric cars, conversion of wind and solar energy, and DC motor regulators.

Control strategies of Chopper

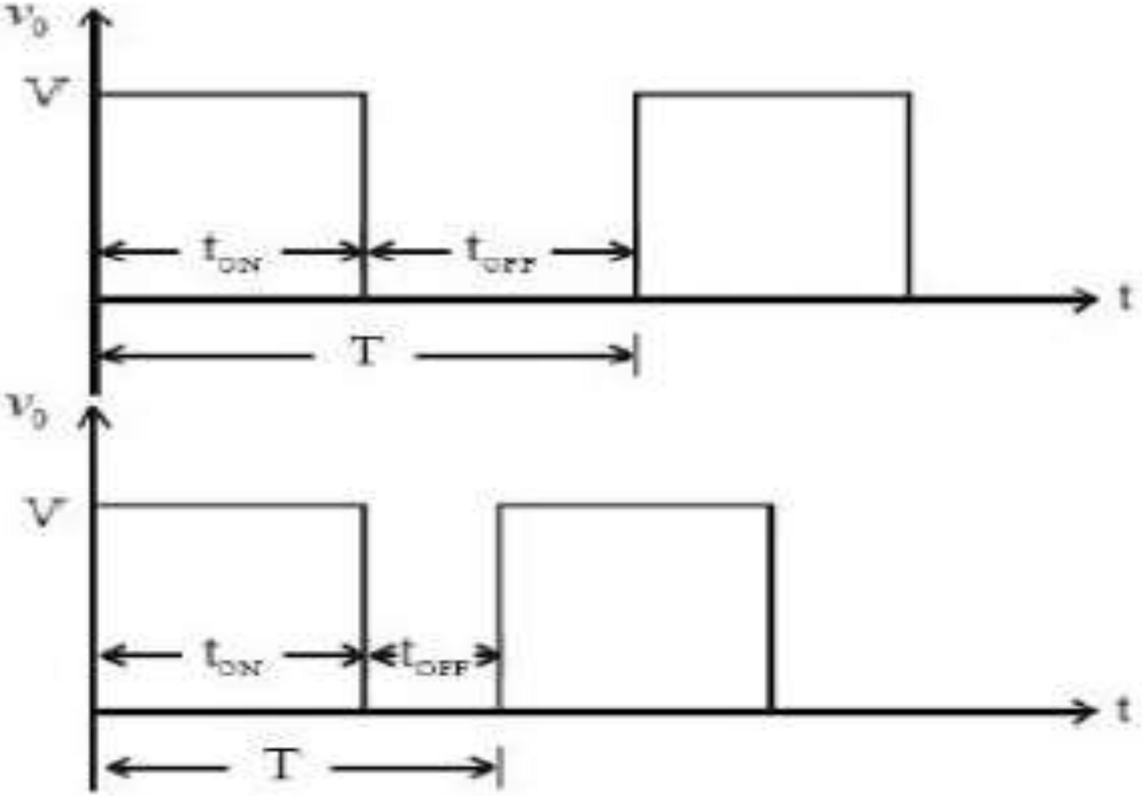
- In DC-DC converters, the average output voltage is controlled by varying the alpha (α) value. This is achieved by varying the Duty Cycle of the switching pulses. Duty cycle can be varied usually in 2 ways:

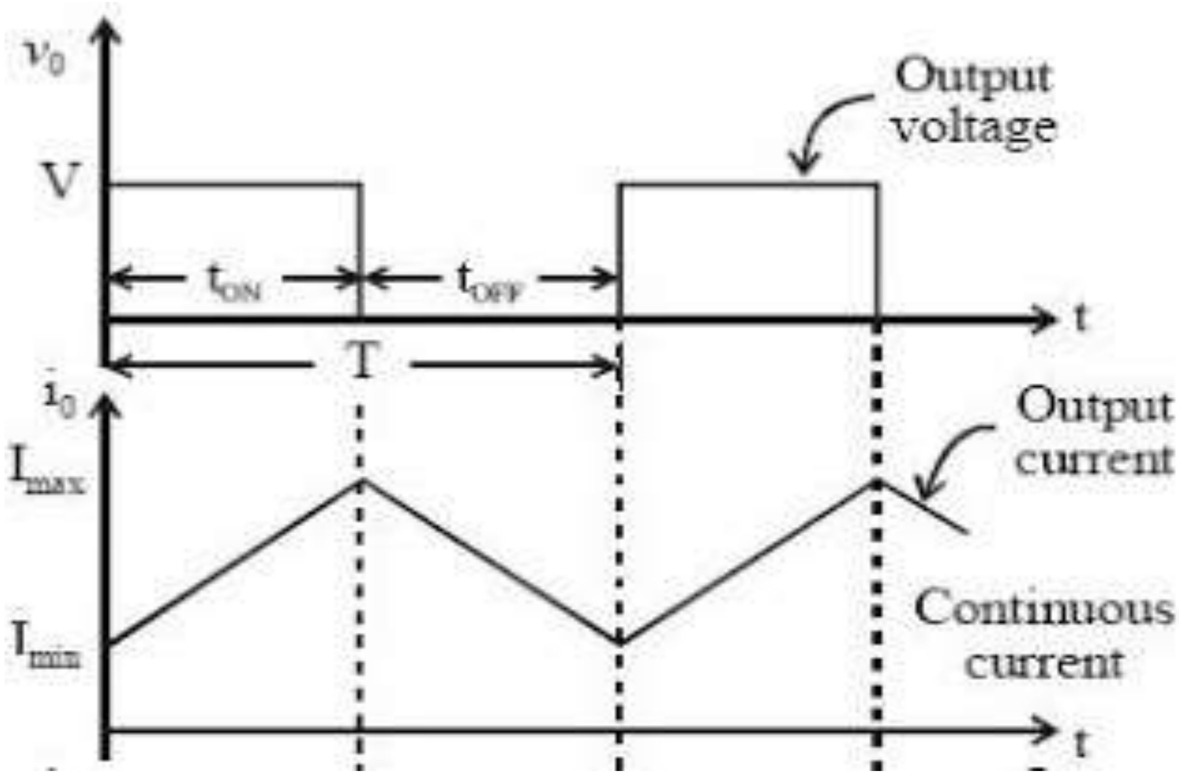
  1. Time Ratio Control

  2. Current Limit Control



V0
V
tON
tOFF
t
T
V0
V
t
tON
tOFF


v_0
V
t_{ON}
t_{OFF}
t
T
v_0
V
t_{ON}
t_{OFF}
t
T



v_0
V
Output voltage
t_{ON}
t_{OFF}
t
T
i_0
I_{max}
Output current
I_{min}
Continuous current
t

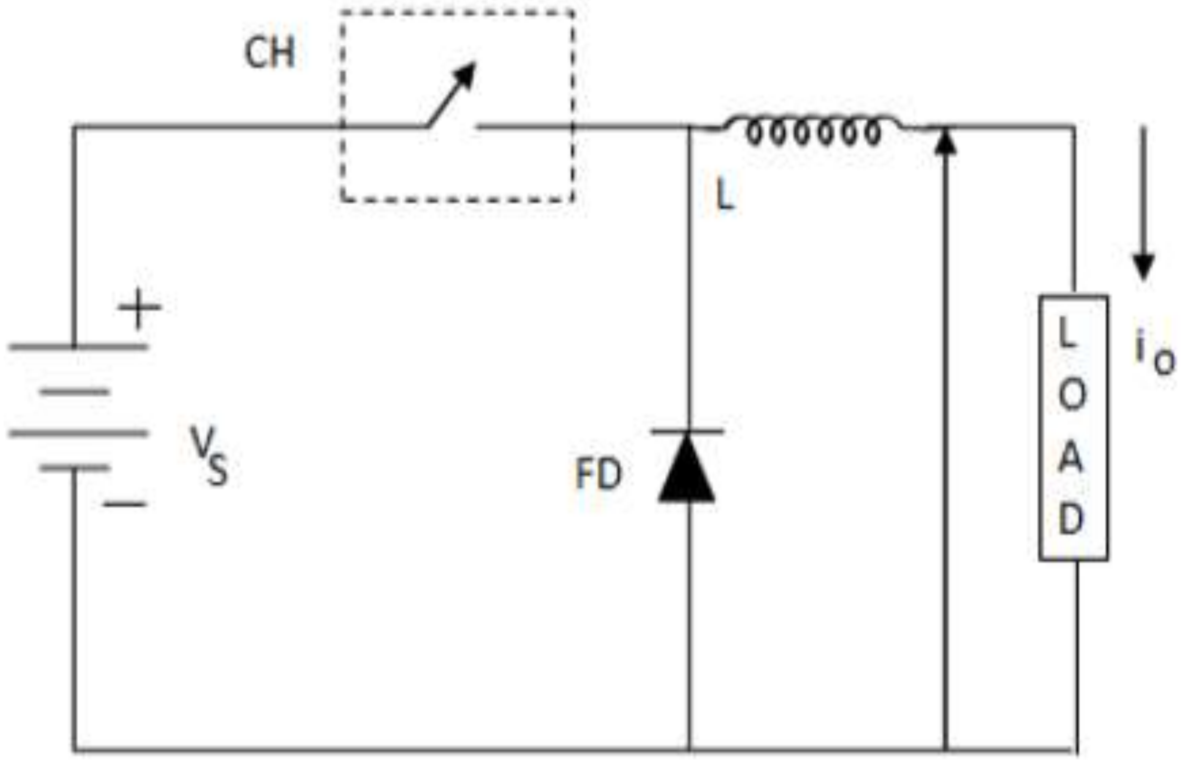
Classification of Choppers

Depending on the voltage output, choppers are classified as –

1. Step Up chopper (boost converter)
2. Step Down Chopper(Buck converter)
3. Step Up/Down Chopper (Buck-boost converter)

Depending upon the direction of the output current and voltage,

1. Class A [One-quadrant Operation]
2. Class B [One-quadrant Operation]
3. Class C [Two-quadrant Operation]
4. Class D Chopper [Two-quadrant Operation]
5. Class E Chopper [Four-quadrant Operation]



Step down chopper

$$\frac{V_S - V_0}{L} T_{ON} = \frac{V_0}{L} T_{OFF}$$

$$\frac{V_S - V_0}{V_0} = \frac{T_{OFF}}{T_{ON}}$$

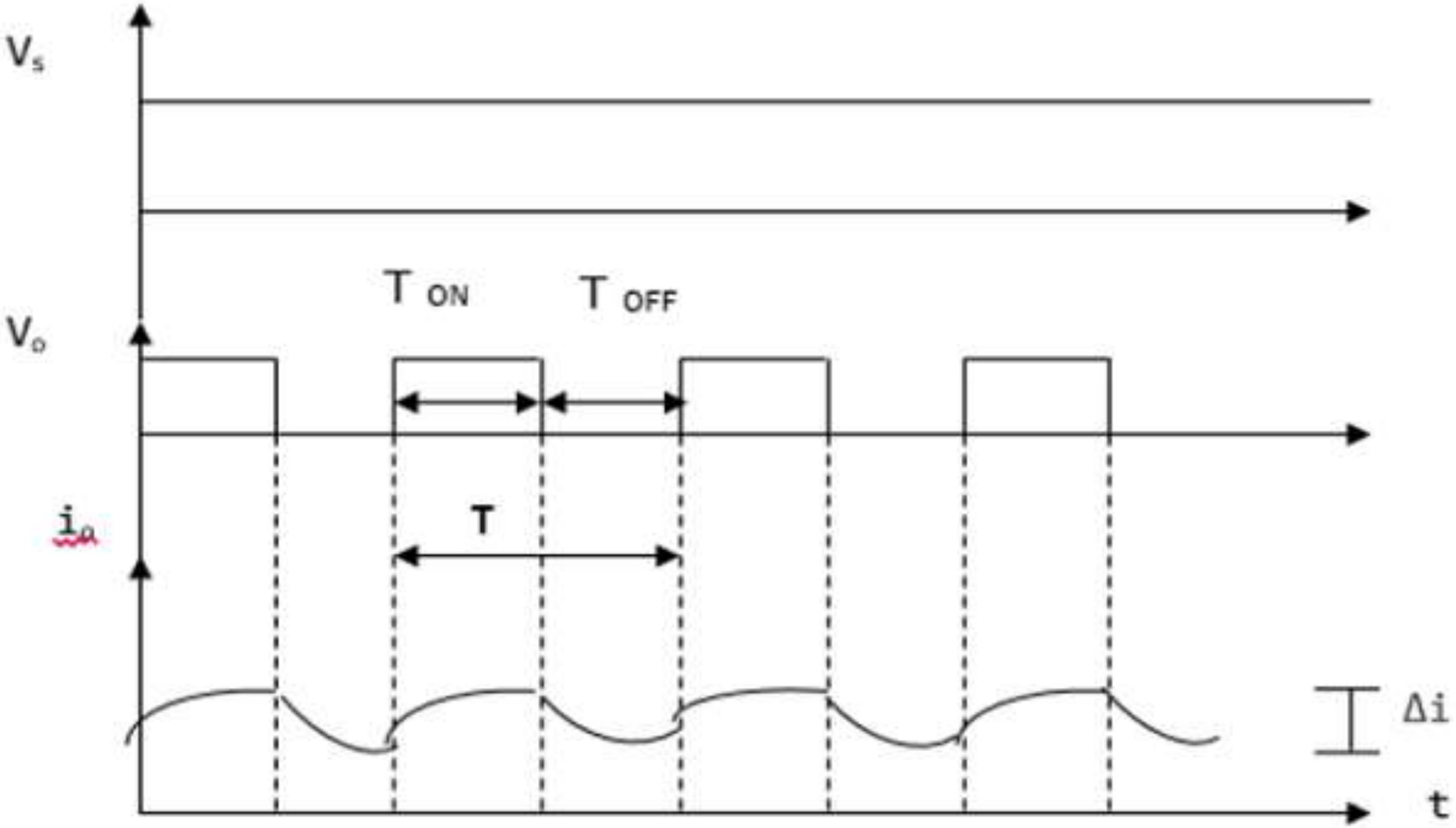
$$\frac{V_S}{V_0} = \frac{T_{ON} - T_{OFF}}{T_{ON}}$$

