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SCHOOL OF ELECTRICAL & ELECTRONICS ENGINEERING

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

UNIT – I
POWER ELECTRONICS – SEE1305

Power Semiconductor Devices

Overview of V-I characteristics of Switching devices - Switching characteristics of Power Diode, Power BJT, Power MOSFETS, IGBT and Thyristor - SCR Protection Circuits - Thyristor Turn-ON methods - Firing Circuits - Commutation Techniques.

UNIT – I

Power Semiconductor Devices

Introduction to Power Electronics

Power Electronics is a field which combines Power (electric power), Electronics and Control systems. Power engineering deals with the static and rotating power equipment for the generation, transmission and distribution of electric power. Electronics deals with the study of solid state semiconductor power devices and circuits for Power conversion to meet the desired control objectives (to control the output voltage and output power). Power electronics may be defined as the subject of applications of solid state power semiconductor devices (Thyristors) for the control and conversion of electric power. Power electronics deals with the study and design of Thyristorised power controllers for variety of application like Heat control, Light/Illumination control, Motor control - AC/DC motor drives used in industries, High voltage power supplies, Vehicle propulsion systems, High voltage direct current (HVDC) transmission.

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. The most desirable power electronic system is one whose efficiency and reliability is 100%.Take a look at the following block diagram. It shows the components of a Power Electronic system and how they are interlinked.

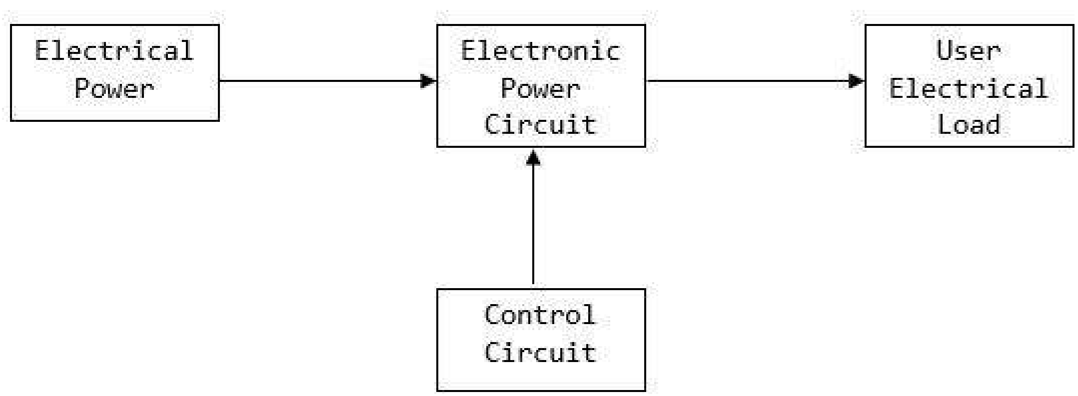


Figure: 1.1. Block diagram of DC power supply

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

- Maximum efficiency
- Maximum reliability
- Maximum availability
- Minimum cost
- Least weight
- Small size

Applications of Power Electronics:

Power Electronic applications are classified into two types − Static Applications and Drive Applications.

Static Applications

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

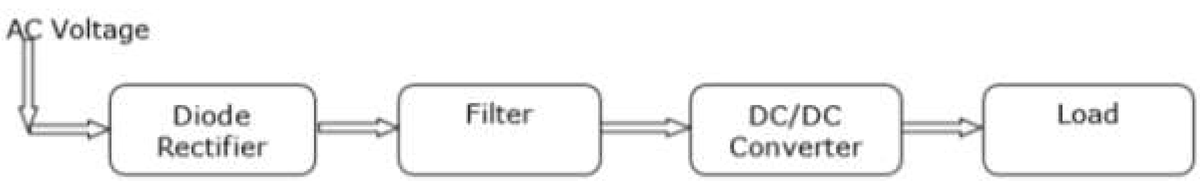


Figure: 1.2. Block diagram of DC power supply

Drive Applications

Drive applications have rotating parts such as motors. Examples include compressors, pumps, conveyer belts and air conditioning systems.

Air Conditioning System

Power electronics is extensively used in air conditioners to control elements such as compressors. A schematic diagram that shows how power electronics is used in air conditioners is shown below.

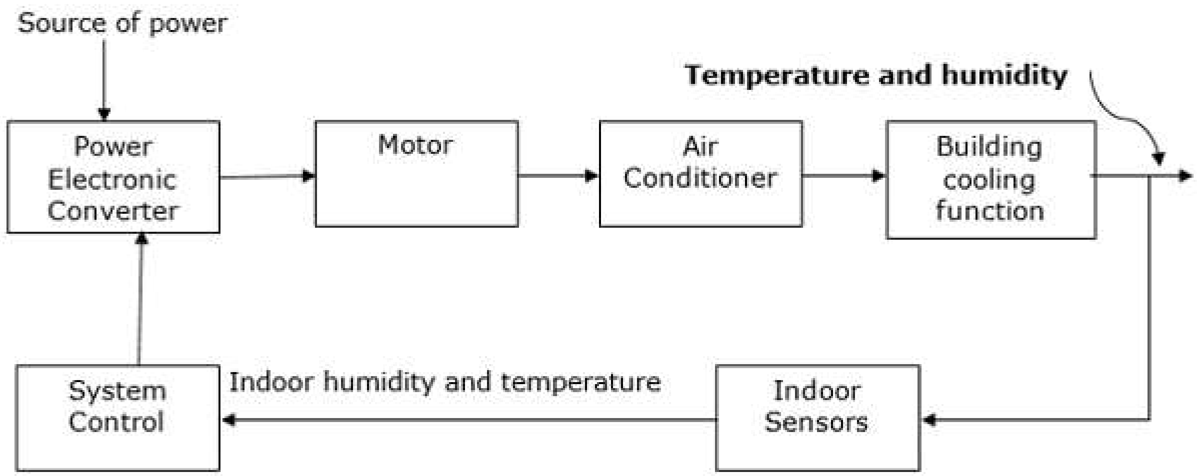


Figure: 1.3. Block diagram of Air Conditioning System

Power Electronic Applications

Commercial applications Heating Systems Ventilating, Air Conditioners, Central Refrigeration, Lighting, Computers and Office equipment, Uninterruptible Power Supplies (UPS), Elevators, and Emergency Lamps

Domestic applications Cooking Equipment, Lighting, Heating, Air Conditioners, Refrigerators & Freezers, Personal Computers, Entertainment Equipment, UPS

Industrial applications Pumps, compressors, blowers and fans Machine tools, arc furnaces, induction furnaces, lighting control circuits, industrial lasers, induction heating, welding equipment

Aerospace applications Space shuttle power supply systems, satellite power systems, aircraft power systems.

Telecommunications Battery chargers, power supplies (DC and UPS), mobile cell phone battery chargers

Transportation Traction control of electric vehicles, battery chargers for electric vehicles, electric locomotives, street cars, trolley buses, automobile electronics including engine controls

Utility systems High voltage DC transmission (HVDC), static VAR compensation (SVC), Alternative energy sources (wind, photovoltaic), fuel cells, energy storage systems, induced draft fans and boiler feed water pumps.

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 one stage conversion.

Power Semiconductor Devices

i. Power Diodes.
ii. Power transistors (BJT's).
iii. Power MOSFETS.
iv. IGBT's.
v. Thyristors

Thyristors are a family of p-n-p-n structured power semiconductor switching devices. Power diodes are made of silicon p-n junction with two terminals, anode and cathode. P-N junction is formed by alloying, diffusion and epitaxial growth. Modern techniques in diffusion and epitaxial processes permit desired device characteristics. The diodes have the following advantages High mechanical and thermal reliability High peak inverse voltage Low reverse current Low forward voltage drop High efficiency Compactness.

Power transistors are devices that have controlled turn-on and turn-off characteristics. These devices are used a switching devices and are operated in the saturation region resulting in low on-state voltage drop. They are turned on when a current signal is given to base or control terminal. The transistor remains on so long as the control signal is present. The switching speed of modern transistors is much higher than that of thyristors and is used extensively in dc-dc and dc-ac converters. However their voltage and current ratings are lower than those of thyristors and are therefore used in low to medium power applications. Power transistors are classified as follows o Bipolar junction transistors (BJTs) o Metal-oxide semiconductor filed-effect transistors (MOSFETs) o Static Induction transistors (SITs) o Insulated-gate bipolar transistors (IGBTs).