$$V_0 = \frac{T_{ON}}{T} V_S = DV_S$$

$$\Delta i = \frac{V_S - DV_S}{L} DT, \text{ from } D = \frac{T_{ON}}{T}$$

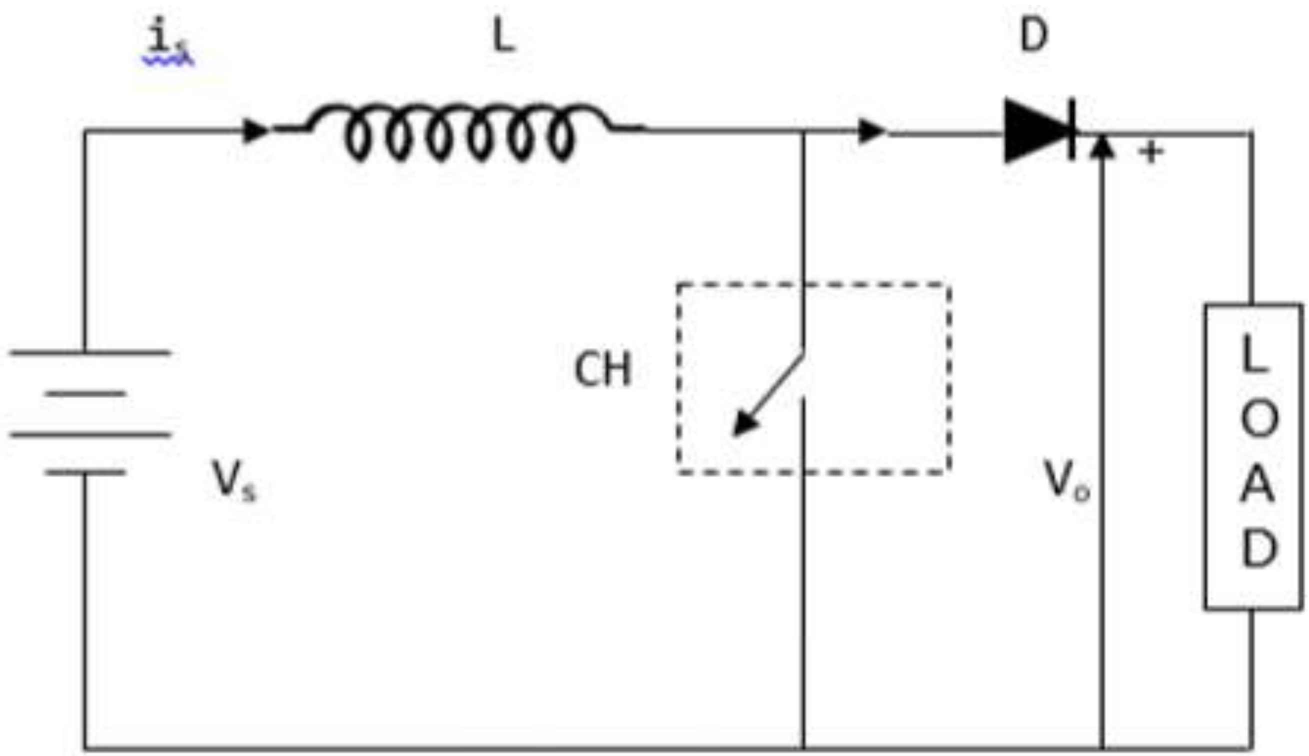
$$= \frac{V_S - (1-D)D}{Lf}$$

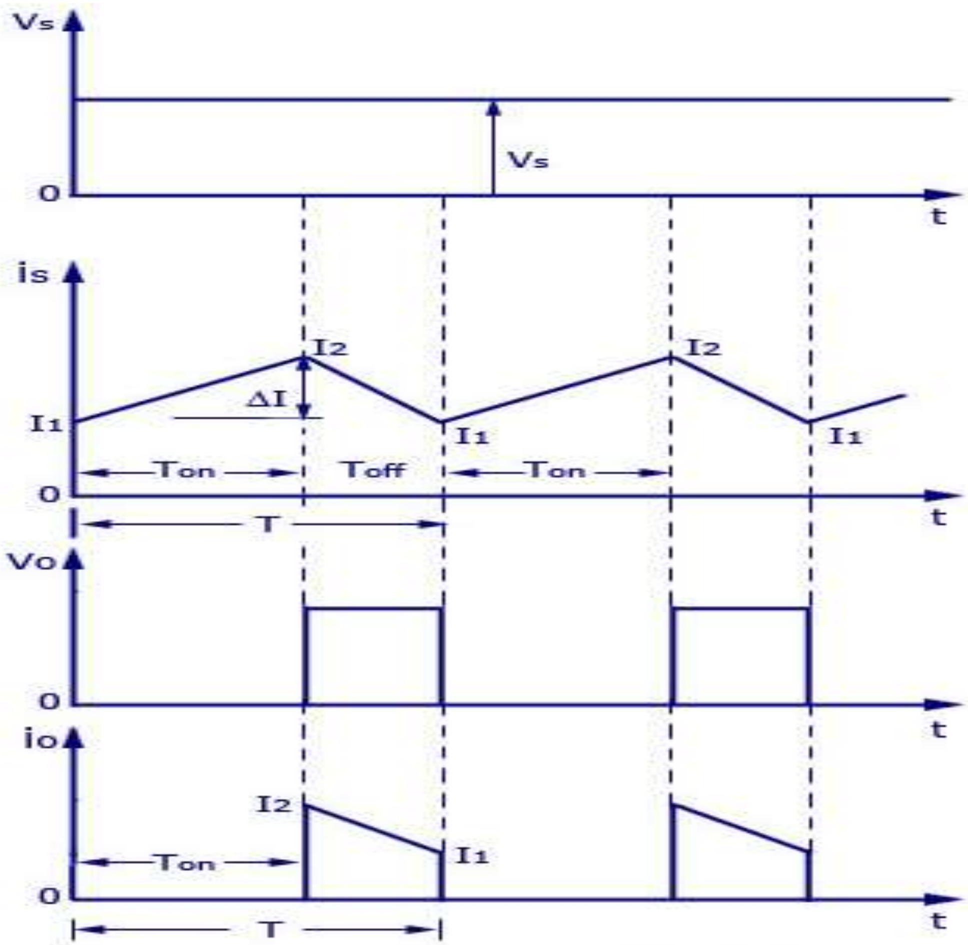
$f = \frac{1}{T}$ =chopping frequency



Input and output waveforms

Step Up Chopper





Input and output waveforms of step up chopper

$$V0 = \frac{1}{T}\int_0^{Ton} Vs\,dt$$

$$Vs = L\,\frac{di}{dt}, \frac{\Delta i}{Ton} = \frac{Vs}{L}$$

$$\Delta i = \frac{Vs}{L} \times Ton$$

V0=VS+VL, VL=V0–VS

$$L\,\frac{di}{dt} = Vo - Vs$$

$$L\,\frac{\Delta i}{Toff} = Vo - Vs$$

$$\Delta i = \frac{Vo - Vs}{L} Toff$$

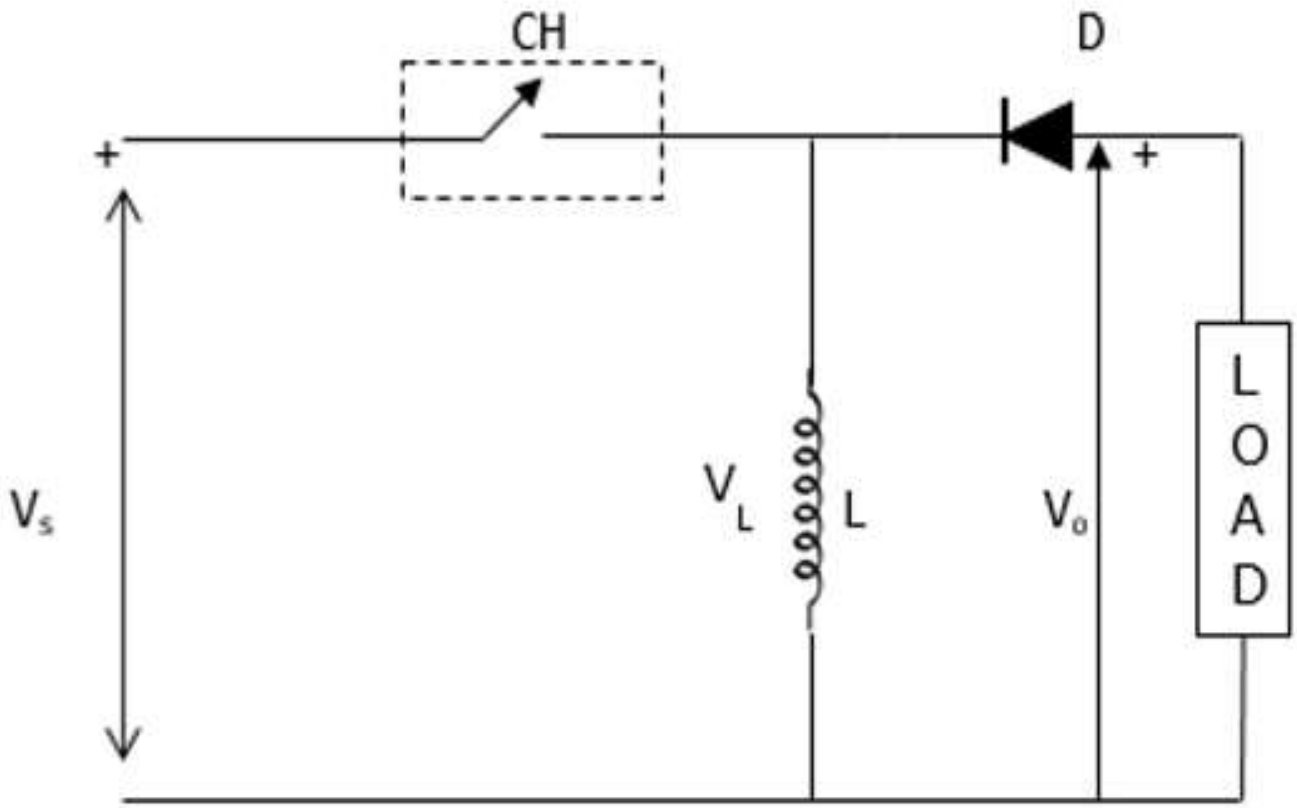
Equating Δi from on state to off state

$$\frac{Vs}{L} \times Ton = \frac{Vo-Vs}{L} Toff$$

$$Vo = \frac{TVs}{Toff}$$

$$Vo = \frac{Vs}{1-D}$$

Step Up/ Step Down Chopper



$$Vs = L\,\frac{di}{dt}\,,\ \frac{\Delta i}{Ton} = \frac{Vs}{L}$$

$$\Delta i = \frac{Vs}{L}Ton \times \frac{T}{T}$$

$$\Delta i = \frac{DVs}{Lf}$$

$$\mathrm{V0} = -\mathrm{VL}$$

$$L\,\frac{di}{dt} = -VL$$

$$\frac{\mathrm{L}\Delta\mathrm{i}}{\mathrm{Toff}} = -\mathrm{VL}$$

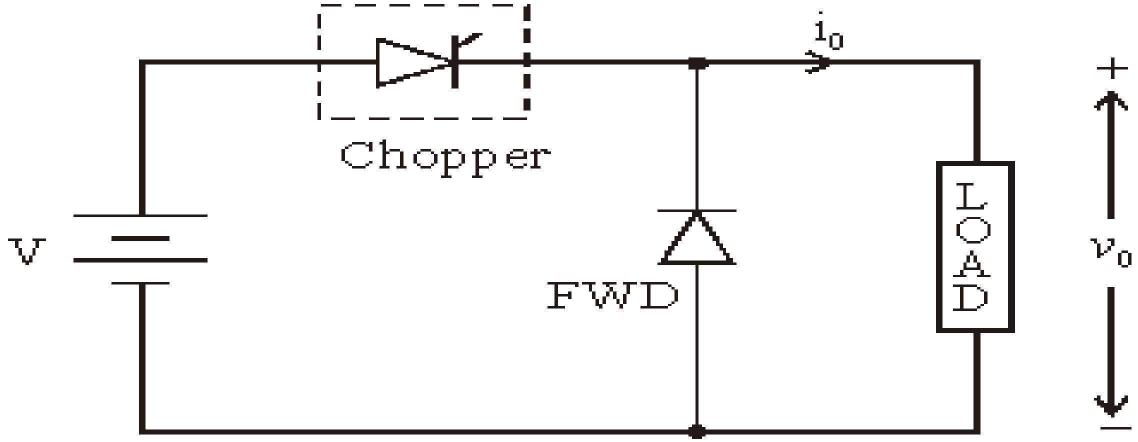
$$\Delta i = -\frac{VL\,Toff}{L}$$

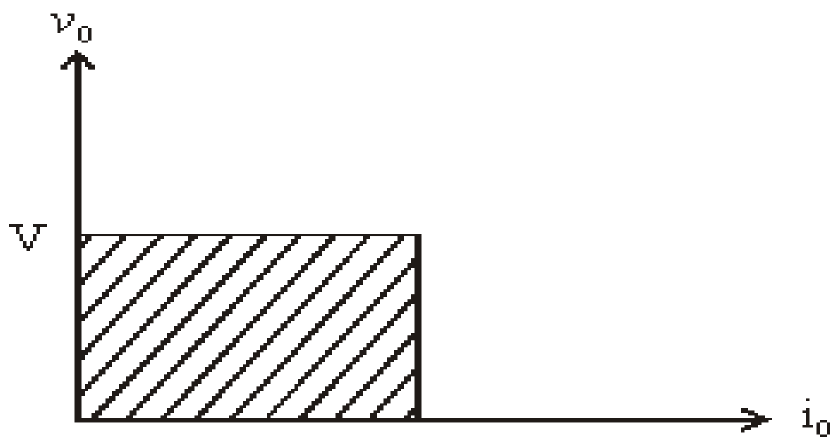
$$\frac{DVs}{Lf} = -\frac{VL\,Toff}{L}$$

$$V_0 = \frac{DVs}{1-D}$$

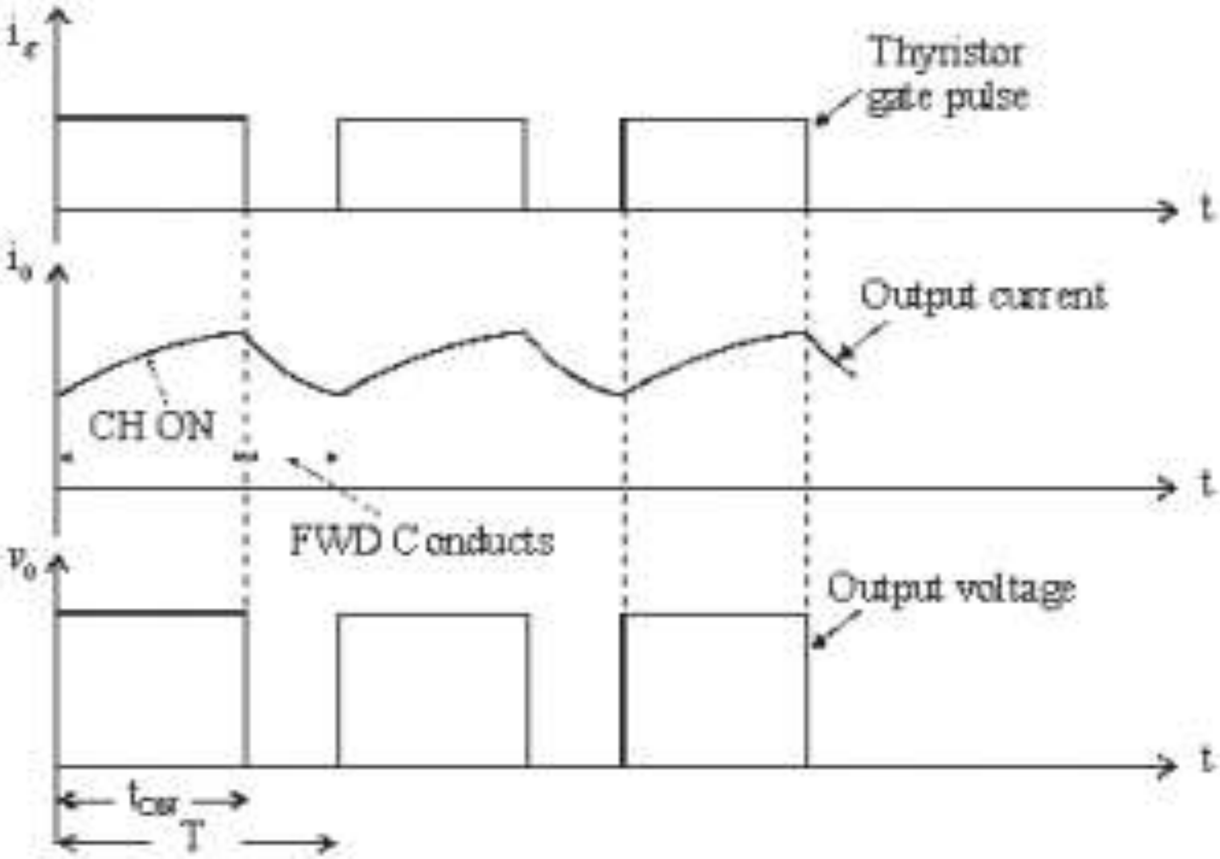
Principle of operation of class A chopper

- Class A Chopper
  - When chopper is ON, supply voltage V is connected across the load.
  - When chopper is OFF, vO = 0 and the load current continues to flow in the same direction through the FWD.
  - The average values of output voltage and current are always positive. Class A Chopper is a first quadrant chopper
  - When chopper is ON, supply voltage V is connected across the load.





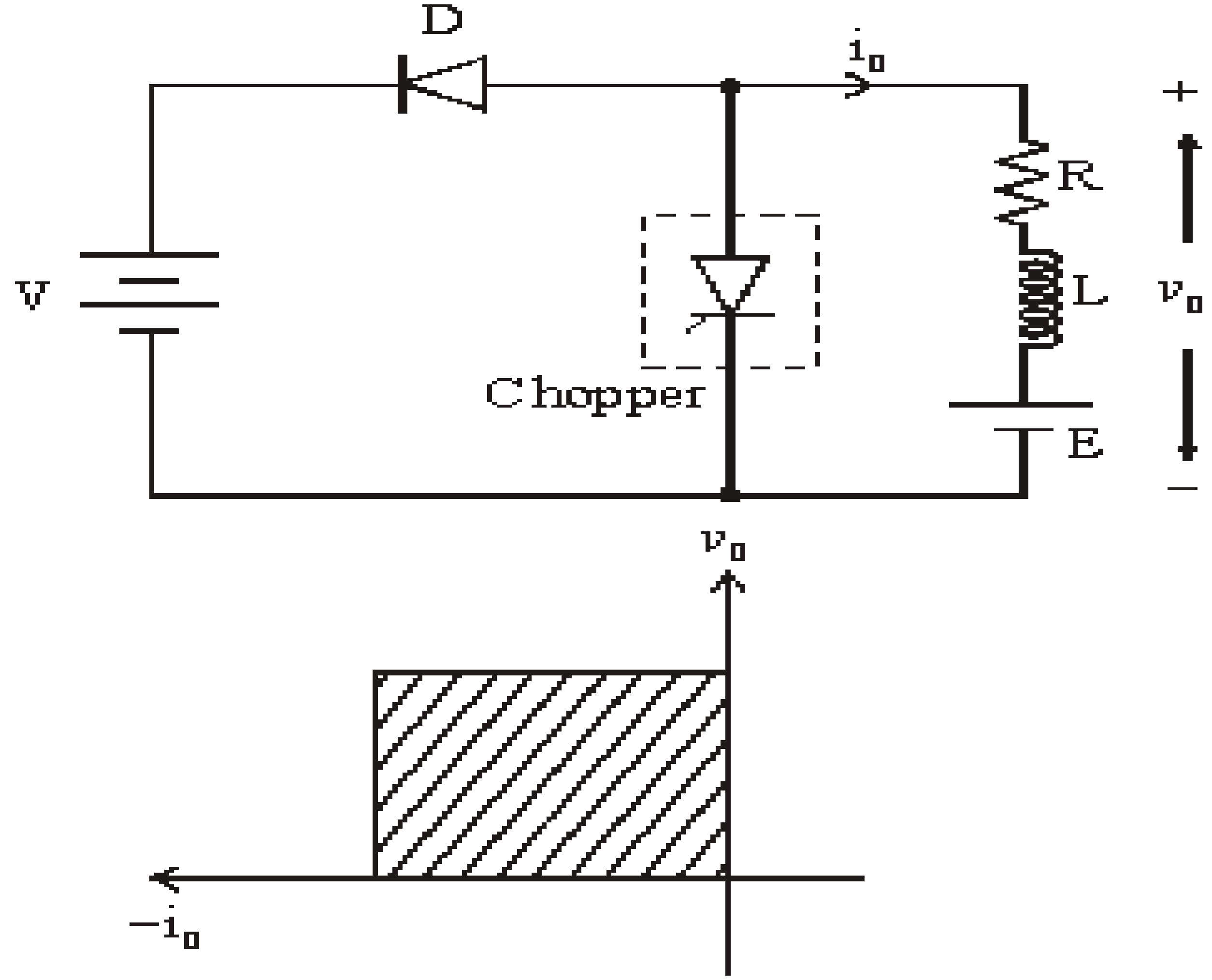
circuit diagram and quadrant operation of Type A chopper



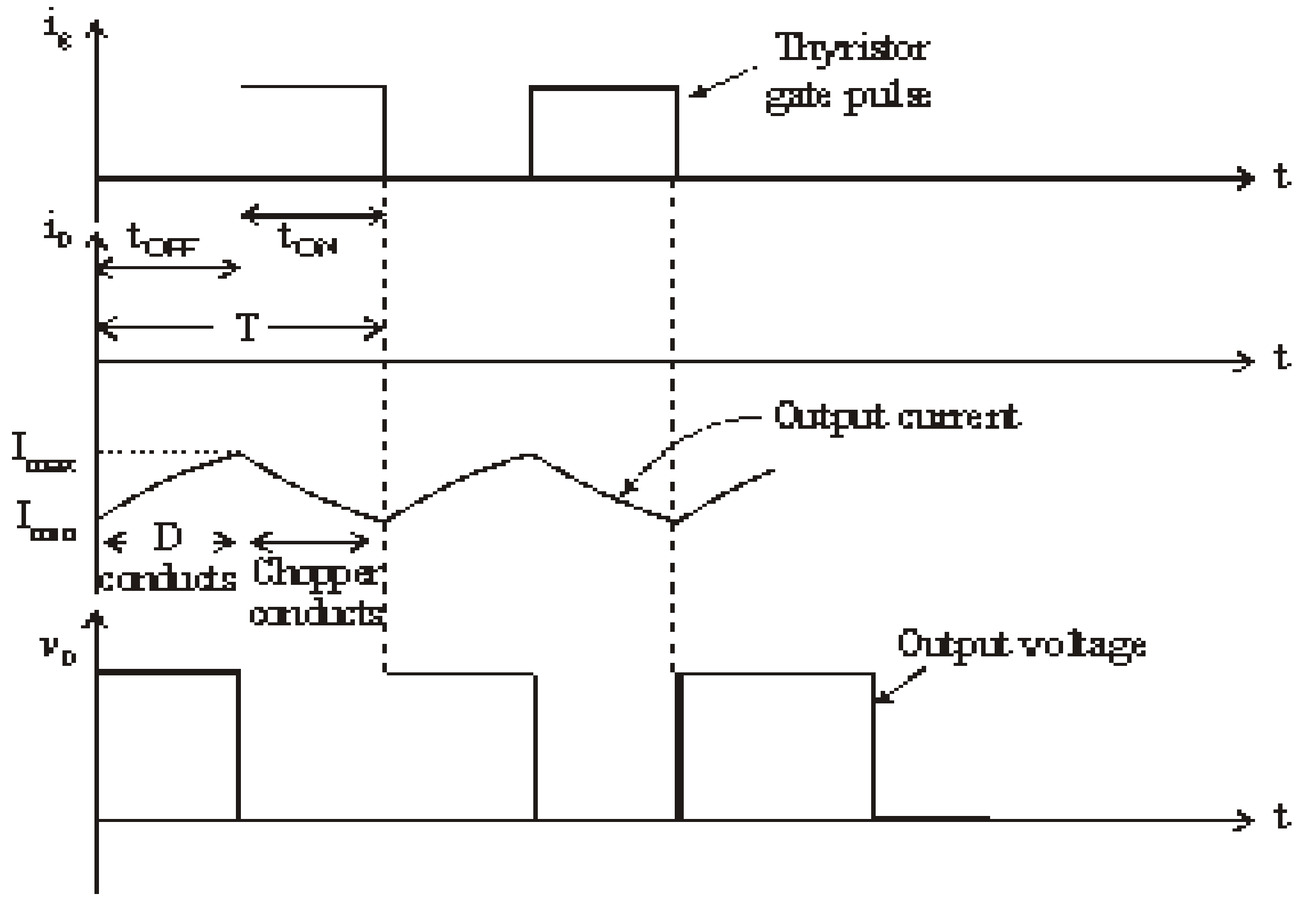
Output voltage and current waveforms of type A chopper

Class B Chopper

- When chopper is ON, E drives a current through L and R in a direction opposite to that shown in figure.
- During the ON period of the chopper, the inductance L stores energy.
- When Chopper is OFF, diode D conducts, and part of the energy stored in inductor L is returned to the supply.
- Average output voltage is positive. Average output current is negative.
- Therefore Class B Chopper operates in second quadrant.
- In this chopper, power flows from load to source.
- Class B Chopper is used for regenerative braking of dc motor.