Power Diode

Figure : 1.4. Symbol of Power Diode

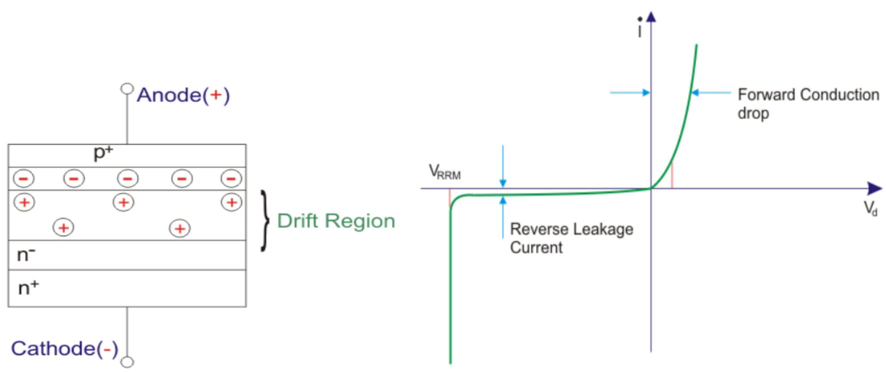


Figure : 1.5. Construction and V-I Characteristics of Power Diode

Whenever the diode is switched off the current decays from IF to zero and further continues in reverse direction owing to the charges stored in the space charge region and the semiconductor region. This reverse current attains a peak IRR and again start approaching zero value and finally the diode is off after time. trr – Reverse Recovery Time.

V – I Characteristics of Power Diode

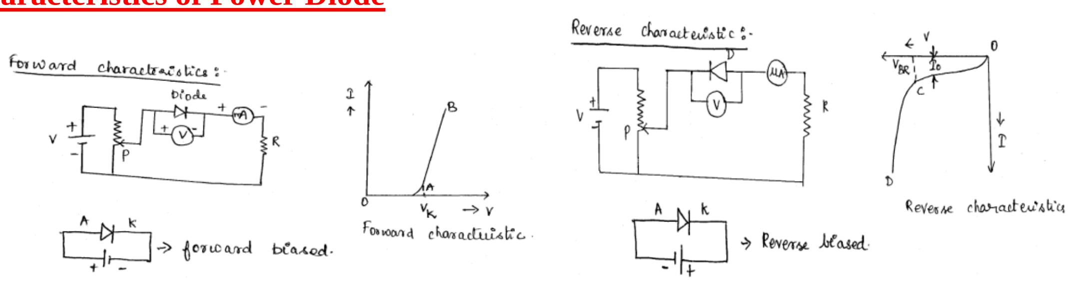


Figure : 1.6. Forward and Reverse characteristics of Power Diode

V_k - Knee Voltage / Cut in Voltage / Threshold Voltage / Barrier Voltage
I_O - Reverse Saturation Current; V_{BR} - Reverse Breakdown Voltage

Reverse Recovery Time

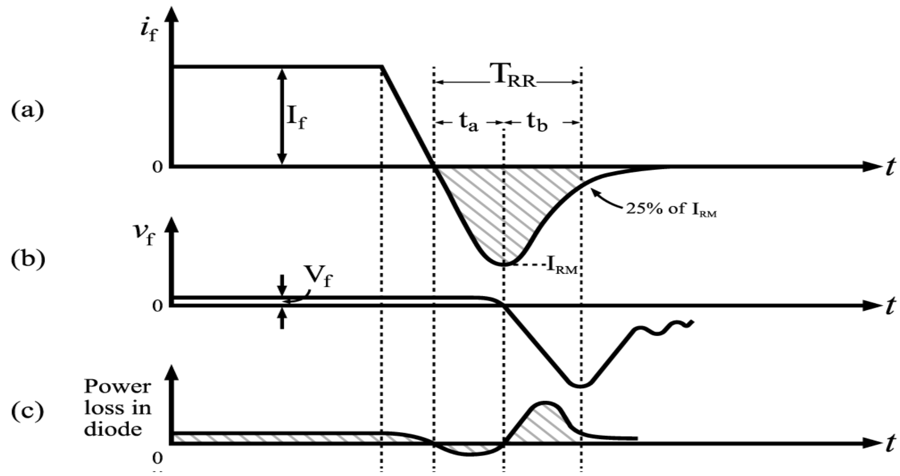


Figure : 1.7. Reverse recovery characteristics of Power Diode

$t_a \rightarrow$ time when charge from depletion region is removed.
$t_b \rightarrow$ time when charge from semiconductor region is removed.

$$t_{rr} = t_a + t_b$$

trr – Reverse Recovery Time is the time taken to change the current from ON state to OFF state.

Classification of Power Diodes

Type	Voltage ratings (V_{RRM})	Current ratings (I_F)	Reverse recovery time (t_{rr})	Applications	Remarks
General Purpose Diodes	50-5000 V	1A to several thousand Amps	~25μs	UPS, battery chargers, welding, traction etc.	–
Fast Recovery Diode	50-3000 V	1A to several thousand Amps	<5μs	SMPS, commutation circuits, choppers, induction heating	Doping done using platinum or gold
Schottky Diodes	Upto 100V	1-300 A	~ns	Very high frequency switching power supplies and instrumentation	Metal-semiconductor junction, usually Al-Si(n-type), majority carrier device, hence very low turn off time

Power Bipolar Junction Transistor (BJT)

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.