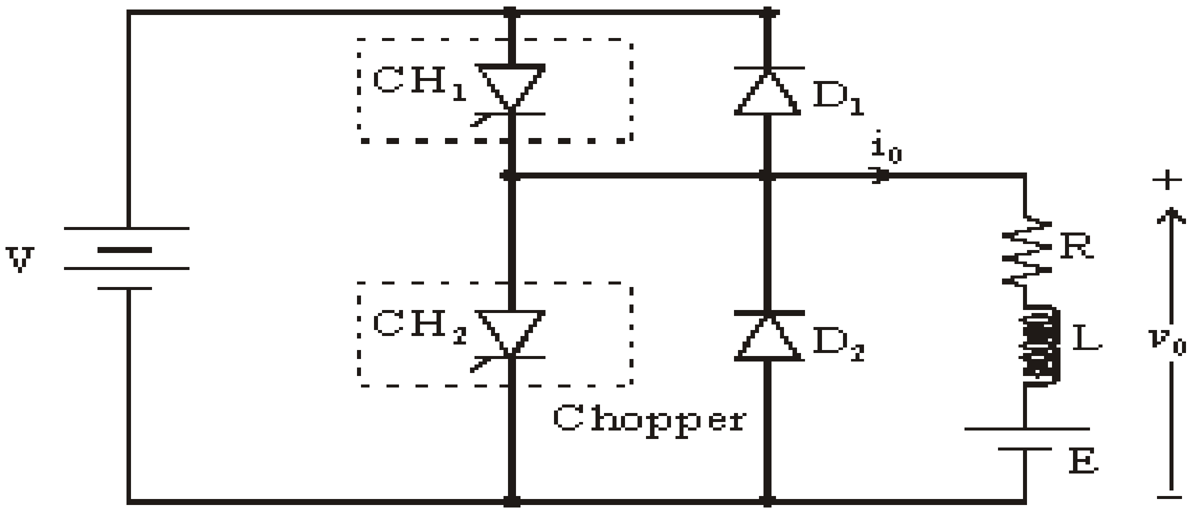


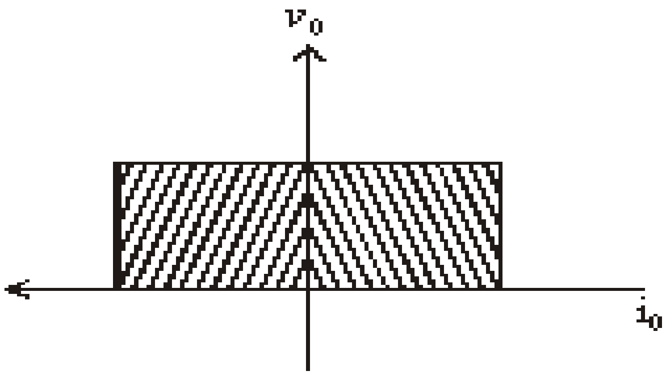
circuit diagram and quadrant operation of Type B chopper

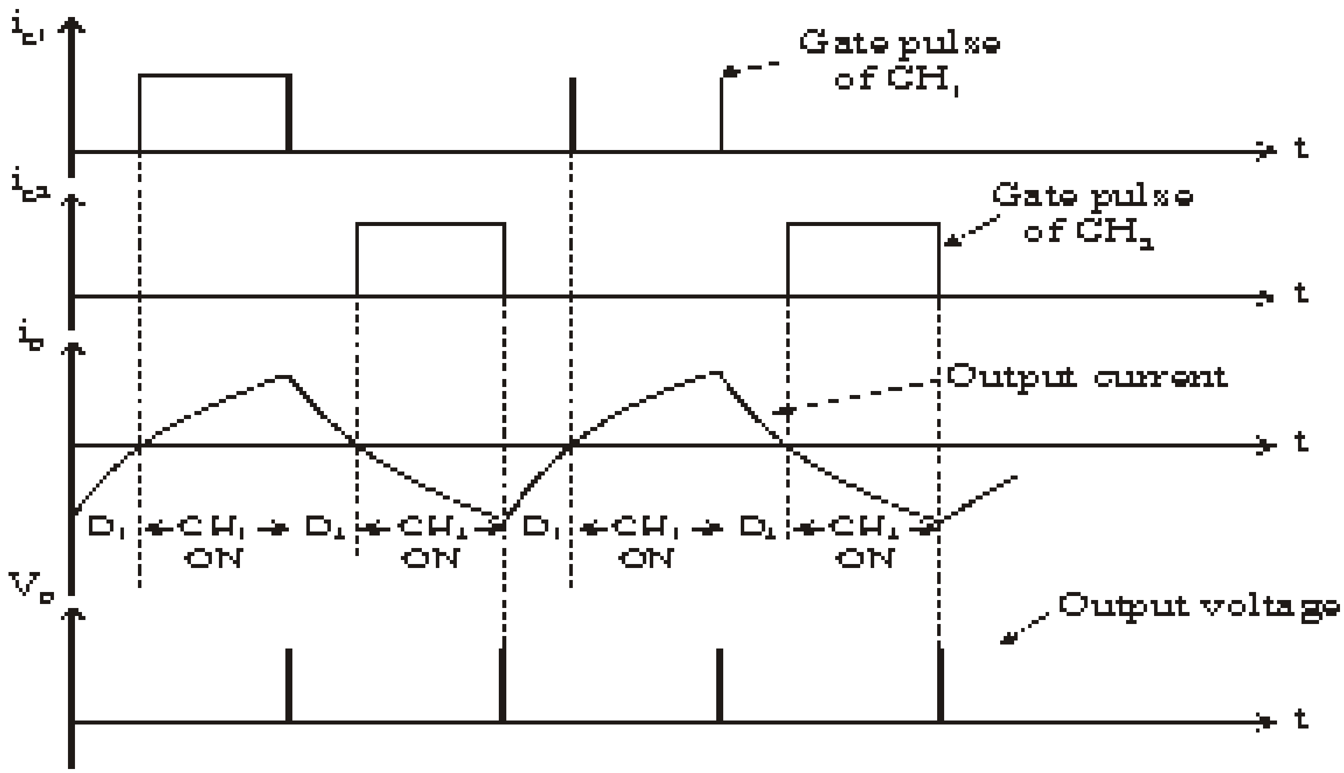


Output voltage and current waveforms of type B chopper

Class C chopper



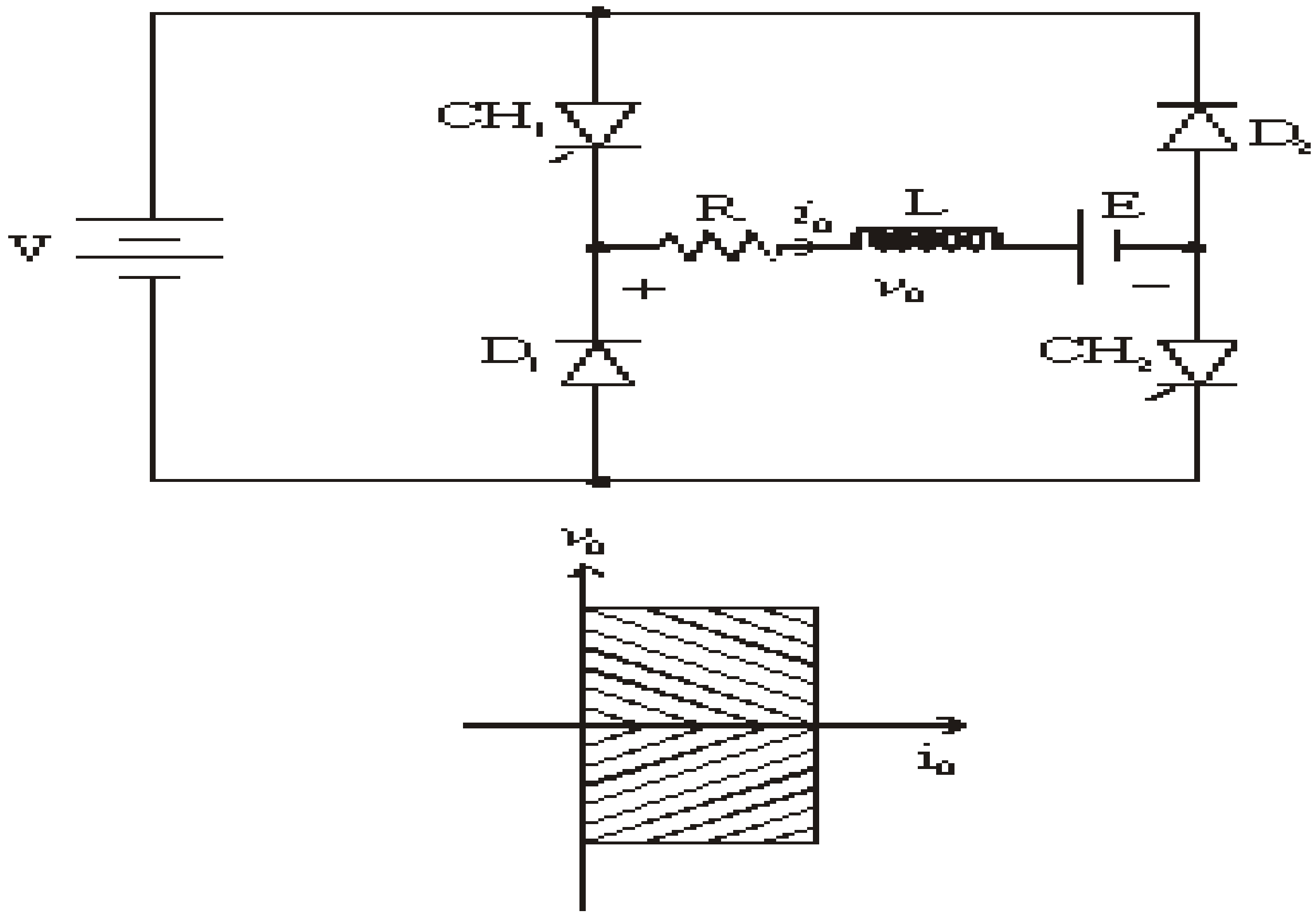




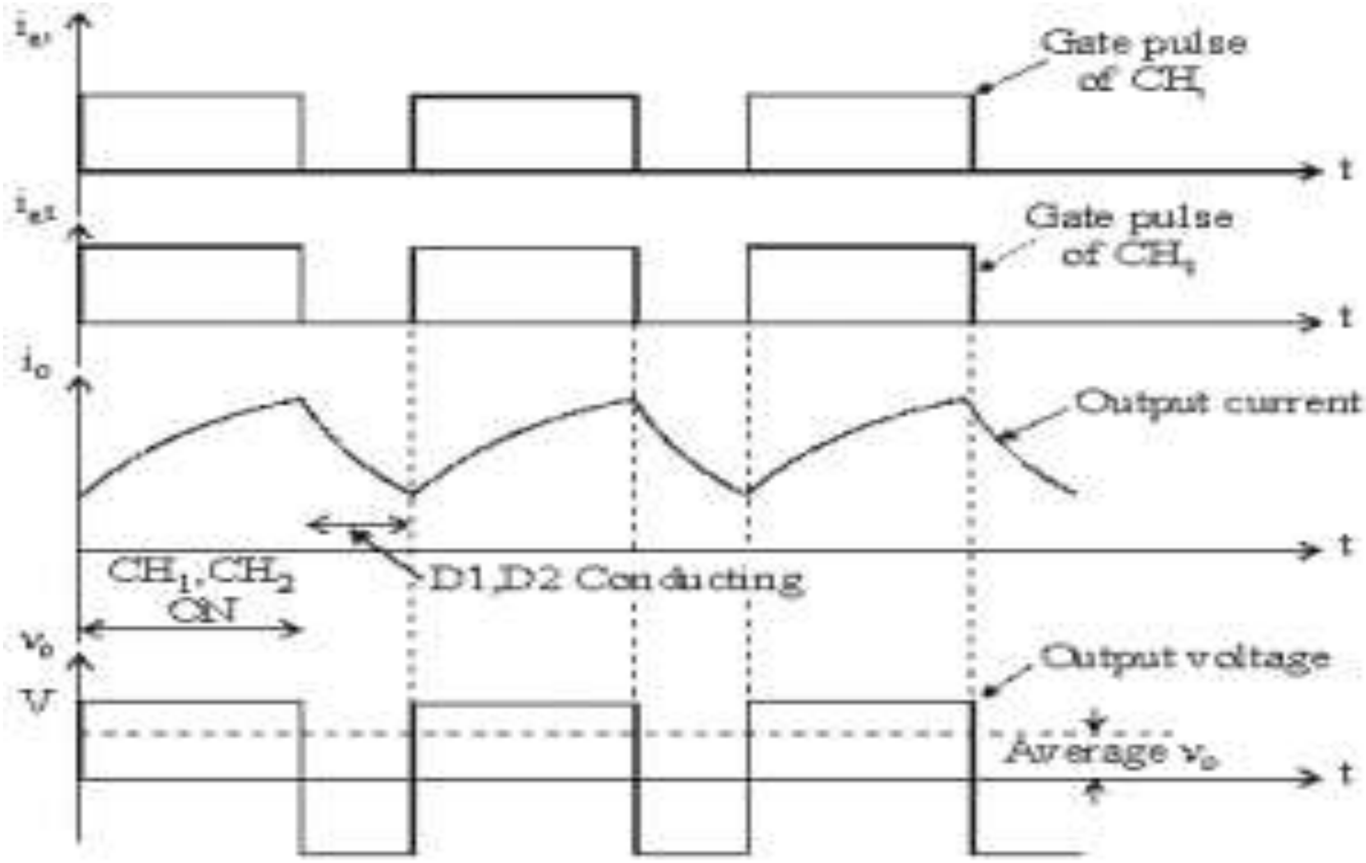
Output voltage and current waveforms of type C chopper

Class D chopper

- Class D is a two quadrant chopper.
  - When both CH1 and CH2 are triggered simultaneously, the output voltage vO = V and output current flows through the load.
  - When CH1 and CH2 are turned OFF, the load current continues to flow in the same direction through load, D1 and D2 , due to the energy stored in the inductor L.
  - Output voltage vO = – V.
  - Average load voltage is positive if chopper ON time is more than the OFF time
  - Average output voltage becomes negative if tON < tOFF .
  - Hence the direction of load current is always positive but load voltage can be positive or negative.



circuit diagram and quadrant operation of Type D chopper

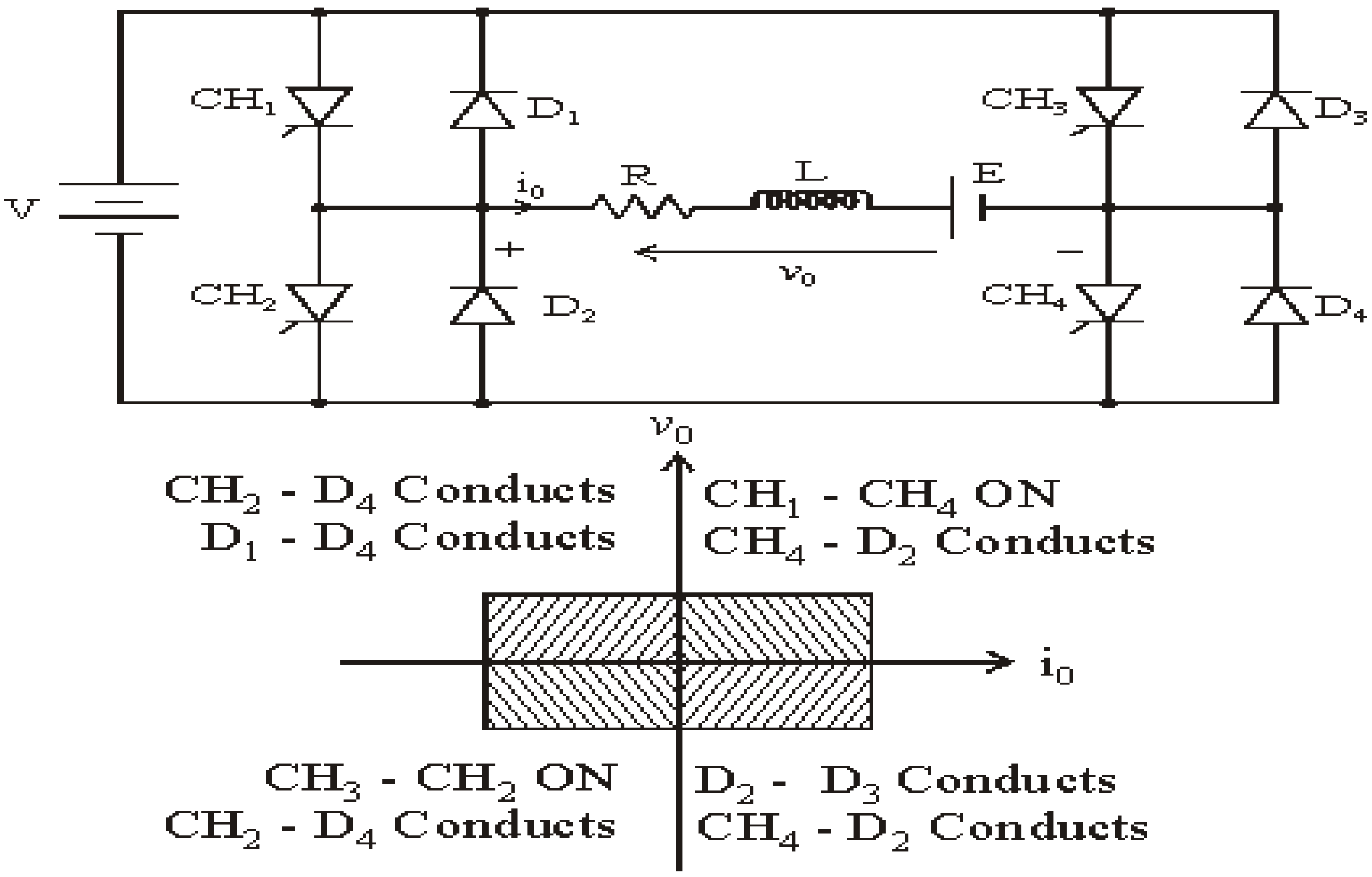


Output voltage and current waveforms of type D chopper

Class E Chopper

- Class E is a four quadrant chopper
  - When CH1 and CH4 are triggered, output current iO flows in positive direction through CH1 and CH4, and with output voltage vO = V.
  - This gives the first quadrant operation.
  - When both CH1 and CH4 are OFF, the energy stored in the inductor L drives iO through D2 and D3 in the same direction, but output voltage vO = -V.
  - Therefore the chopper operates in the fourth quadrant.

- When CH2 and CH3 are triggered, the load current iO flows in opposite direction & output voltage vO = -V.
- Since both iO and vO are negative, the chopper operates in third quadrant.
- When both CH2 and CH3 are OFF, the load current iO continues to flow in the same direction D1 and D4 and the output voltage vO = V.
- Therefore the chopper operates in second quadrant as vO is positive but iO is negative.



circuit diagram and quadrant operation of Type E chopper

Numerical problems

1. A step up chopper has an input voltage of 150V. The voltage output needed is 450V. Given, that the thyristor has a conducting time of 150μseconds. Calculate the chopping frequency.

Solution:

$$f = \frac{1}{T}$$

Where **T** – Chopping time period = $T_{ON} + T_{OFF}$

Given – $V_S = 150V$ $V_0 = 450V$ $T_{ON} = 150\mu sec$

$$V_0 = V_{S\left(\frac{T}{T - T_{ON}}\right)}$$

$$450 = 150\frac{T}{T - 150^{-6}} \quad T = 225\mu sec$$

Therfore, $f = \frac{1}{225 * 10^{-6}} = 4.44KHz$

The new voltage output, on condition that the operation is at constant frequency after the halving the pulse width.

Halving the pulse width gives

$$T_{ON} = \frac{150 \times 10^{-6}}{2} = 75\mu sec$$

The frequency is constant thus,

$$f = 4.44KHz$$

$$T = \frac{1}{f} = 150\mu sec$$

The voltage output is given by –

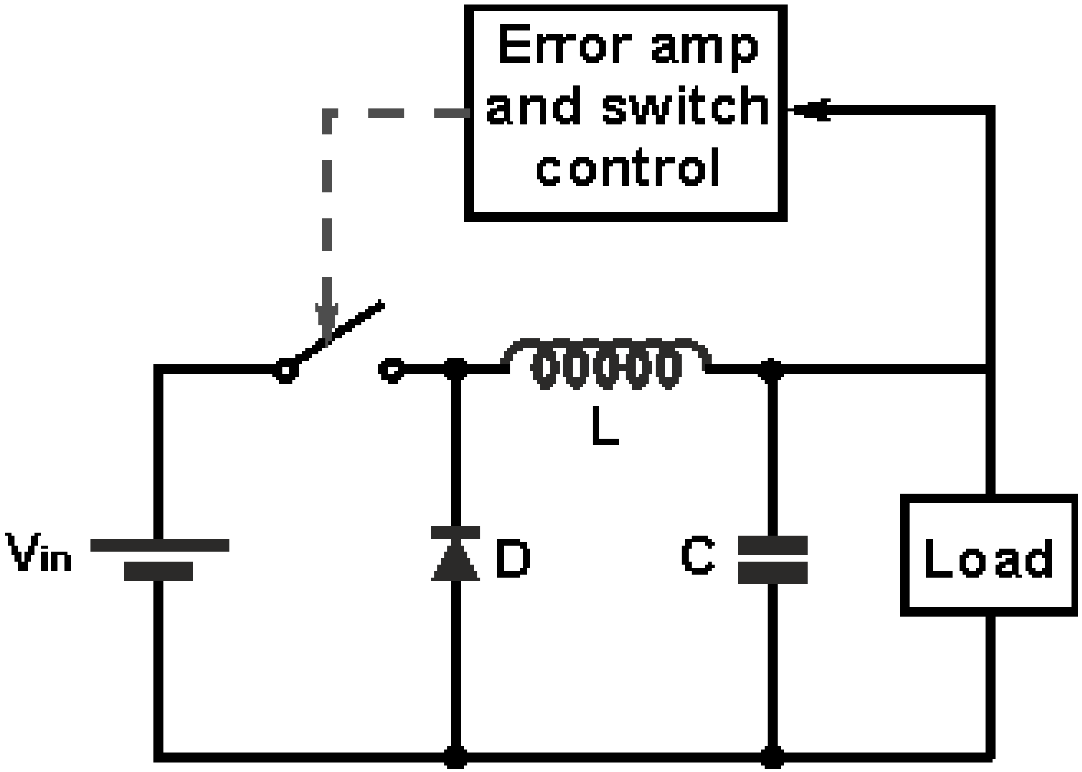
$$V_0 = V_S\left(\frac{T}{T - T_{ON}}\right) = 150 \times \left(\frac{150 \times 10^{-6}}{(150 - 75) \times 10^{-6}}\right) = 300Volts$$

2. In a type A chopper, the input supply voltage is 230 V the load resistance is 10Ω and there is a voltage drop of 2 V across the chopper thyristor when it is on. For a duty ratio of 0.4, calculate the average and rms values of the output voltage. Also find the chopper efficiency

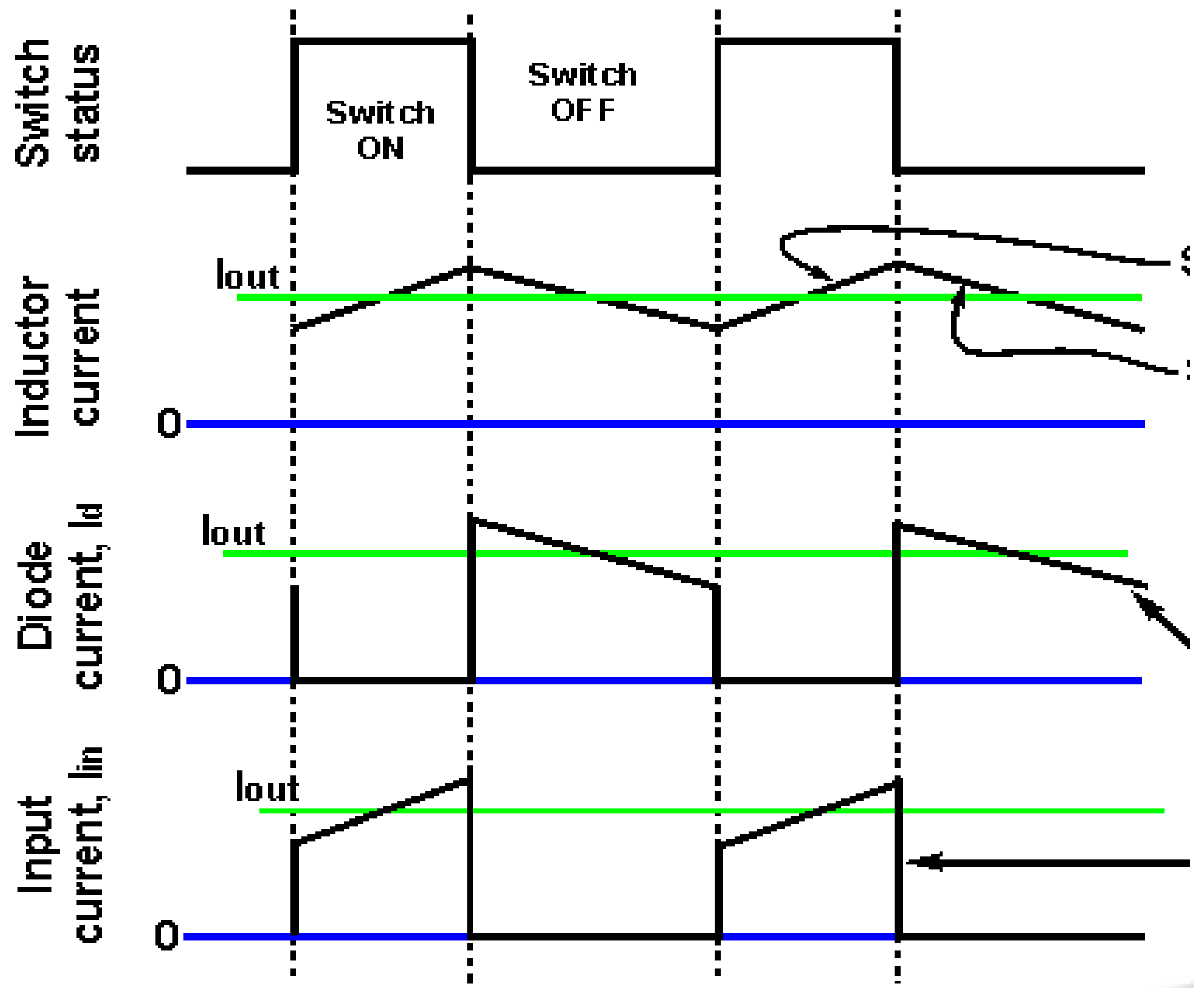
3. A step-up chopper supplies a load of 480 V from 230 V dc supply. Assuming the non conduction period of the thyristor to be 50 microsecond, find the on time of the thyristor

Buck regulator

- With power being a key parameter in many designs, step down or "buck" regulators are widely used.
- Although a resistor would enable voltage to be dropped, power is lost, and in applications such as the many battery powered items used today, power consumption is a crucial element.
- As a result step down switch mode converters or as they are more commonly termed, buck regulators are widely used.
- Linear step down
- The most basic form of step down transition is to use a resistor as a potential divider or voltage dropper. In some cases a zener diode may also be used to stabilize the voltage.

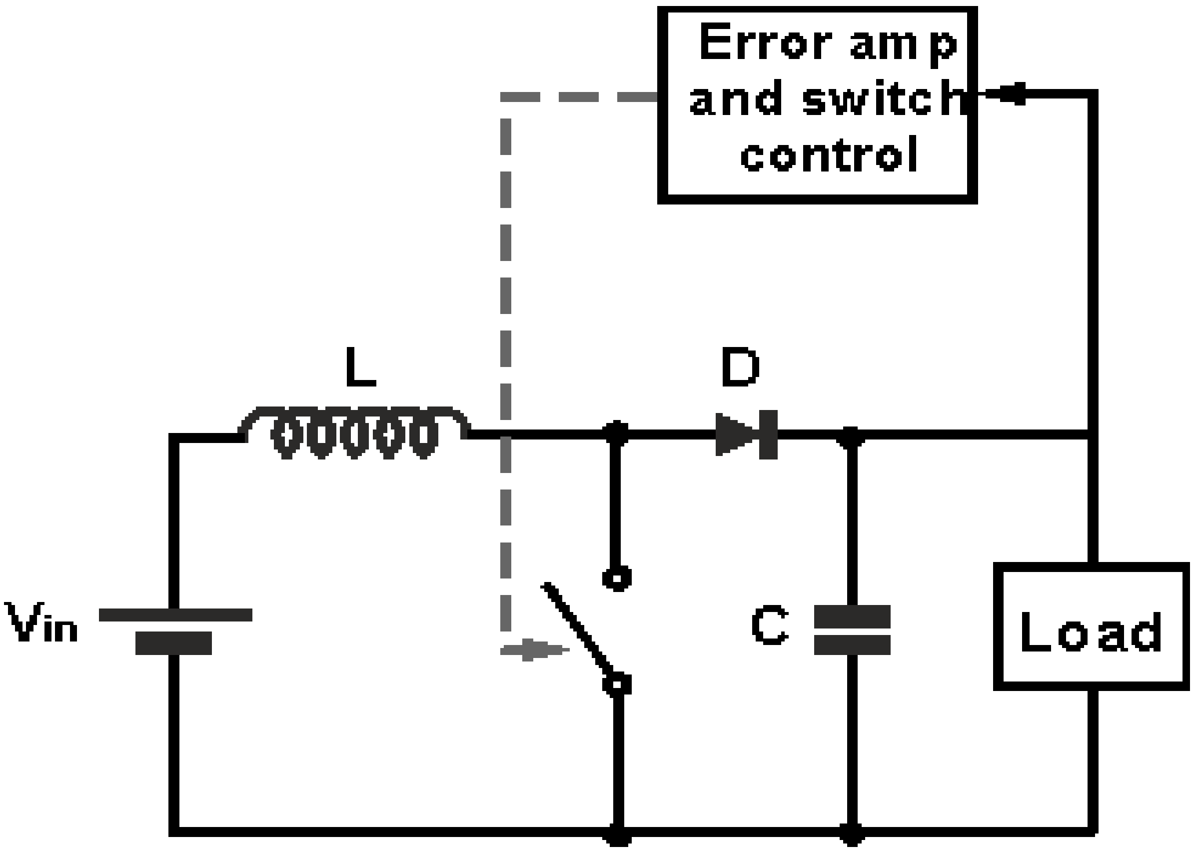


circuit diagram of Buck regulator

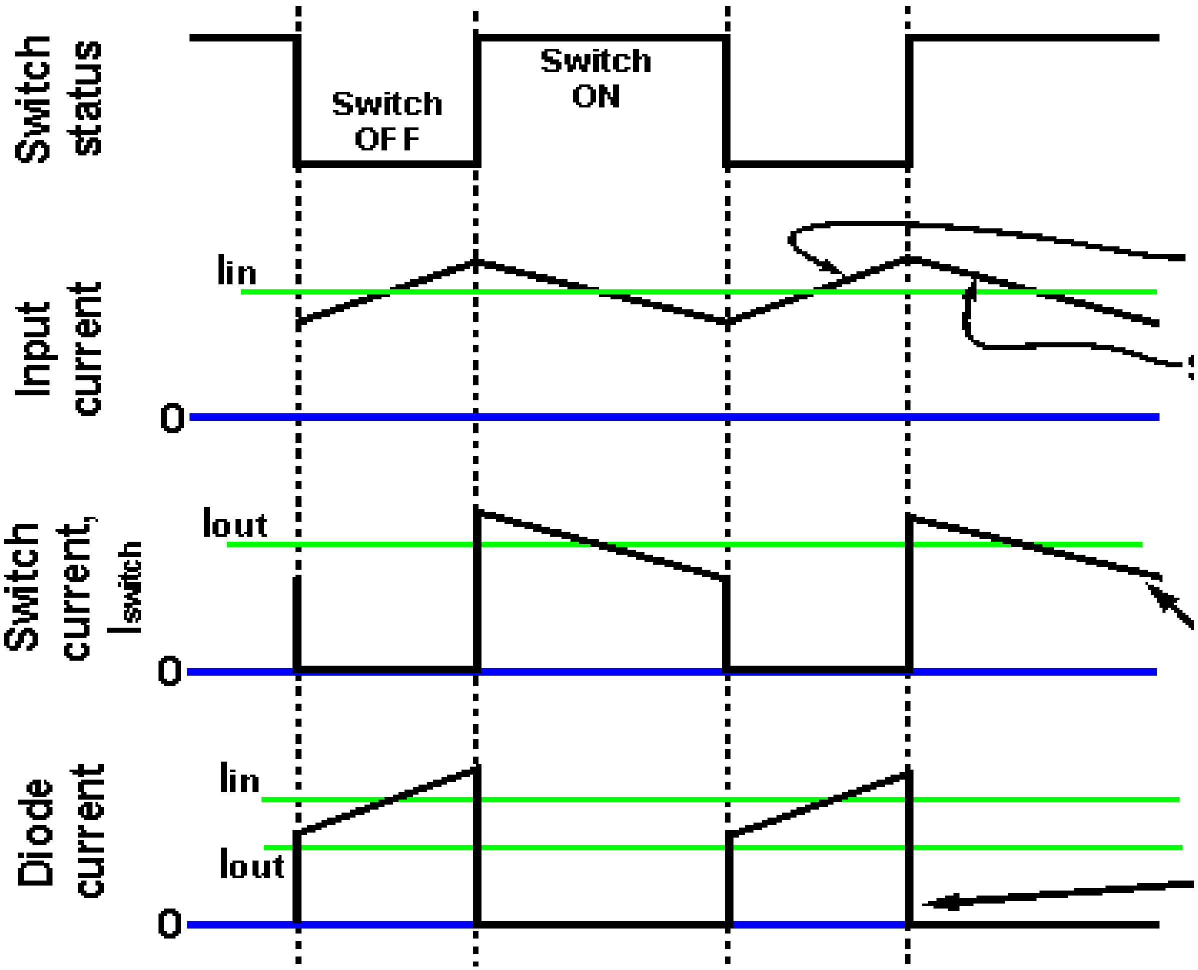


Input and output waveforms of Buck regulator

Boost regulator



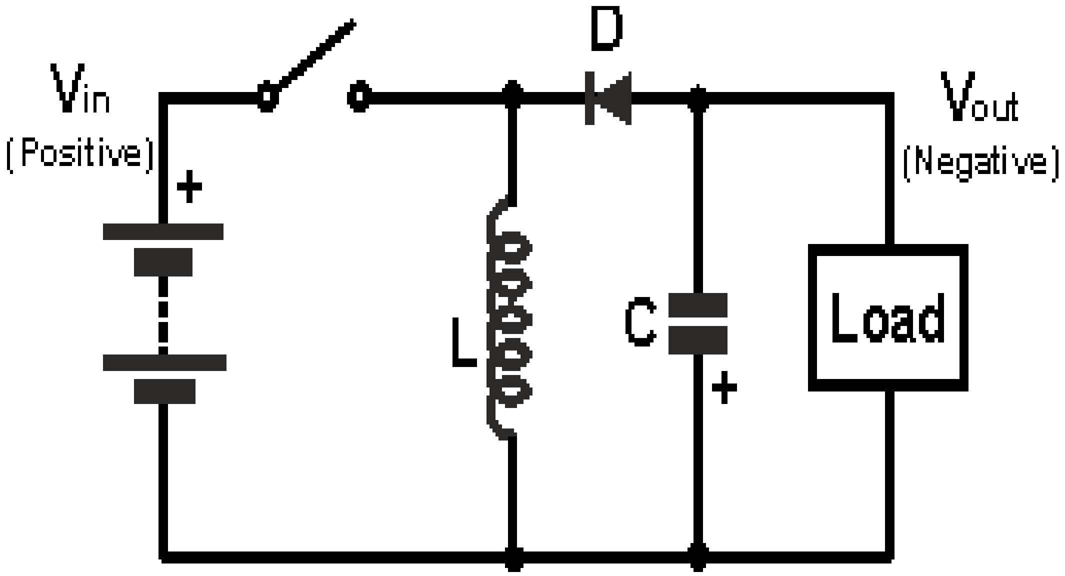
circuit diagram of Boost regulator



Input and output waveforms of Boost regulator

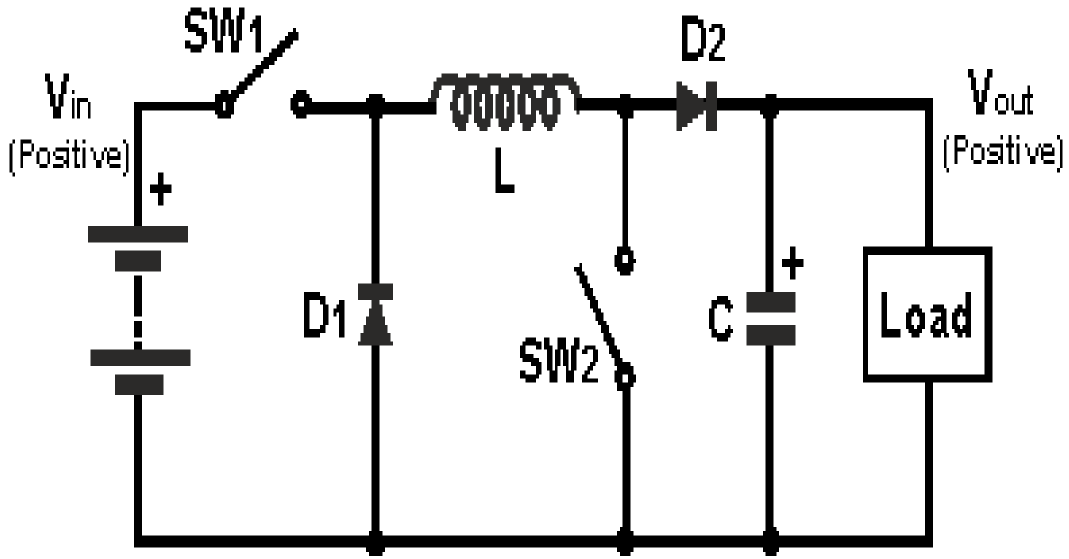
Buck boost regulator

- The buck-boost DC-DC converter offers a greater level of capability than the buck converter of boost converter individually, it as expected it extra components may be required to provide the level of functionality needed.
- There are several formats that can be used for buck-boost converters:
- *+Vin, -Vout:* This configuration of a buck-boost converter circuit uses the same number of components as the simple buck or boost converters. However this buck-boost regulator or DC-DC converter produces a negative output for a positive input. While this may be required or can be accommodated for a limited number of applications, it is not normally the most convenient format.



circuit diagram of buck boost regulator

- When the switch in closed, current builds up through the inductor. When the switch is opened the inductor supplies current through the diode to the load.
- Obviously the polarities (including the diode) within the buck-boost converter can be reversed to provide a positive output voltage from a negative input voltage.
- *+Vin, +Vout:* The second buck-boost converter circuit allows both input and output to be the same polarity. However to achieve this, more components are required. The circuit for this buck boost converter is shown below.



circuit diagram of buck boost regulator with two switches

Numerical problems

1. In a dc chopper, the average load current is 30 Amps, chopping frequency is 250 Hz. Supply voltage is 110 volts. Calculate the ON and OFF periods of the chopper if the load resistance is 2 ohms.

$I_{dc} = 30$ Amps, f = 250 Hz, V = 110 V, $R = 2\Omega$

Chopping period, $T = \frac{1}{f} = \frac{1}{250} = 4\times10^{-3} = 4$ msecs

$$I_{dc} = \frac{V_{dc}}{R} \text{ and } V_{dc} = dV$$

Therefore $I_{dc} = \frac{dV}{R}$

$$d = \frac{I_{dc}R}{V} = \frac{30\times2}{110} = 0.545$$

Chopper ON period, $t_{ON} = dT = 0.545\times4\times10^{-3} = 2.18$ msecs

Chopper OFF period, $t_{OFF} = T - t_{ON}$

$$t_{OFF} = 4\times10^{-3} - 2.18\times10^{-3}$$

$$t_{OFF} = 1.82\times10^{-3} = 1.82 \text{ msec}$$

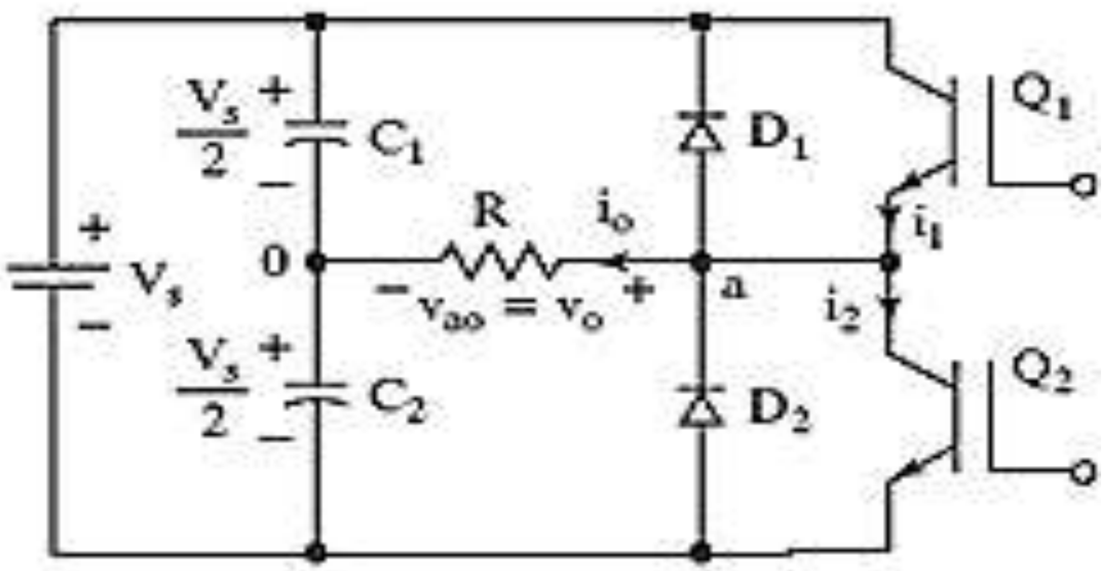
2. A step up chopper has input voltage of 220 V and output voltage of 660 V. If the non-conducting time of thyristor chopper is 100 micro sec compute the pulse width of output voltage. In case the pulse width is halved for constant frequency operation , find the new output voltage

3. A chopper operating from 220V dc supply with for a duty cycle of 0.5 and chopping frequency of 1KHz drives an R L load with R = 1Ω , L=1mH and E = 105V. Find whether the current is continuous and also find the values of I_{max} and I_{min}.