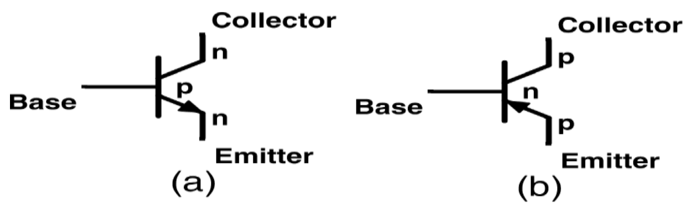


Figure: 1.8. Symbol of transistor

The BJT is a three-layer and two-junction NPN or PNP semiconductor device. Although BJTs have lower input capacitance as compared to MOSFET or IGBT, BJTs are considerably slower in response due to low input impedance. BJTs use more silicon for the same drive performance. In the case of MOSFET studied earlier, power BJT is different in configuration as compared to simple planar BJT. In planar BJT, collector and emitter is on the same side of the wafer while in power BJT it is on the opposite edges as shown in Fig. 33. This is done to increase the power-handling capability of BJT.

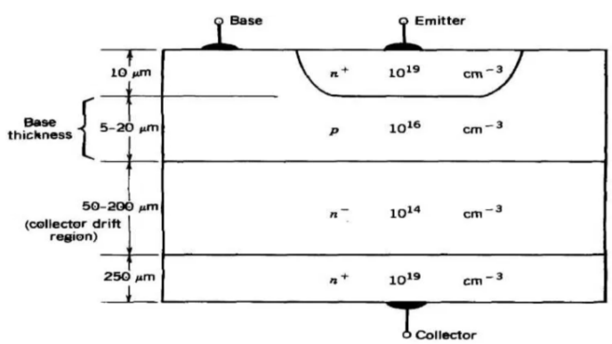


Figure: 1.9. Construction of Power BJT

Power n-p-n transistors are widely used in high-voltage and high-current applications which will be discussed later. Input and output characteristics of planar BJT for common-emitter configuration are shown in fig. These are current-voltage characteristics curves.