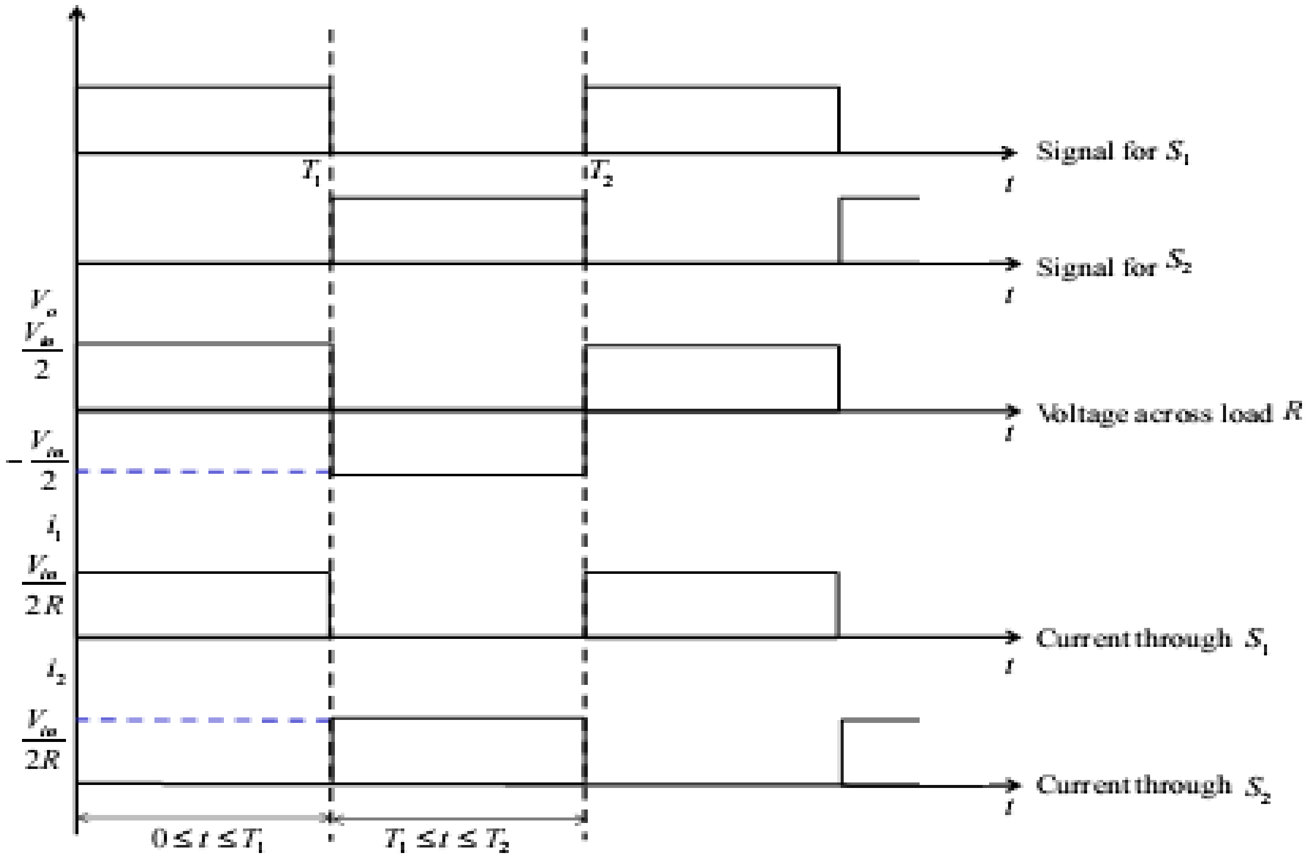
UNIT V
INVERTERS

Introduction to Inverters

- The word 'inverter' in the context of power-electronics denotes a class of power conversion (or power conditioning) circuits that operates from a dc voltage source or a dc current source and converts it into ac voltage or current. The inverter does reverse of what ac-to-dc converter does (refer to ac to dc converters). Even though input to an inverter circuit is a dc source, it is not uncommon to have this dc derived from an ac source such as utility ac supply.

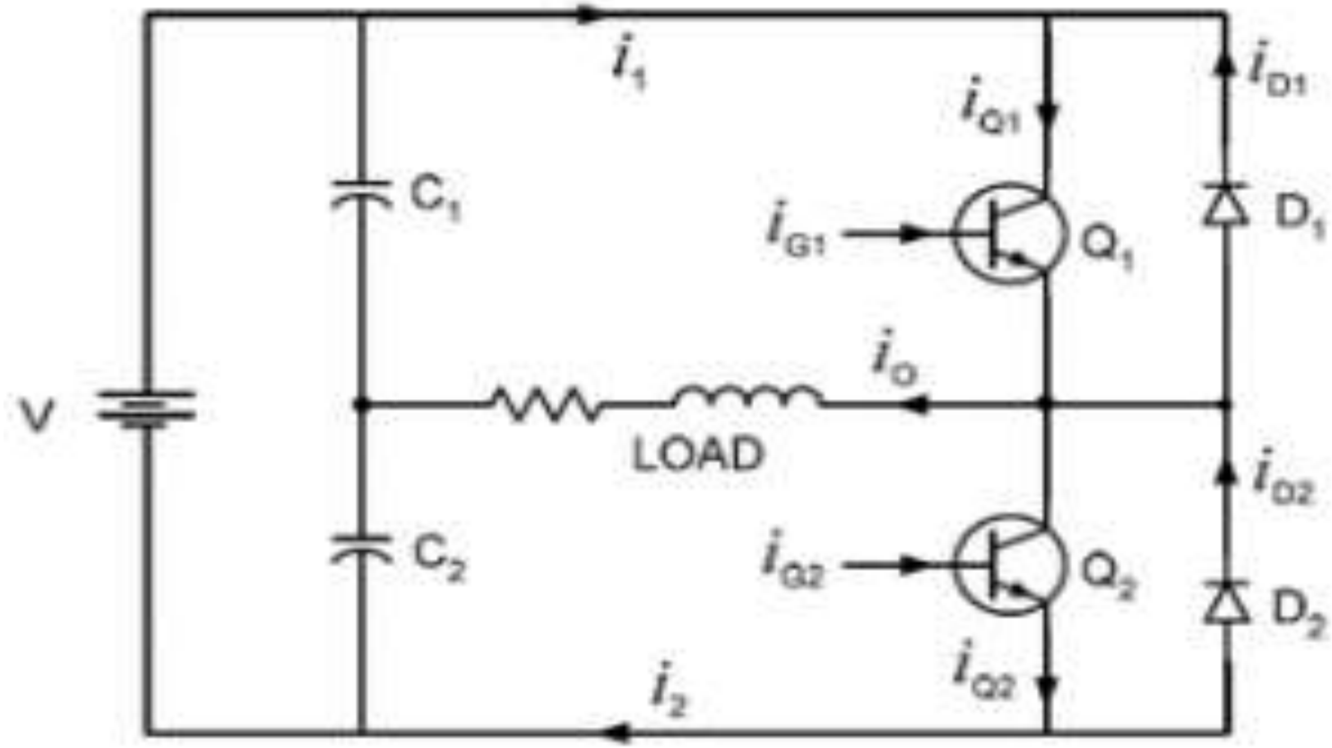


Single phase Half Bridge DC-AC inverter with R load



Single phase Half Bridge DC-AC inverter output waveforms

Half Bridge DC-AC Inverter with L Load and R-L Load

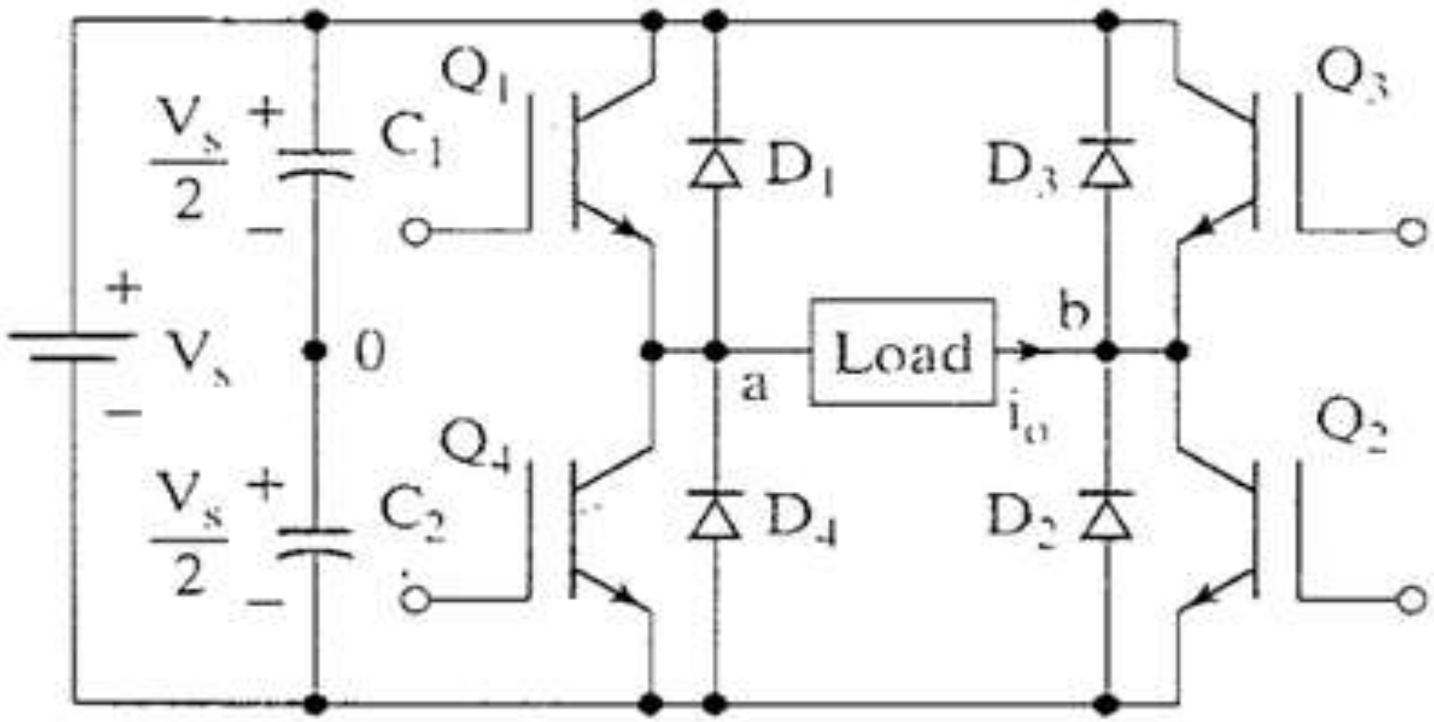


Operation of single phase full bridge inverter

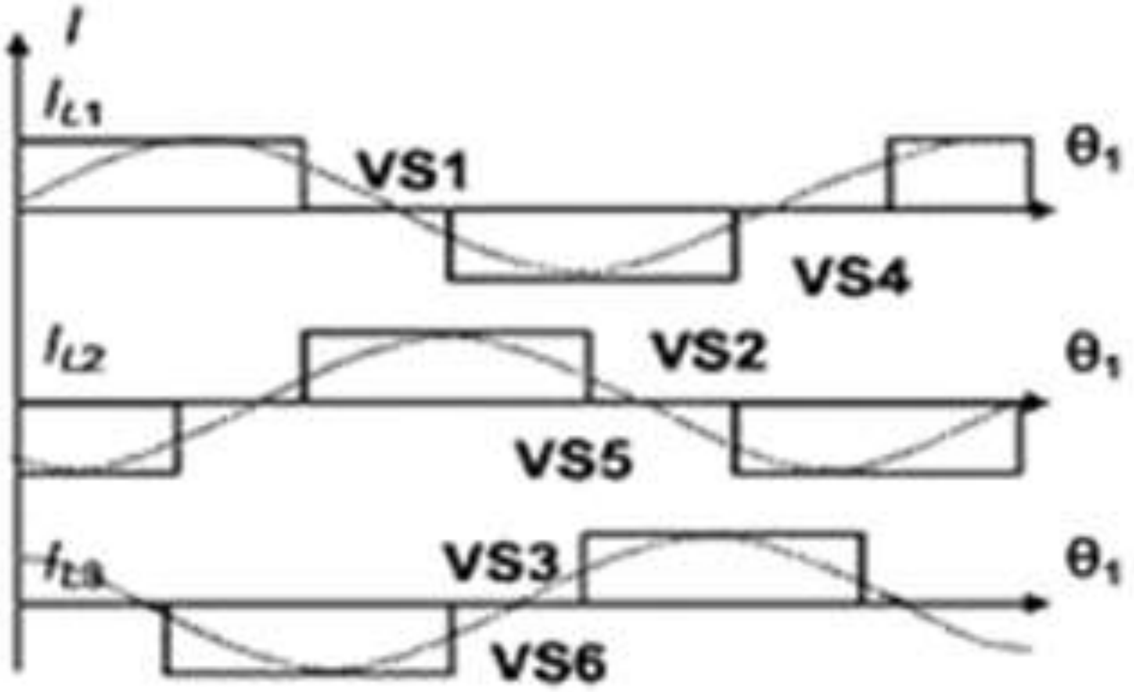
- A single phase bridge DC-AC inverter is shown in Figure below. The analysis of the single phase DC-AC inverters is done taking into account following assumptions and conventions.

  1) The current entering node a in Figure 8 is considered to be positive.

  2) The switches S1, S2, S3 and S4 are unidirectional, i.e. they conduct current in one direction.

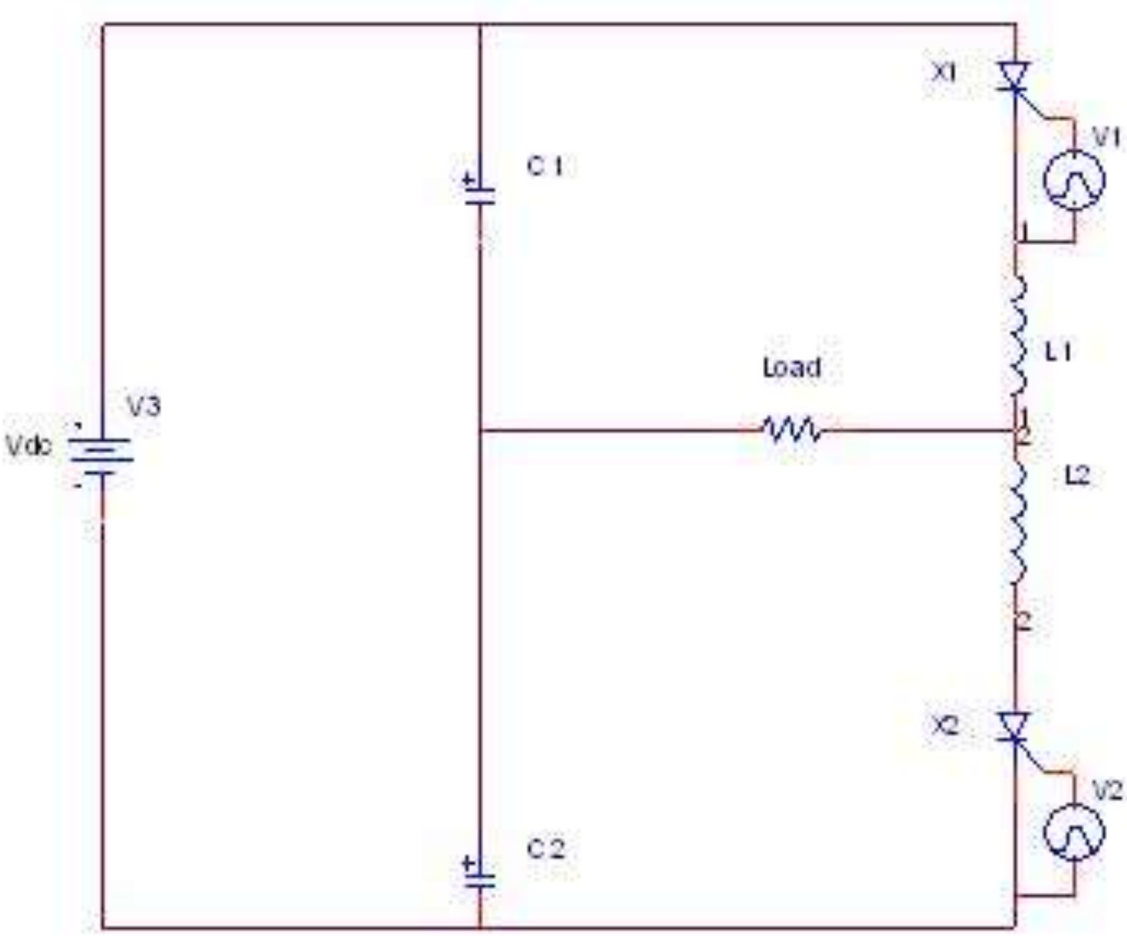


Single phase Full Bridge DC-AC inverter with R load



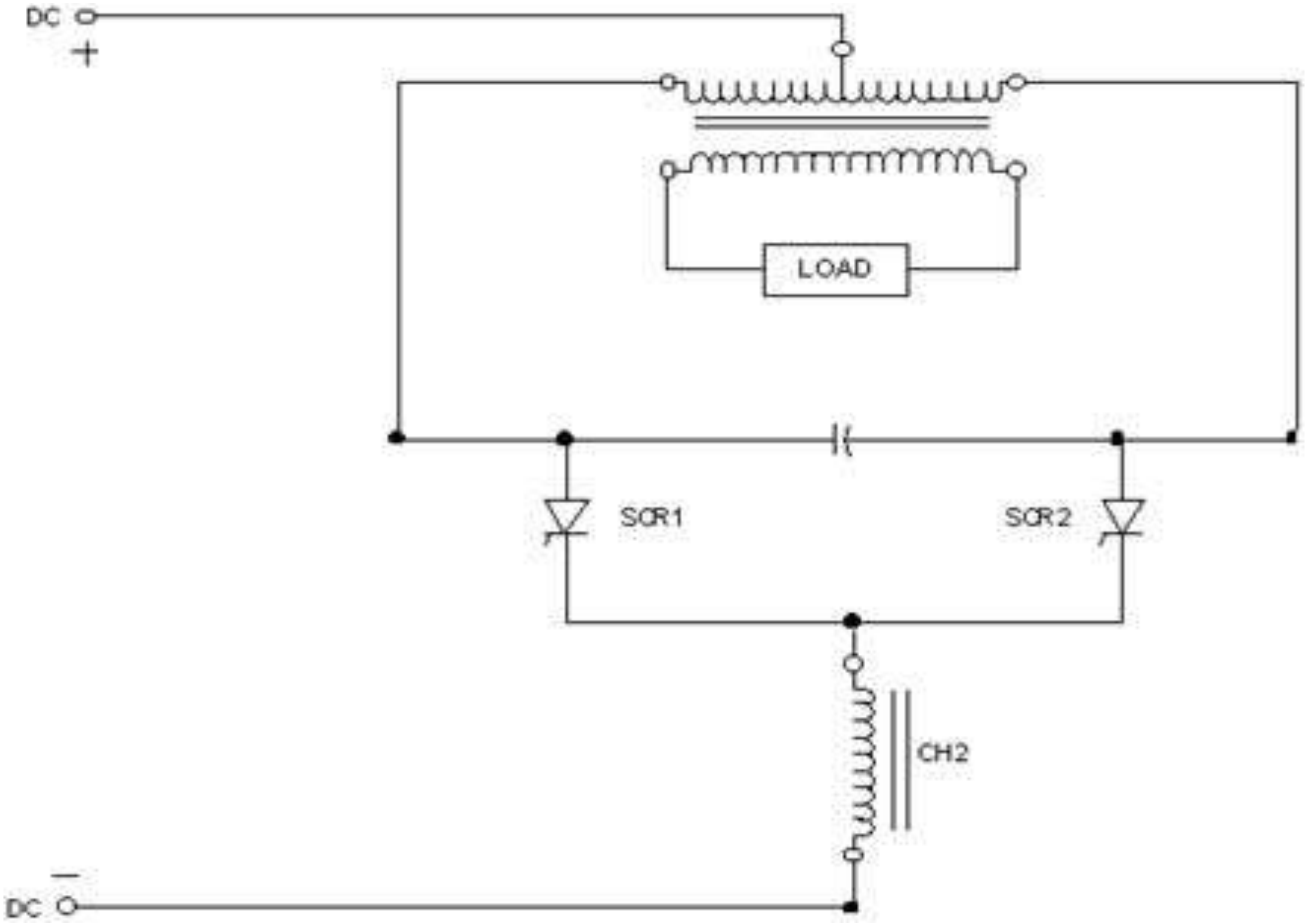
Single phase Full Bridge DC-AC inverter waveforms

Series inverter

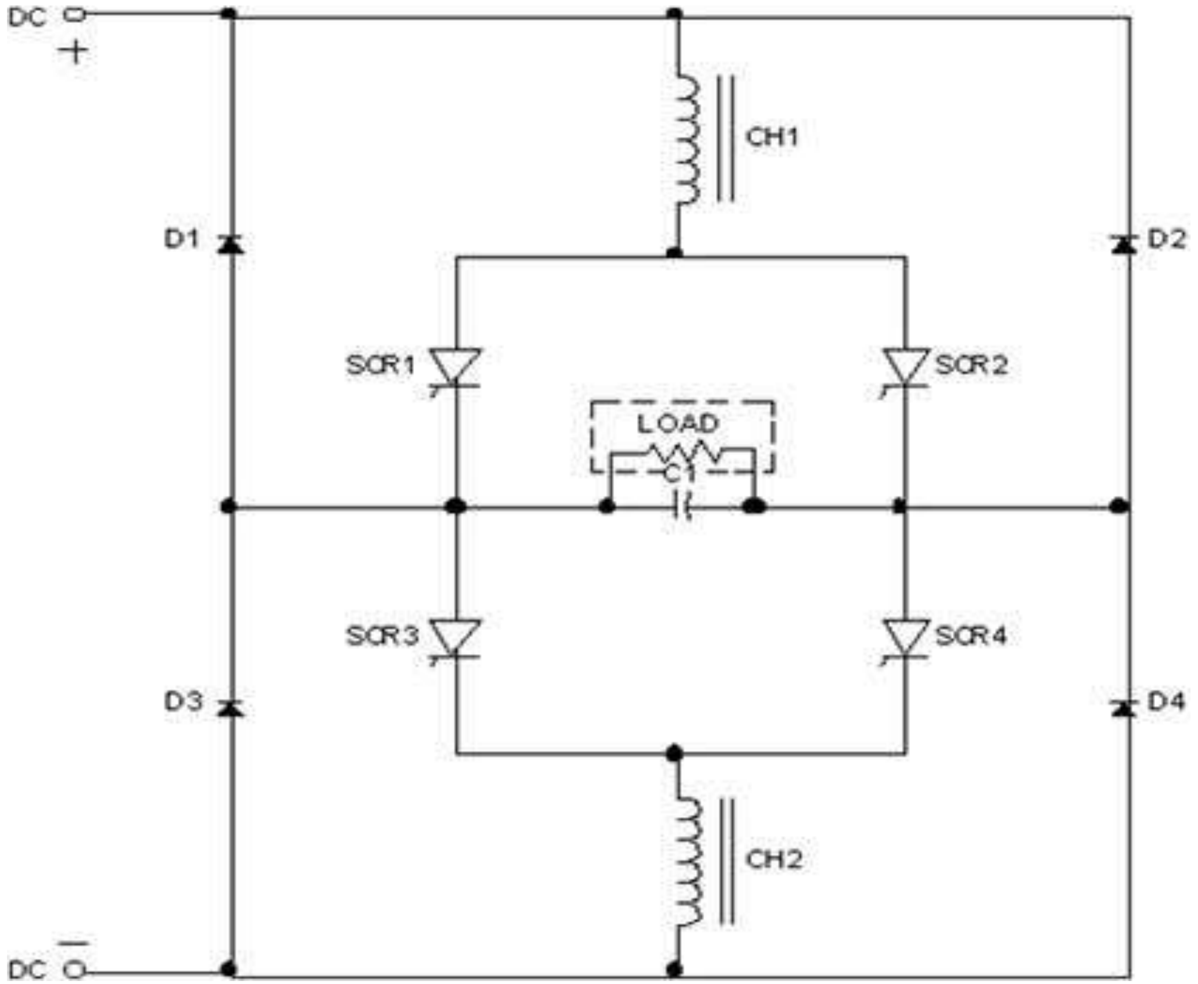


Operation of parallel inverter

- The single phase parallel inverter circuit consists of two SCRs T1 and T2, an inductor L, an output transformer and a commutating capacitor C. The output voltage and current are Vo and Io respectively. The function of L is to make the source current constant. During the working of this inverter, capacitor C comes in parallel with the load via the transformer. So it is called a parallel inverter.



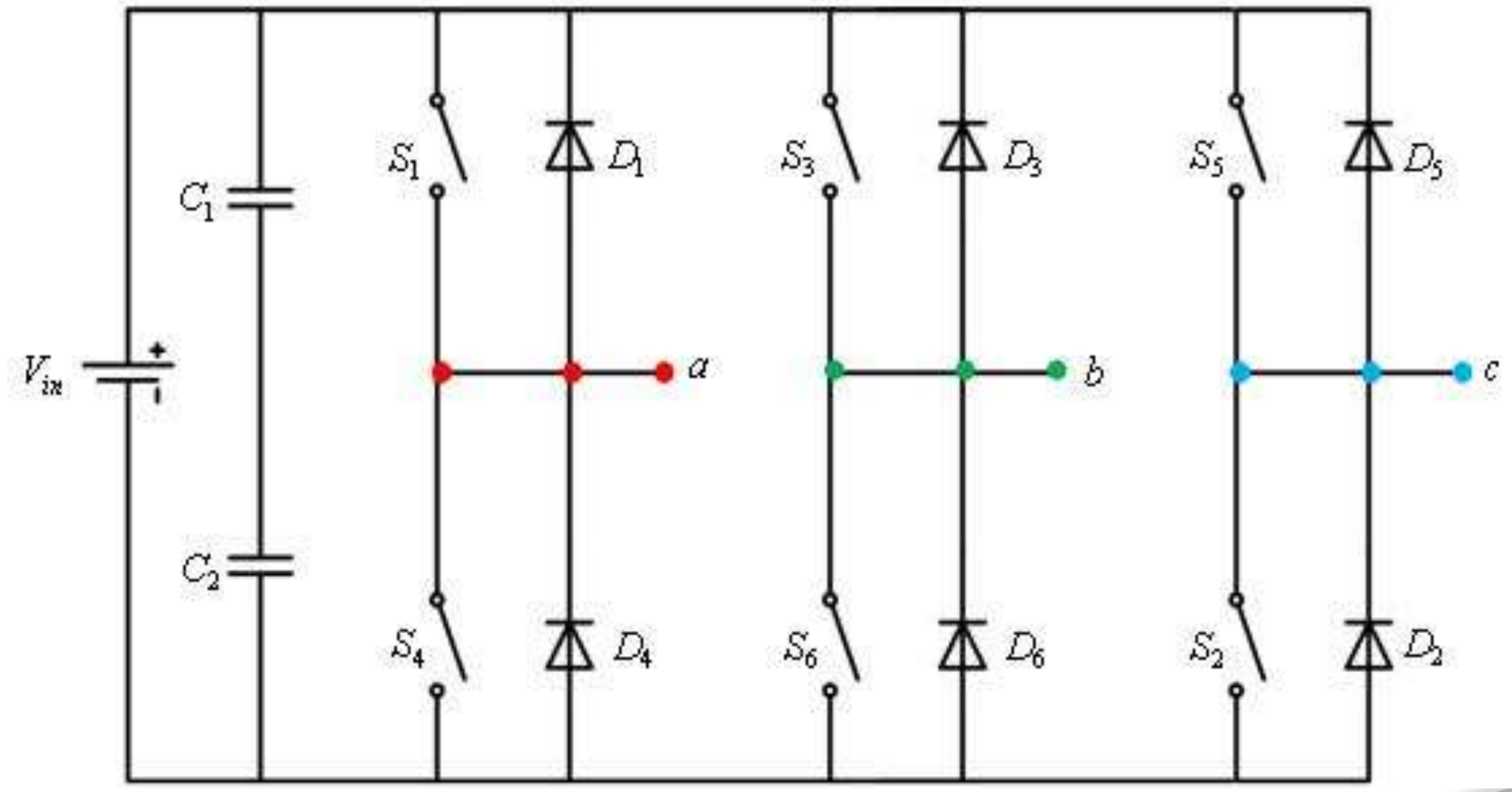
Circuit diagram of parallel inverter



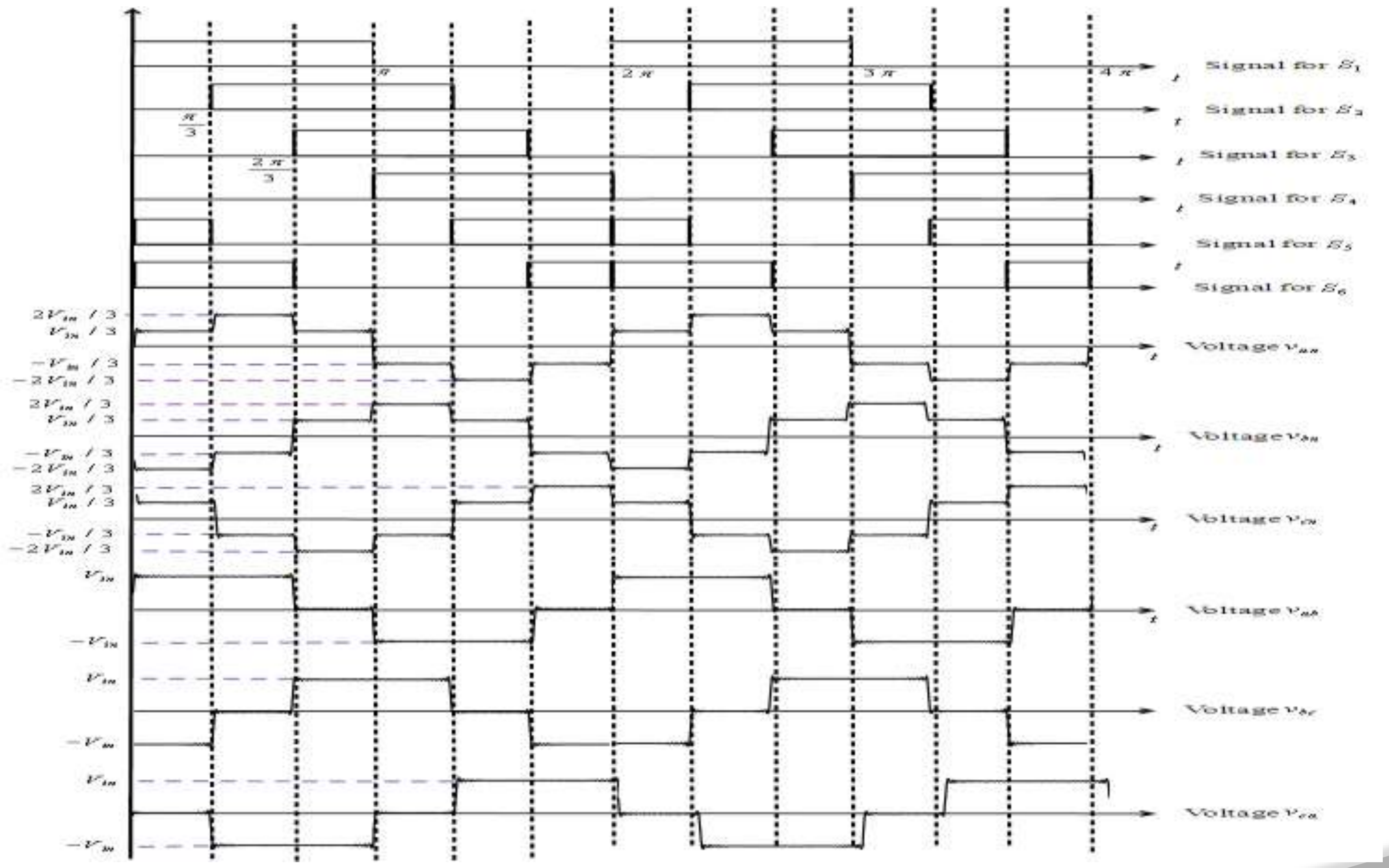
Circuit diagram of parallel commutated inverter

Three Phase DC-AC Converters

- Three phase inverters are normally used for high power applications. The advantages of a three phase inverter are:
- The frequency of the output voltage waveform depends on the switching rate of the swtiches and hence can be varied over a wide range.
- The direction of rotation of the motor can be reversed by changing the output phase sequence of the inverter.
- The ac output voltage can be controlled by varying the dc link voltage.



Circuit diagram of three phase bridge inverter



Line and phase voltages of three phase bridge inverter

$$v_{an} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin(n\omega t)$$

$$v_{bn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t-\frac{2n\pi}{3}\right)$$

$$v_{cn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t-\frac{4n\pi}{3}\right)$$

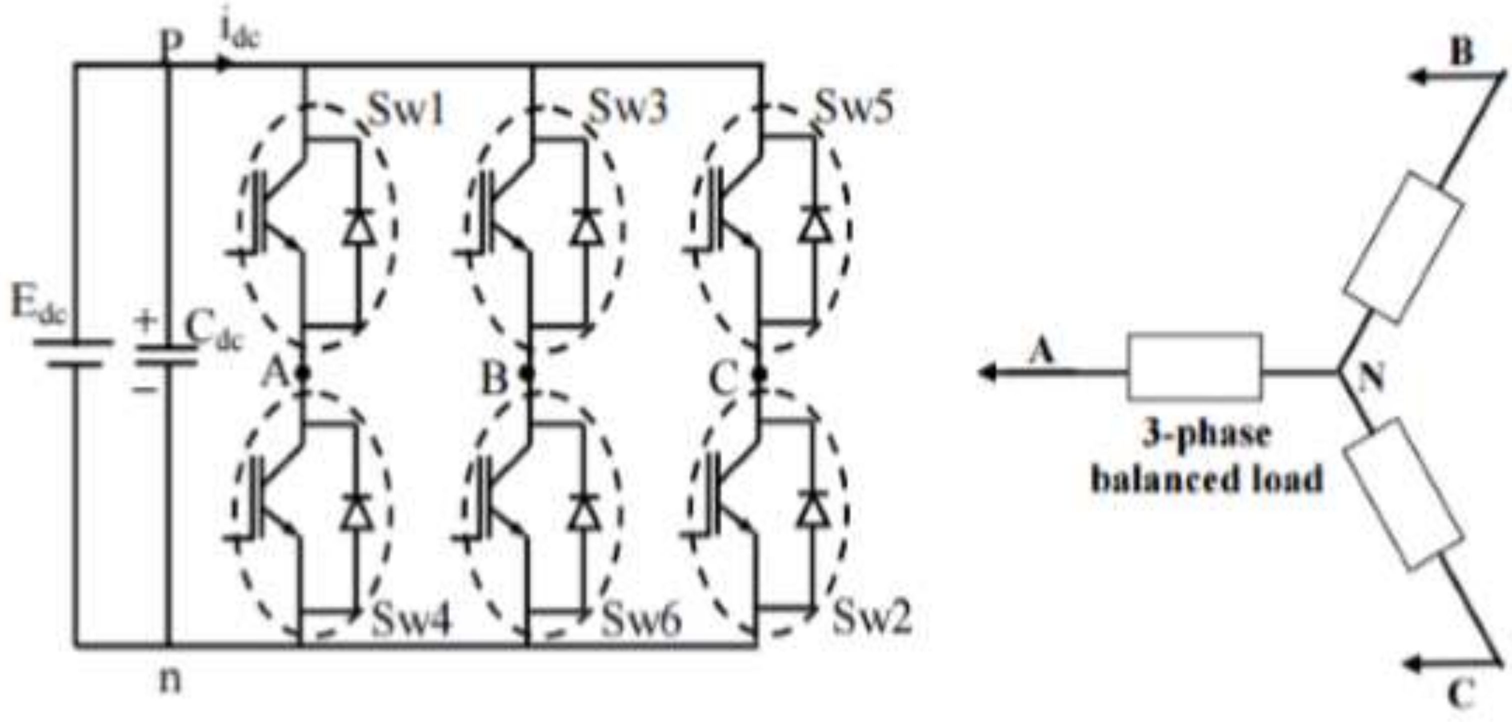
$$v_{ab} = v_{an} - v_{bn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t+\frac{n\pi}{6}\right)$$

$$v_{bc} = v_{bn} - v_{cn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t-\frac{n\pi}{2}\right)$$

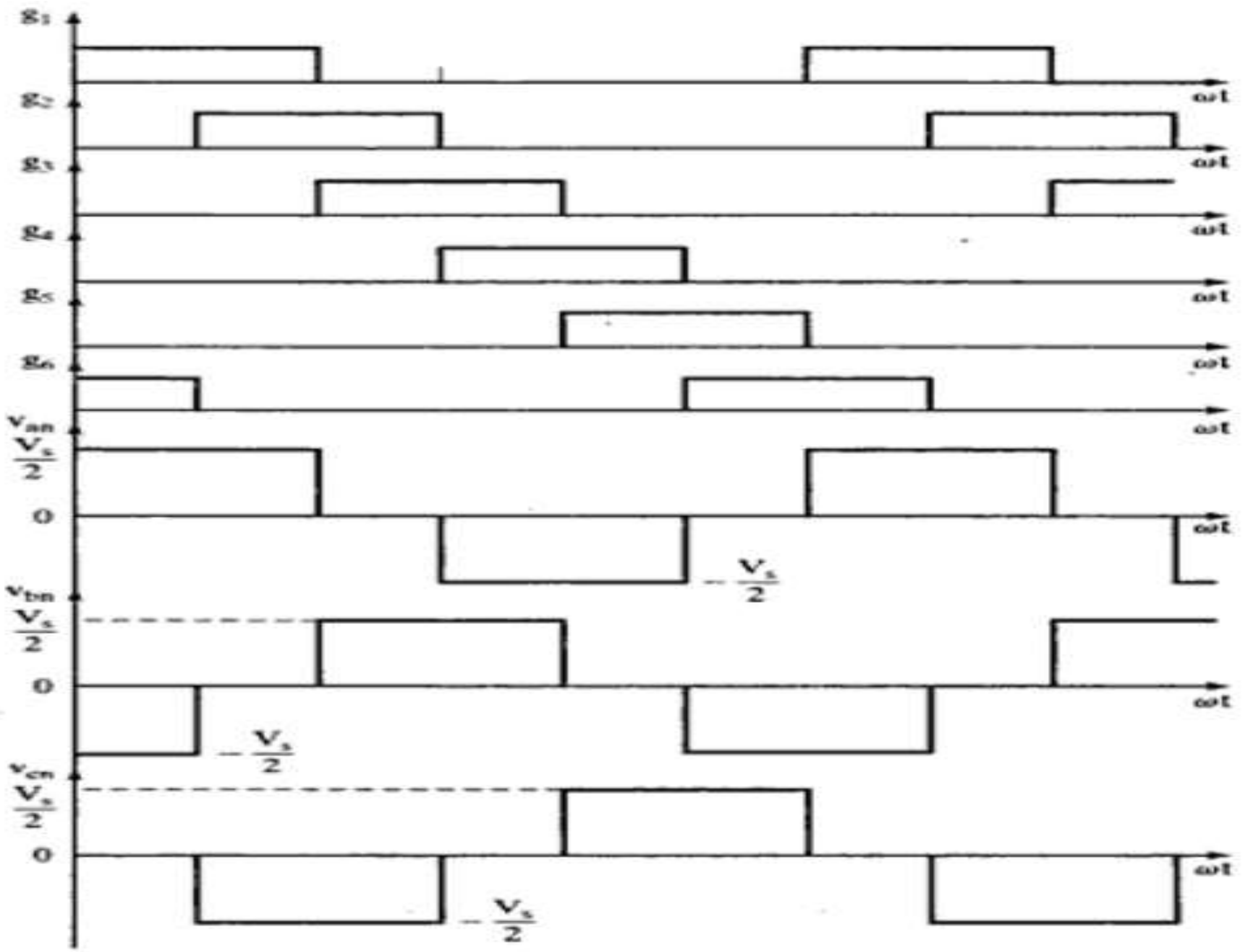
$$v_{ca} = v_{cn} - v_{an} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t-\frac{7n\pi}{6}\right)$$

Three Phase DC-AC Converters with 120 degree conduction mode

- In this mode of conduction, each electronic device is in a conduction state for 120°. It is most suitable for a delta connection in a load because it results in a six-step type of waveform across any of its phases. Therefore, at any instant only two devices are conducting because each device conducts at only 120°.
- The terminal A on the load is connected to the positive end while the terminal B is connected to the negative end of the source. The terminal C on the load is in a condition called floating state. Furthermore, the phase voltages are equal to the load voltages as shown below.
- Phase voltages = Line voltages
- $V_{AB} = V$
- $V_{BC} = -V/2$
- $V_{CA} = -V/2$