V – I Characteristics of BJT

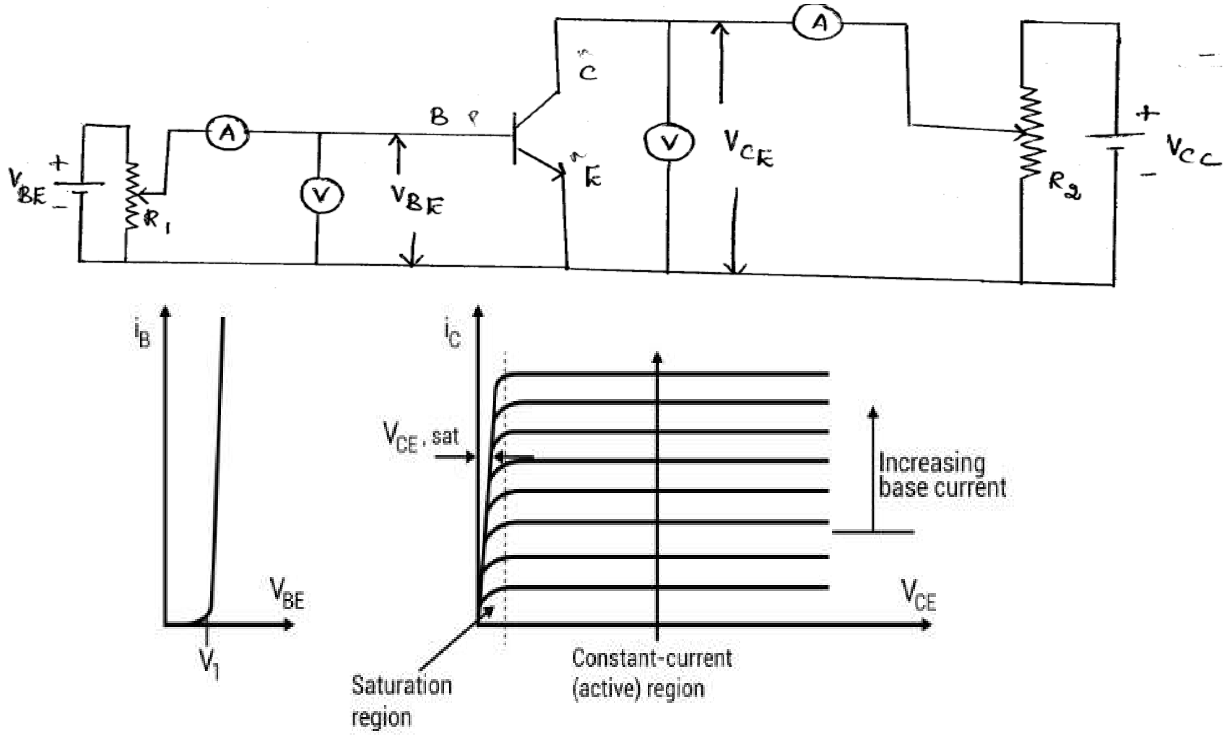


Figure: 1.10. Input and Output Characteristics of Power BJT

Switching Characteristics (or) Turn – ON / Turn – Off Characteristics of Power BJT

$$\mathbf{t_{on} = t_d + t_r \; ; \; t_{off} = t_s + t_f}$$

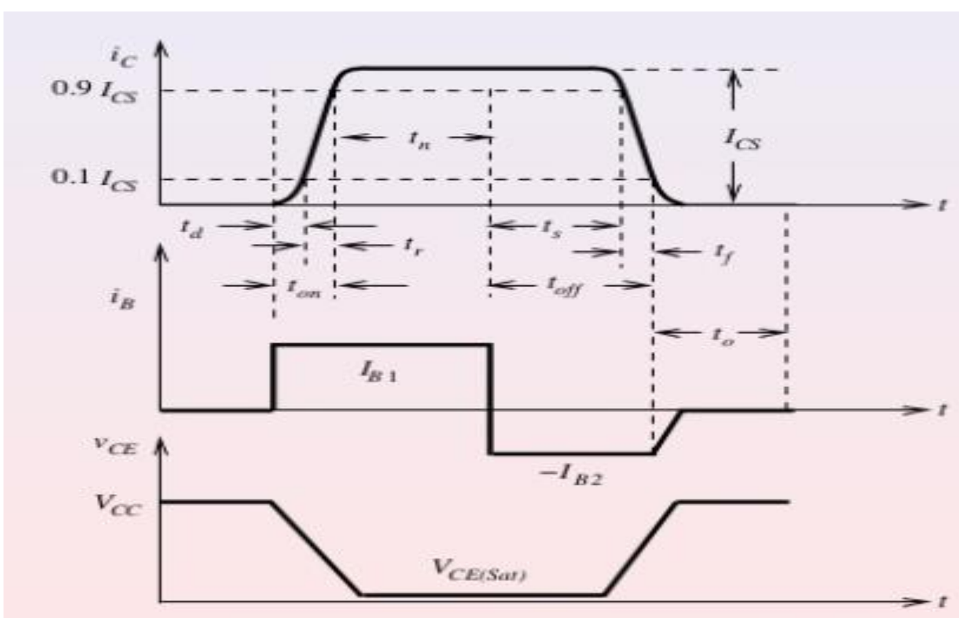


Figure: 1.11. Switching Characteristics of Power BJT

- As the positive base voltage is applied, base current starts to flow but there is no collector current for some time. This time is known as the **delay time** (t_d) required to charge the junction capacitance of the base to emitter to 0.7 V approx.

- For $t > t_d$, collector current starts rising and V_{CE} starts to drop with the magnitude of 9/10th of its peak value. This time is called **rise time**, required to turn on the transistor.
- For turning off the BJT, excess minority carrier charges are stored in the base region which needs to be removed. The time required to nullify this charge is the **storage time**, t_s.
- t_f is the falling time. After the falling time, I_c decreases to 0.1 I_{cs} almost to zero.

Advantages of BJT'S

i. BJT's have high switching frequencies since their turn-on and turn-off time are low.
ii. The turn-on losses of a BJT are small.
iii. BJT has controlled turn-on and turn-off characteristics since base drive control is possible.
iv. BJT does not require commutation circuits

Demerits of BJT

i. Drive circuit of BJT is complex.
ii. It has the problem of charge storage which sets a limit on switching frequencies.
iii. It cannot be used in parallel operation due to problems of negative temperature coefficient.

Power Metal-Oxide Semiconductor Field-Effect Transistor

Power MOSFET is a Metal Oxide Semiconductor Field Effect Transistor. It has three terminals Gate, Source, Drain.The gate is insulated from the channel by a layer of SiO2. It is also called as Insulated Gate Field Effect Transistor (IGFET). It is a Unipolar device. The gate terminal has the complete control over the operation of MOSFET. The operation of Power MOSFET depends on flow of majority charge carriers, it is called as Voltage Controlled Device. It operates in two modes : Depletion Mode and Enhancement Mode. In depletion Mode, a negative voltage is applied to decrease the width of the channel. In Enhancement Mode, a positive voltage is applied to increase the width of the channel.Both depletion and enhancement mode have N-Channel and P-Channel MOSFET. Power MOSFETs which are most widely used are N-channel Enhancement Mode. These exhibit high switching speed and can work much better in comparison with other normal MOSFETs.