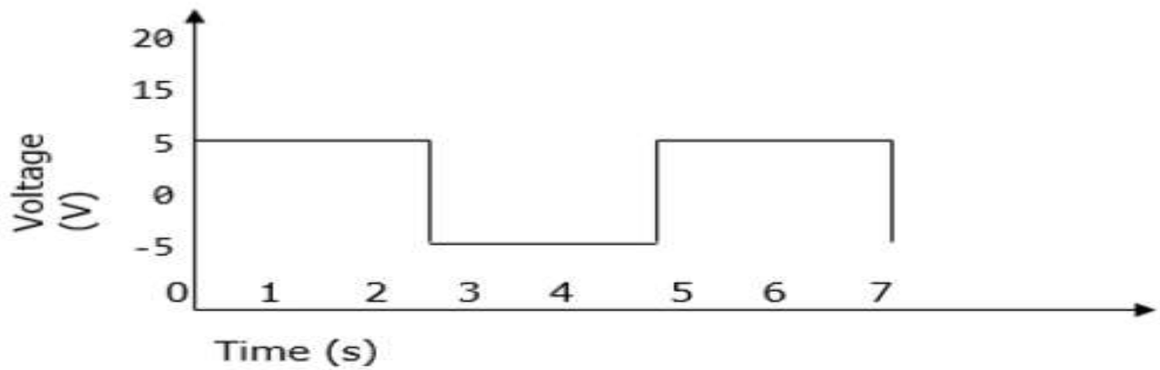


Circuit diagram of three phase bridge inverter

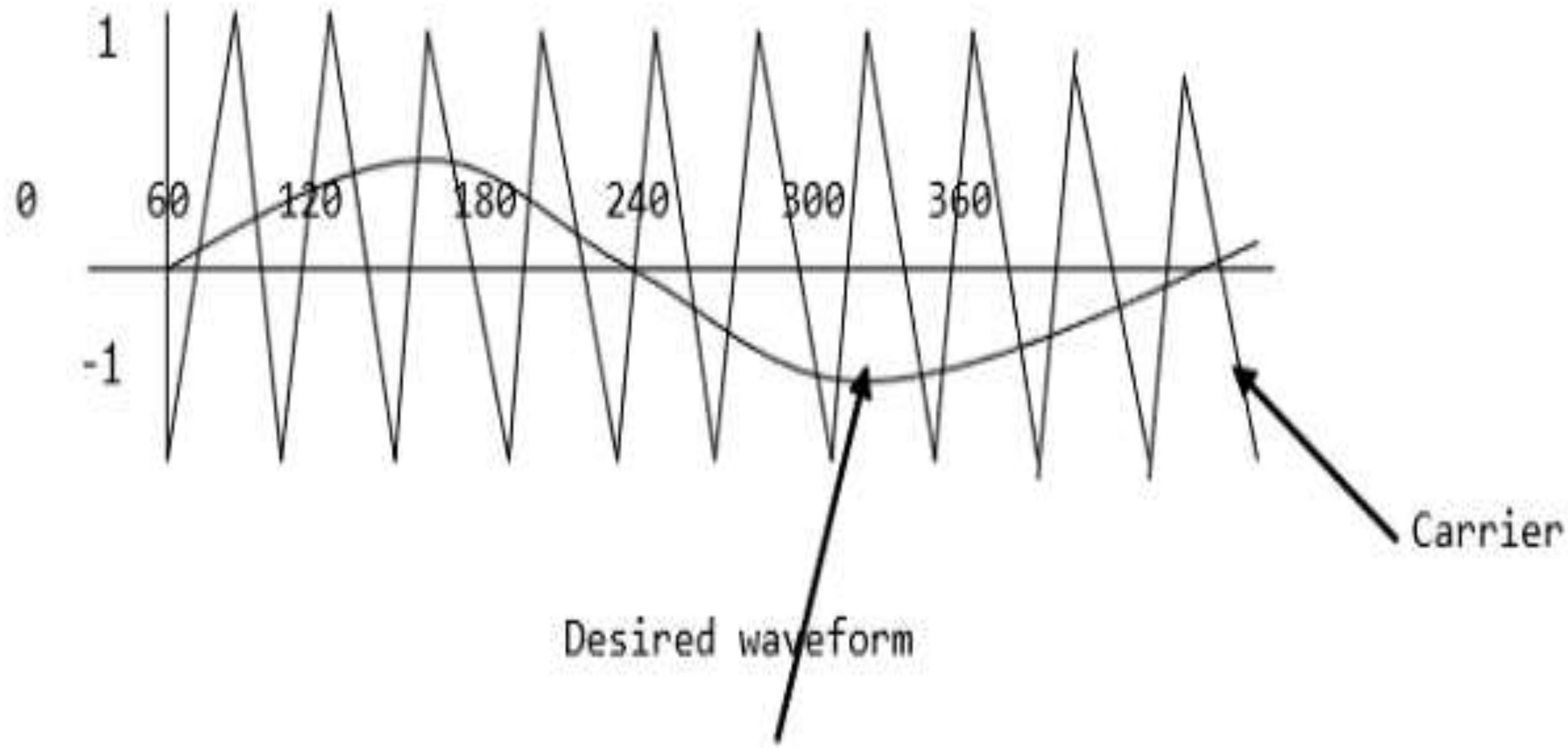


Line and phase voltages of three phase bridge inverter

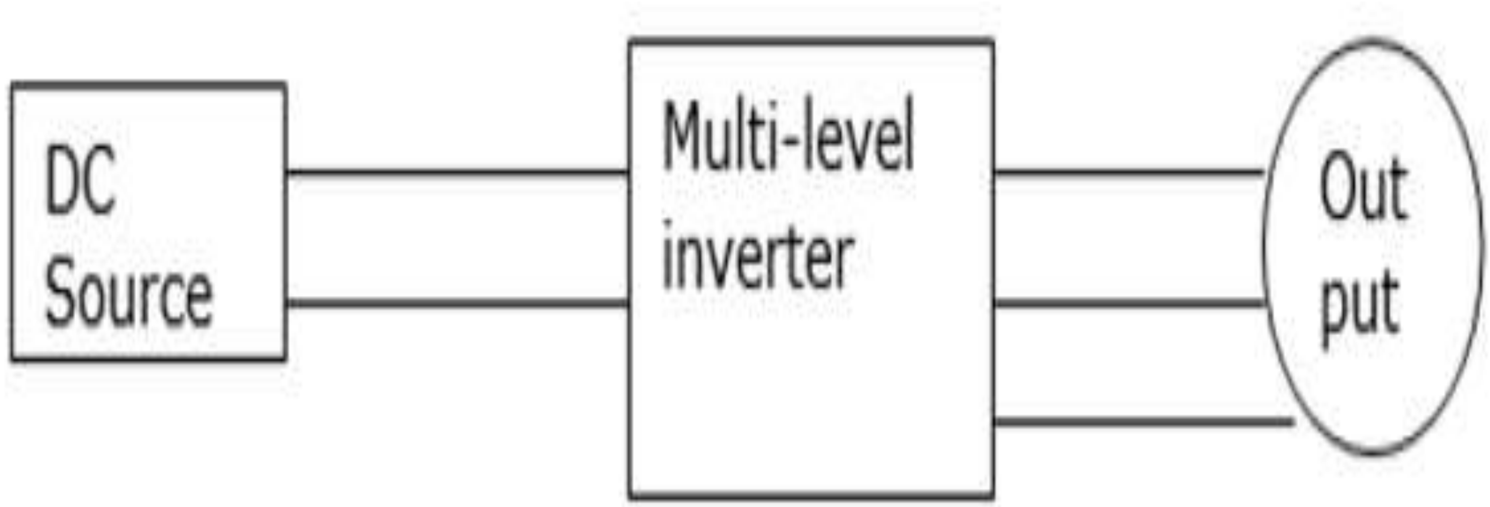
- PWM is a technique that is used to reduce the overall harmonic distortion (THD) in a load current. It uses a pulse wave in rectangular/square form that results in a variable average waveform value f(t), after its pulse width has been modulated. The time period for modulation is given by T.