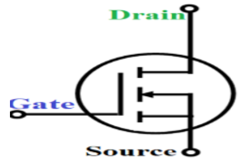


Figure : 1.20. Symbol of Power MOSFET

Construction

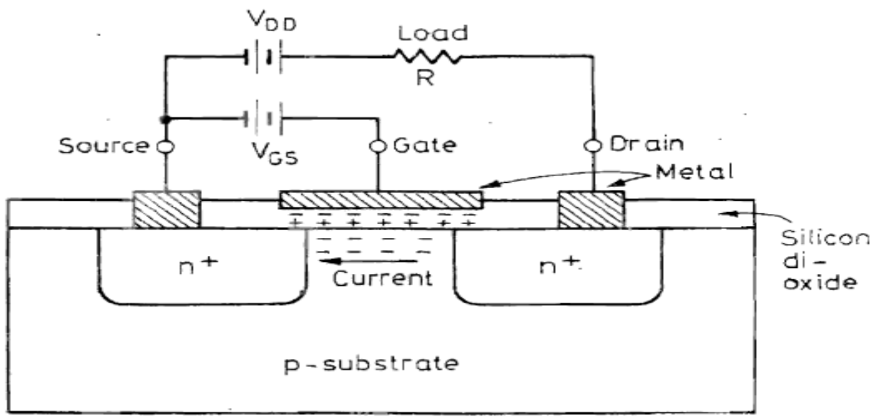


Figure : 1.21. Basic Structure of N Channel Enchancement MOSFET

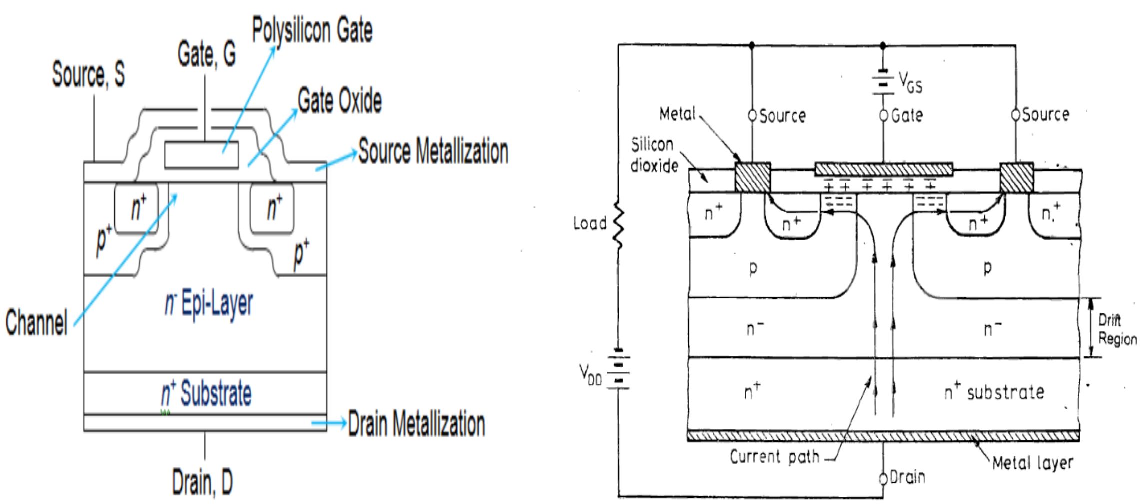


Figure : 1.22. Basic Structure of N Channel Enchancement Power MOSFET

Drift region shown in Fig. 37 determines the voltage-blocking capability of the MOSFET. When V_{GS} = 0, ⇒ V_{DD} makes it reverse biased and no current flows from drain to source. When V_{GS}> 0, ⇒ Electrons form the current path as shown in Fig. Thus, current from the drain to the source flows. Now, if we will increase the gate-to-source voltage, drain current will also increase.

V – I Characteristics of Power MOSFET

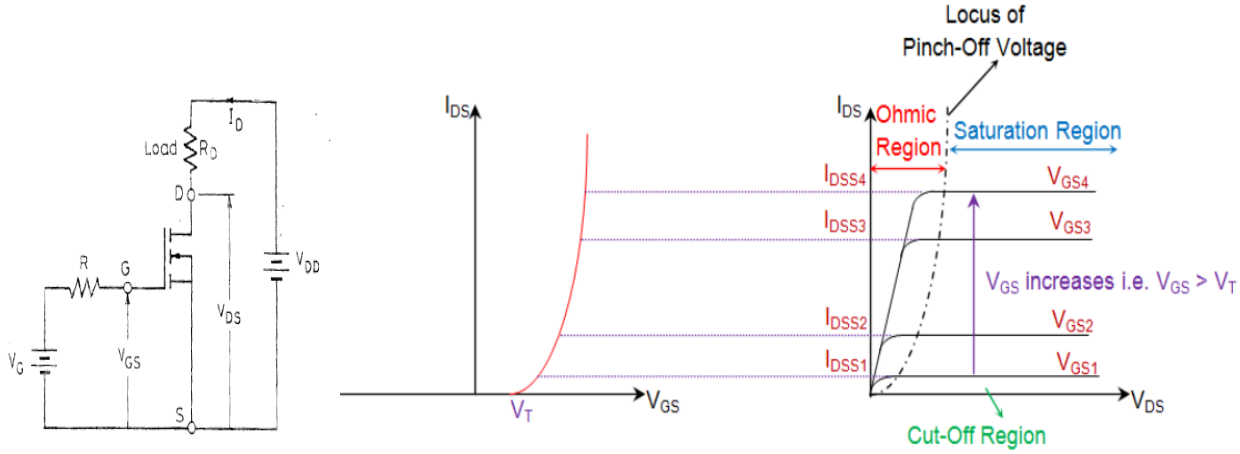
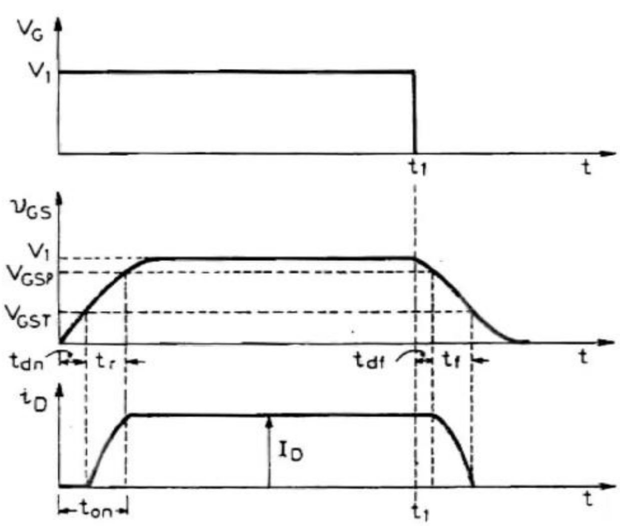


Figure : 1.23. Circuit diagram and V-I Characteristics of Power MOSFET

For lower value of V_{DS}, MOSFET works in a linear region where it has a constant resistance equal to V_{DS} / I_D. For a fixed value of V_{GS} and greater than threshold voltage V_{TH}, MOSFET enters a saturation region where the value of the drain current has a fixed value. Besides the output characteristics curves, transfer characteristics of power MOSFET is also shown in Fig.

Switching Characteristics (or) Turn – ON / Turn – Off Characteristics of Power MOSFET



$$t_{on} = t_{dn} + t_r \; ; \quad t_{off} = t_{df} + t_f$$

The MOSFET can be turned on by providing positive gate voltage. When the gate voltage is applied, the gate to source capacitance CGS starts charging. When the voltage across CGS reached certain voltage level called Threshold voltage (VGST), the drain current ID starts rising. The time required to charge CGS to the threshold voltage level is known as turn on delay time (td).The CGS charges from threshold voltage to full gate voltage (VGSP).

The time required for this charging is called rise time (tr).During this period, the drain current rises to its full value. Thus the MOSFET is fully turned ON. The total turn-on time of MOSFET is $t_{ON} = t_{dn} + t_r$. The turn-on time can be reduced by using low-impedance gate drive source. To turn off the MOSFET, the gate voltage is made negative or zero. Due to this, the gate to source voltage then reduces from V_I to V_{GSP}. As MOSFET is a majority carrier device, turn-off process is initiated soon after removal of gate voltage at time t_1.That is, C_{GS} discharges from gate voltage V_I to V_{GSP}. The time required for this discharge is called turn-off delay time ($t_{d(off)}$).During this period, the drain current also starts reducing. The C_{GS} keeps on discharging and its voltage becomes equal to threshold voltage (V_{GST}).The time required to discharge C_{GS} from V_{GSP} to V_{GST} is called fall time (t_f). The drain current becomes zero when $V_{GS} < V_{GST}$. The MOSFET is then said to be have turned-off. Thus the total turn-off time of MOSFET is $t_{OFF} = t_{df} + t_f$.