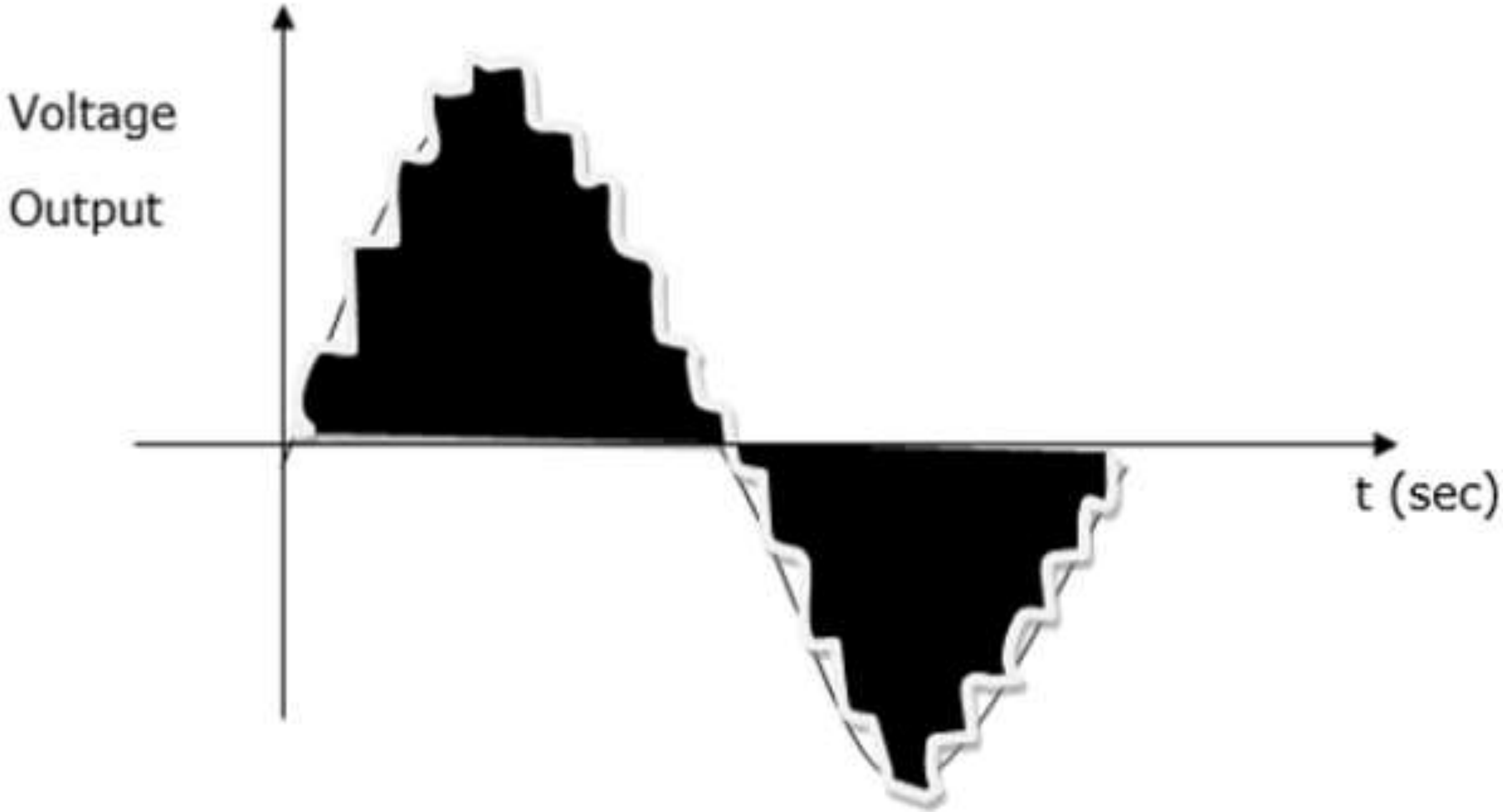


Sinusoidal Pulse Width Modulation



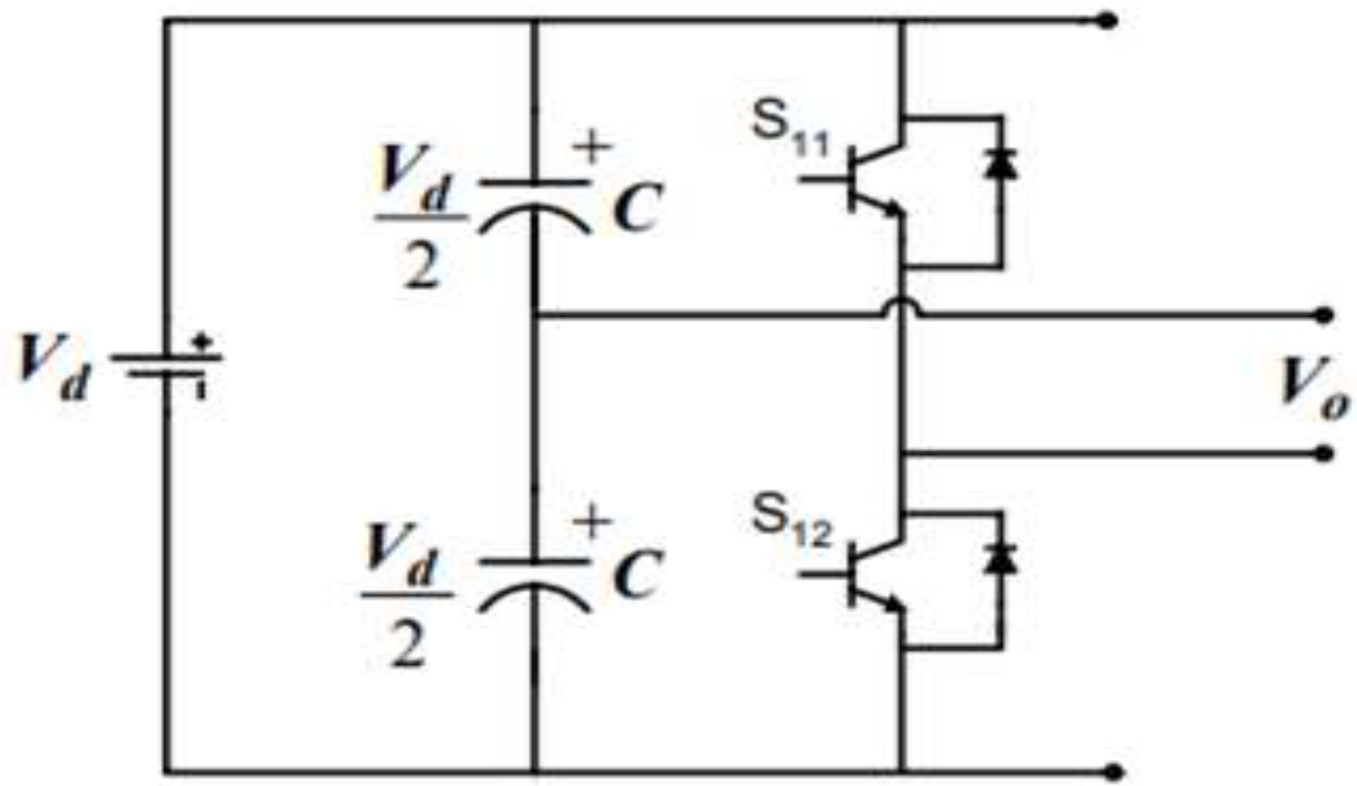
Multiple PWM



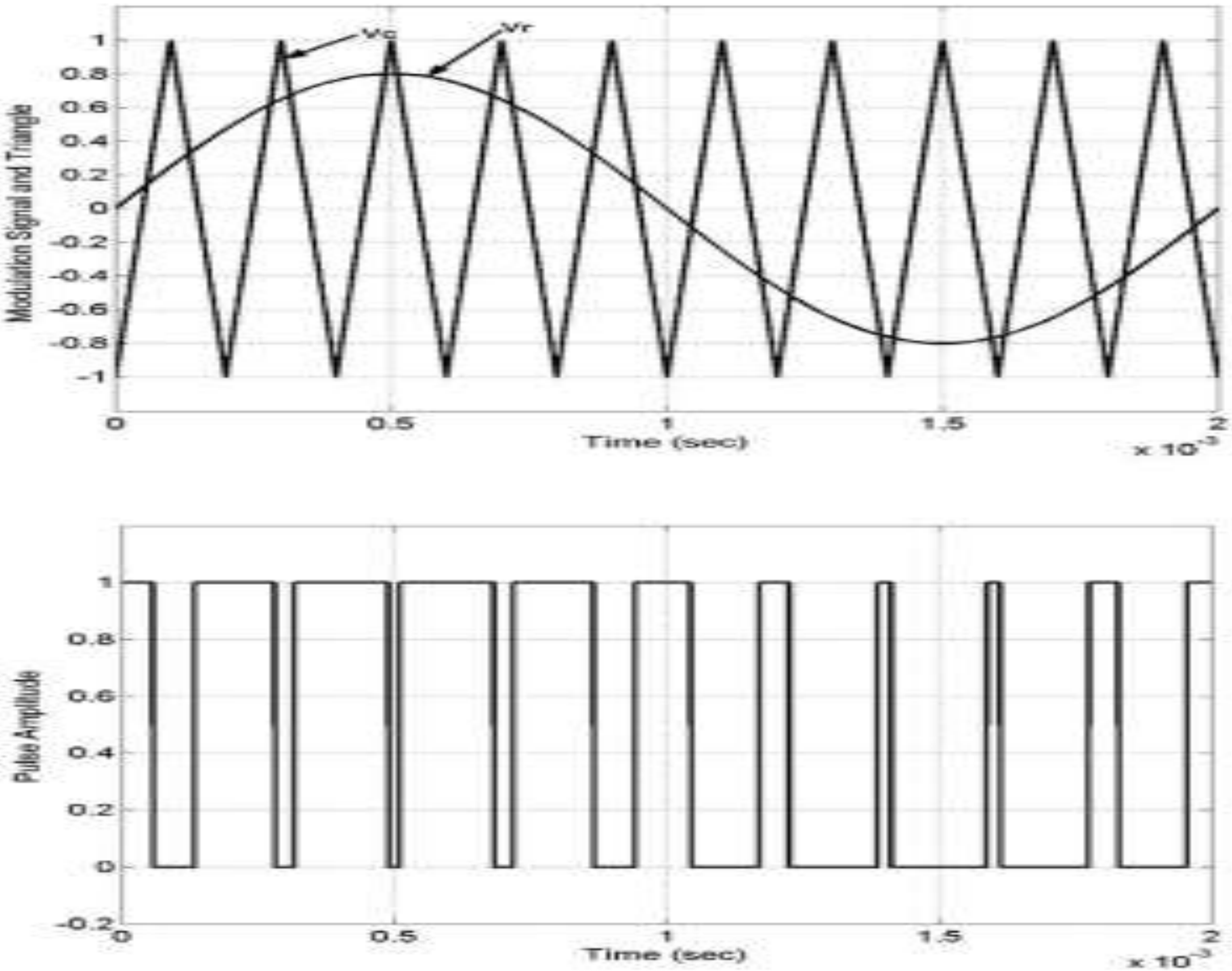


Waveform of multiple PWM technique

Operation of sinusoidal pulse width modulation

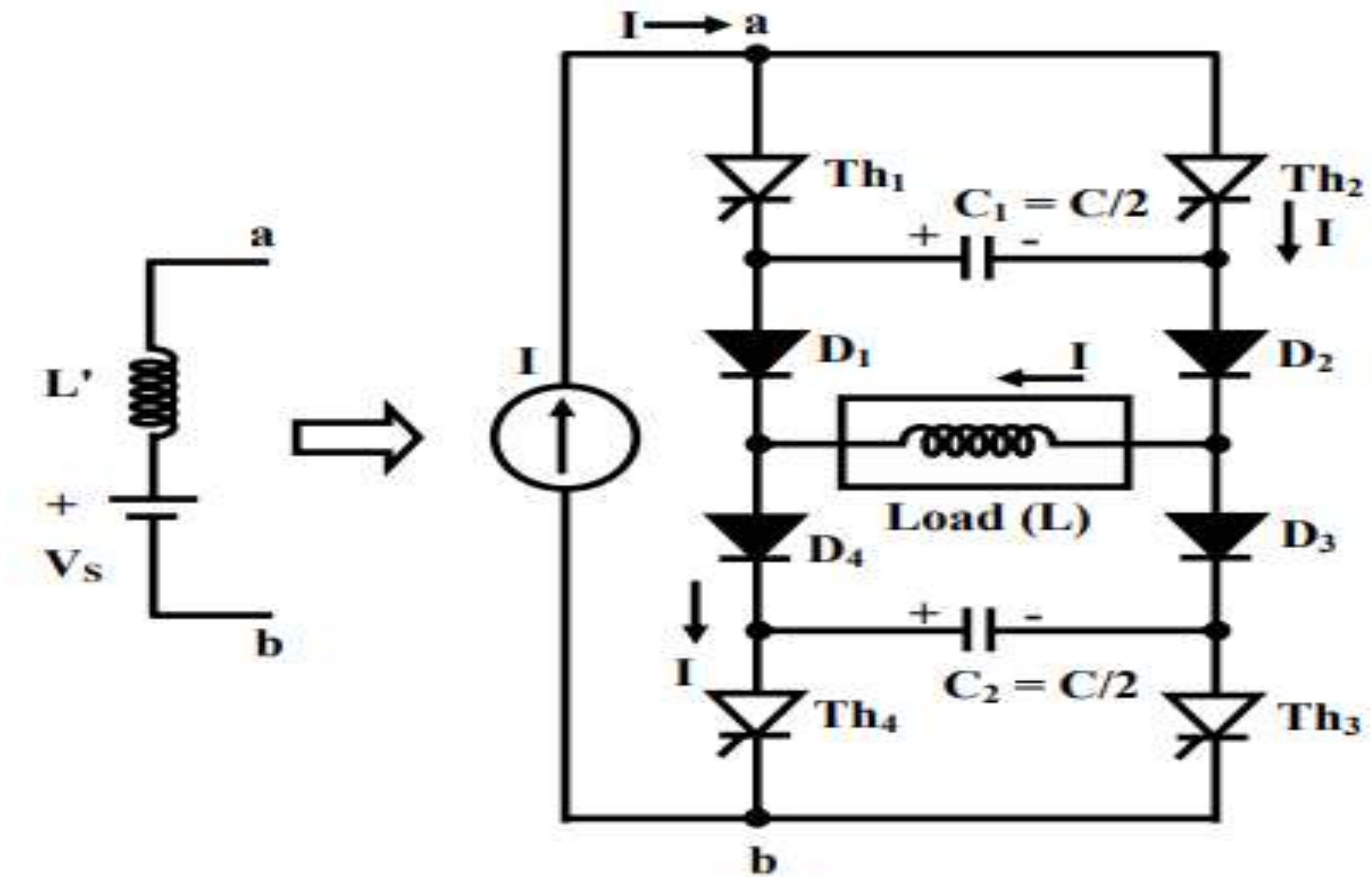


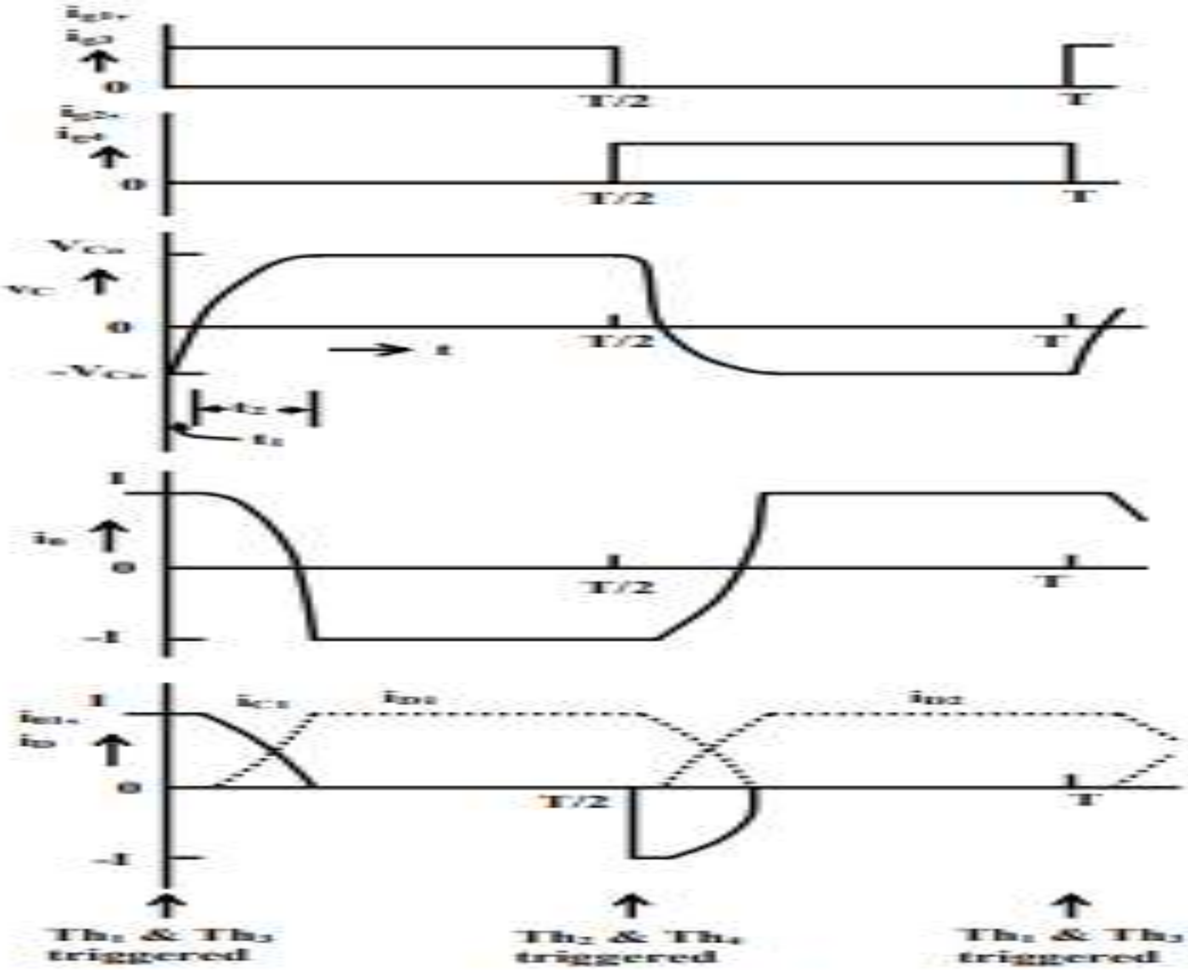
schematic diagram of Half bridge PWM inverter



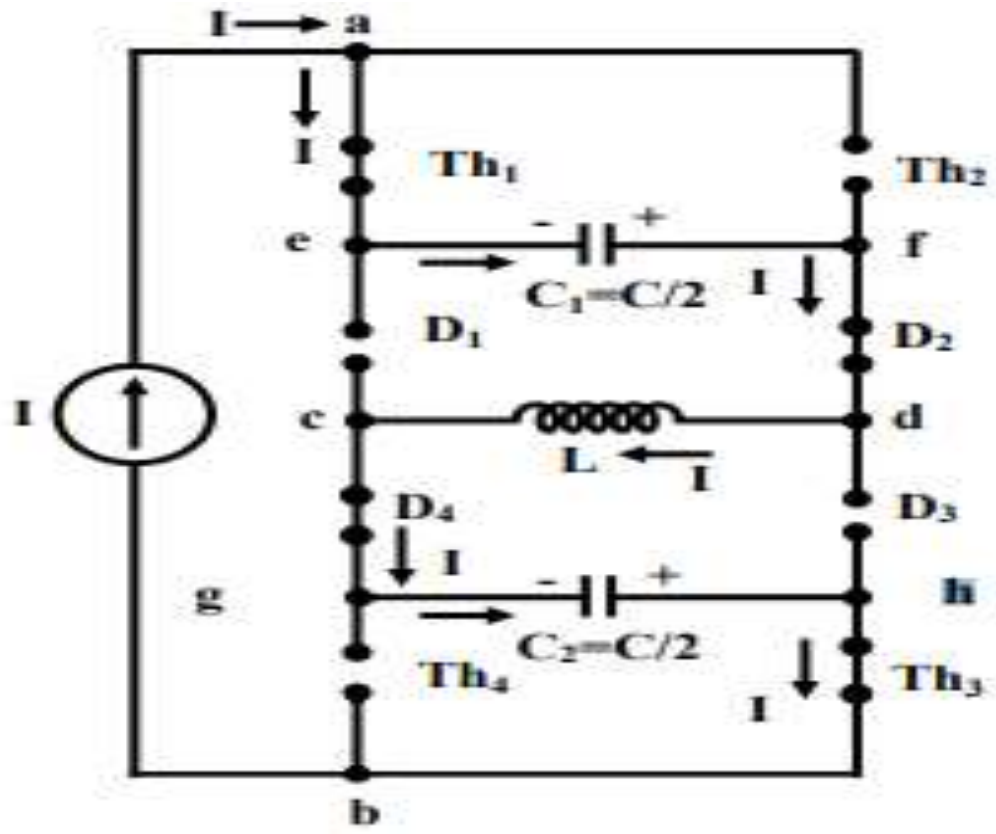
Sine-Triangle Comparison and switching pulses of half bridge PWM inverter

Operation of current source inverter with ideal switches

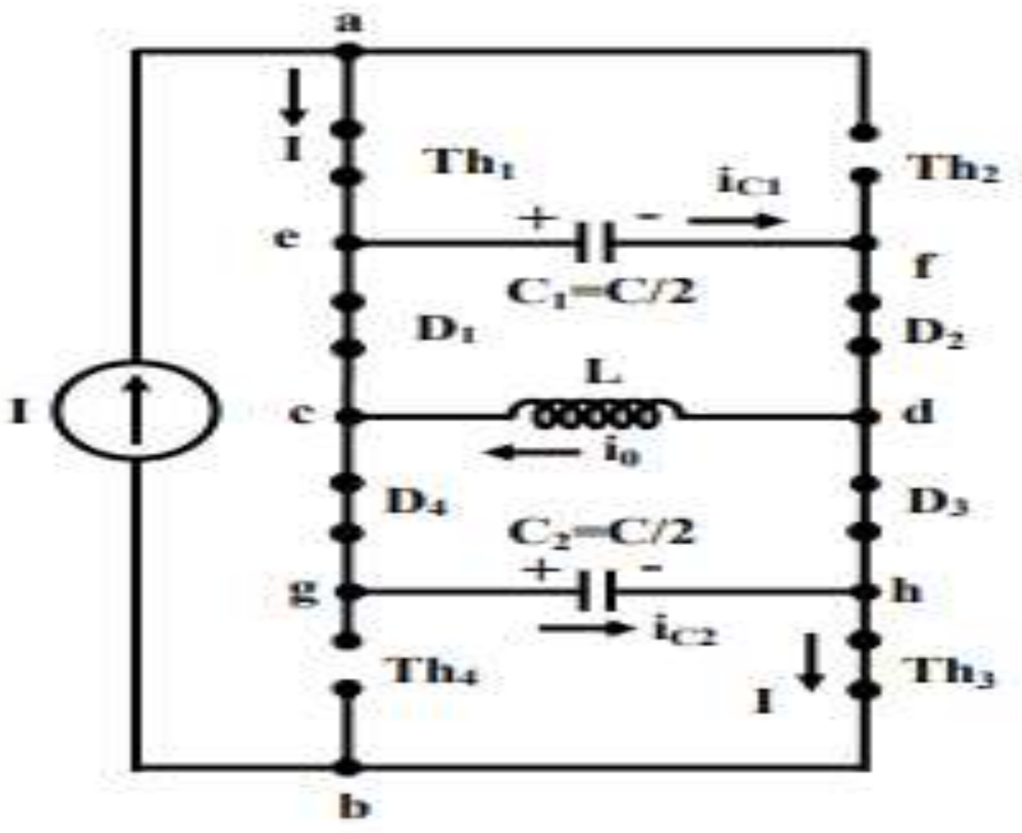




output waveforms of Single phase current source inverter



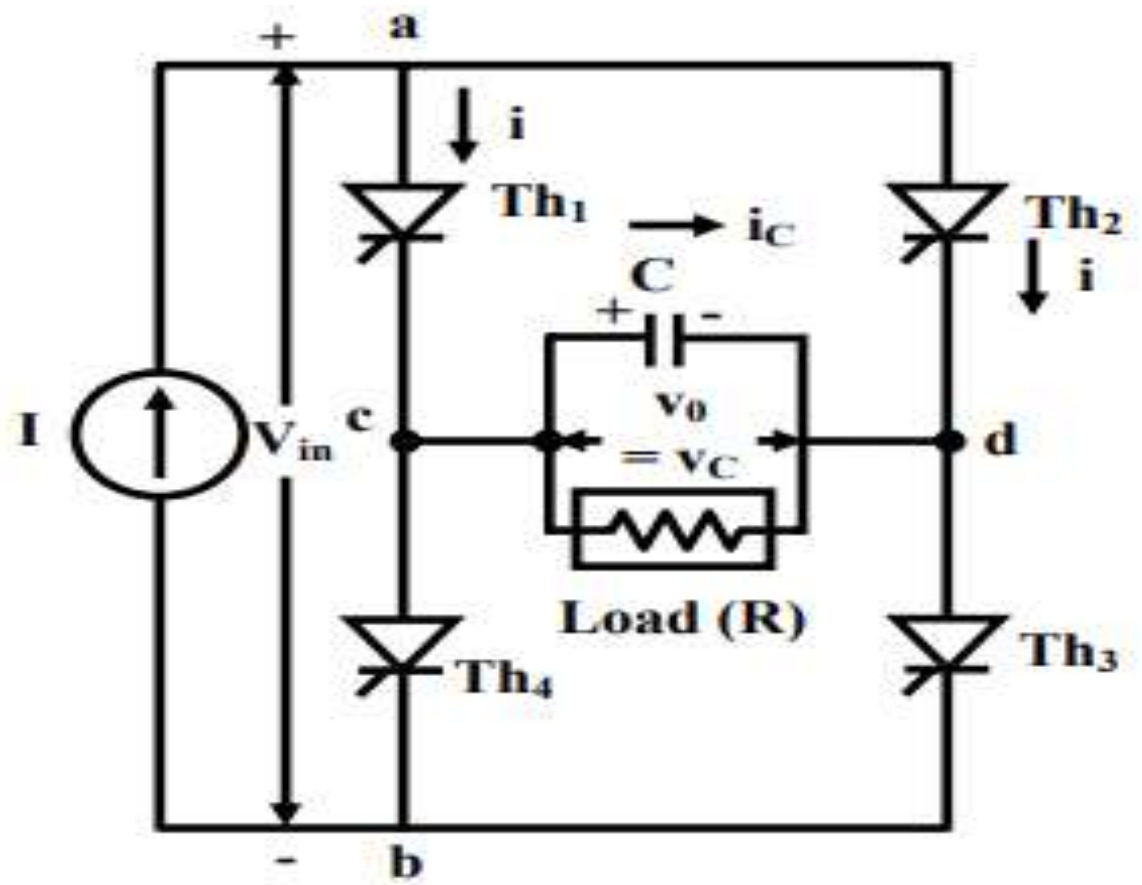
Mode I operation of CSI



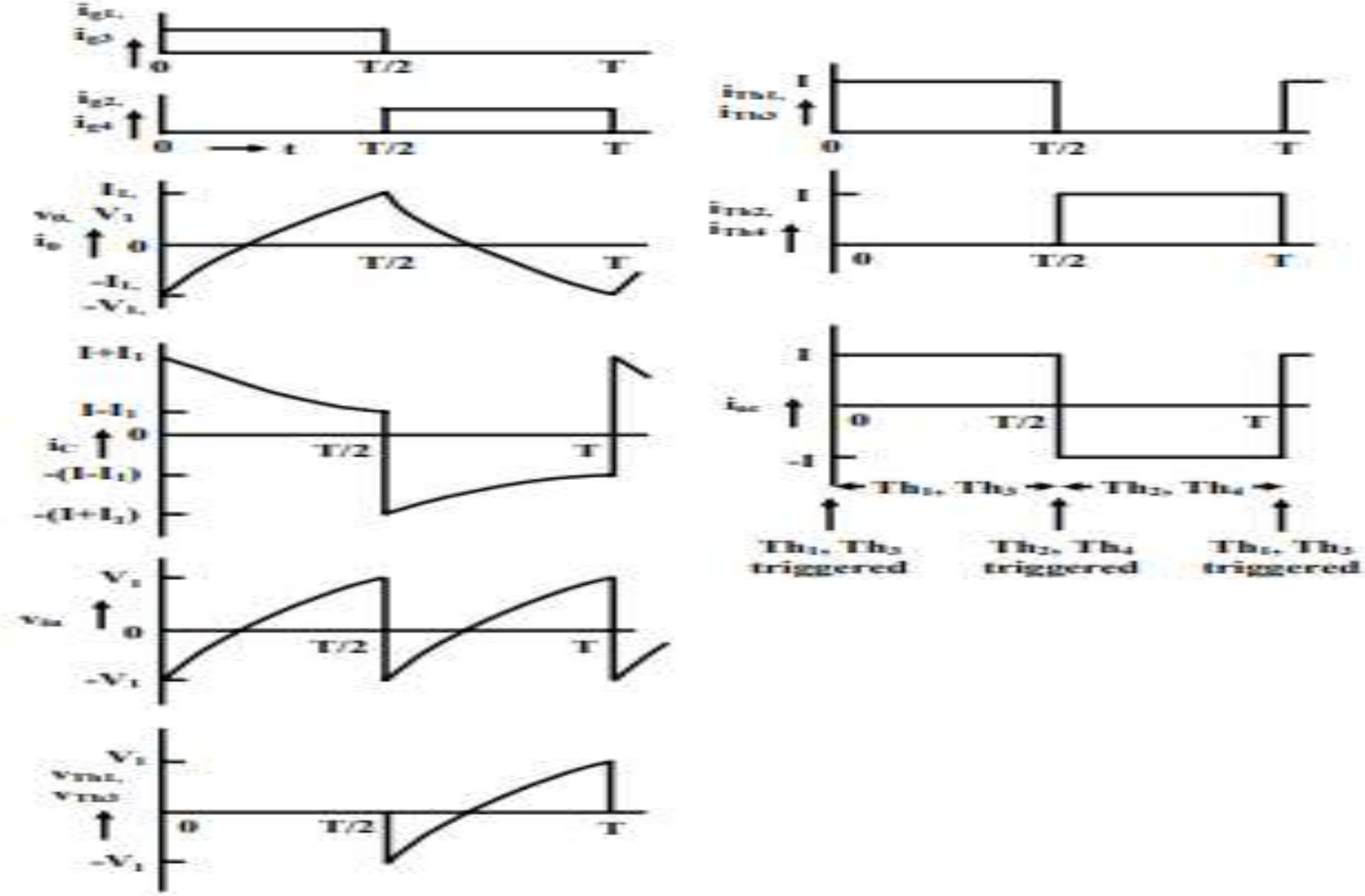
Mode II operation of CSI

Operation of commutated type CSI

- The power switching devices used here is the same, i.e. four Thyristors only in a full- bridge configuration. The positive direction for load current and voltage is shown in Fig. 5.40 Before t = 0, the capacitor voltage is , i.e. the capacitor has left plate negative and right plate positive. At that time, the thyristor pair, Th2 & Th4 was conducting. When (at t = 0), the thyristor pair, Th1 & Th3 is triggered by the pulses fed at the gates, the conducting thyristor pair, Th2 & Th4 is reverse biased by the capacitor voltage C = −Vv 1 , and turns off immediately. The current path is through Th1, load (parallel combination of R & C), Th3, and the source. The current in the thyristors is I_{Ti} , the output current is
- Iac= I



Circuit diagram of load commutated CSI



Voltage and current waveforms of load commutated CSI

Numerical Problems

1. A single-phase half bridge inverter has a resis load of 2.4 W and the d.c. input voltage of 48 V.

   Determine:-

   (i) RMS output voltage at the fundamental frequency

   (ii) Output power *P*0

   (iii) Average and peak currents of each transistor

   (iv) Peak blocking voltage of each transistor.

   (v) Total harmonic distortion and distortion factor.

   (vi) Harmonic factor and distortion factor at the lowest order harmonic.

Solution:

(i) RMS output voltage of fundamental frequency, $E1 = 0.9 ¥ 48 = 43.2$ V.

(ii) RMS output voltage, Eorms = E = 48 V.

Output power = $E^2/R = (48)^2/2.4 = 960$ W.

(iii) Peak transistor current = $Ip = Ed/R = 48/2.4 = 20$ A.

Average transistor current = $Ip/2 = 10$ A.

(iv) Peak reverse blocking voltage,

$VBR = 48$ V.

(v) RMS harmonic voltage

$$En = \left[\sum_{n=3,5,7}^{8} E_n^2 \right]^{1/2}$$

$$= (E^2_{orms} - E_1{}^2_{rms})^{1/2}$$

$$= [(48)^2 - (43.2)^2]^{1/2}$$

$$= 20.92 \text{ V.}$$

$$\therefore \quad THD = \frac{20.92}{43.2} = 48.43\%.$$

$$\text{(vi)} \quad D.F. = \frac{\left[\sum_{n=3,5,7}^{\infty} \left(E_n / n^2\right)^2 \right]^{1/2}}{0.9}$$

$$= \frac{0.03424}{0.9} = 3.8\%$$

2. A single phase full bridge inverter has a resistive load of R = 10 Ω and the input voltage V_{dc} of 100 V. Find the average output voltage and rms output voltage at fundamental frequency.

3. A single PWM full bridge inverter feeds an RL load with R=10Ω and L= 10 mH. If the source voltage is 120V, find out the total harmonic distortion in the output voltage and in the load current. The width of each pulse is 120° and the output frequency is 50Hz.