Comparsion of Power BJT and Power MOSFET

Sl No	BJT	MOSFET
1	It is a Bipolar Device	It is majority carrier Device
2	Current control Device	Voltage control Device.
3	Output is controlled by controlling base current	Output is controlled by controlling gate voltage
4	Negative temperature coefficient	Positive temperature coefficient
5	So paralleling of BJT is difficult.	So paralleling of this device is easy.
6	Dive circuit is complex. It should provide constant current(Base current)	Dive circuit is simple. It should provide constant voltage(gate voltage)
7	Losses are low.	Losses are higher than BJTs.

8	So used in high power applications.	Used in low power applications.
9	BJTs have high voltage and current ratings.	They have less voltage and current ratings.
10	Switching frequency is lower than MOSFET.	Switching frequency is high.

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. It has no body diode as in case of MOSFET but this can be seen as an advantage to use external fast recovery diode for specific applications. They are replacing the MOSFET for most of the high voltage applications with less conduction losses. Its physical cross-sectional structural diagram and equivalent circuit diagram is presented in Fig. It has three terminals called collector, emitter and gate.

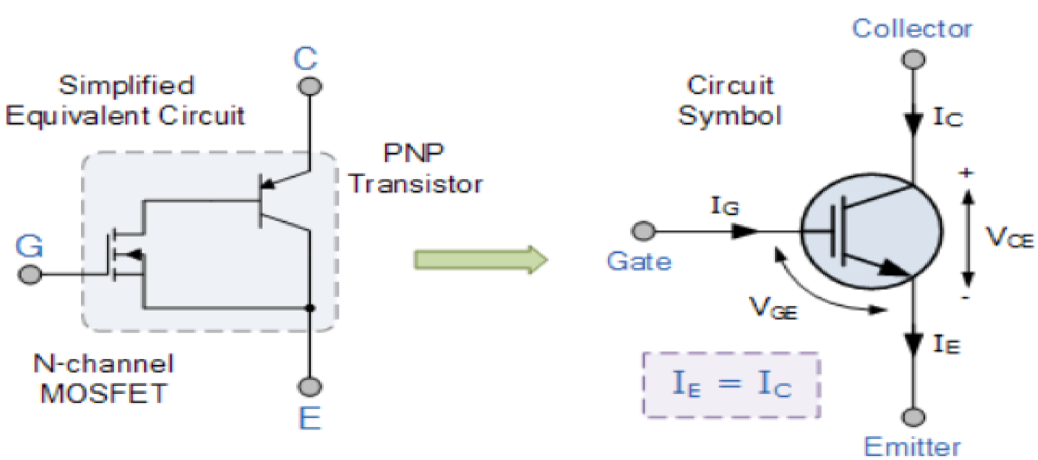


Figure : 1.24. Equivalent diagram and Symbol

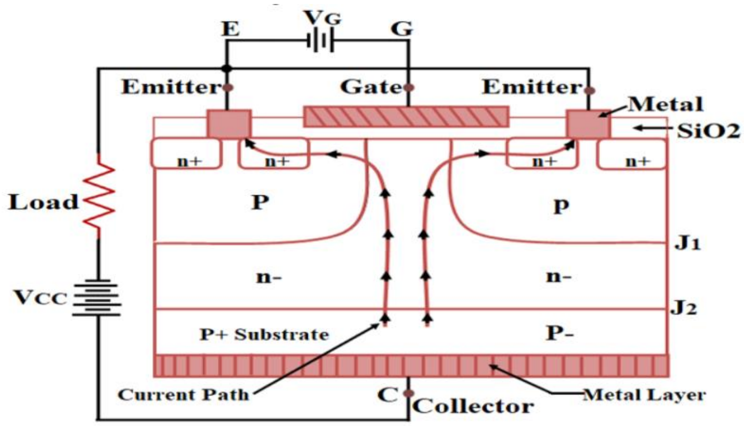


Figure : 1.25. Basic Structure

There is a p+ substrate which is not present in the MOSFET and responsible for the minority carrier injection into the n-region. Gain of NPN terminal is reduced due to wide epitaxial base and n+ buffer layer.There are two structures of IGBTs based on doping of buffer layer:

a) Punch-through IGBT: Heavily doped n buffer layer ➔less switching time

b) Non-Punch-through IGBT: Lightly doped n buffer layer ➔ greater carrier lifetime ➔ increased conductivity of drift region ➔reduced on-state voltage drop ;   (Note: ➔means implies)

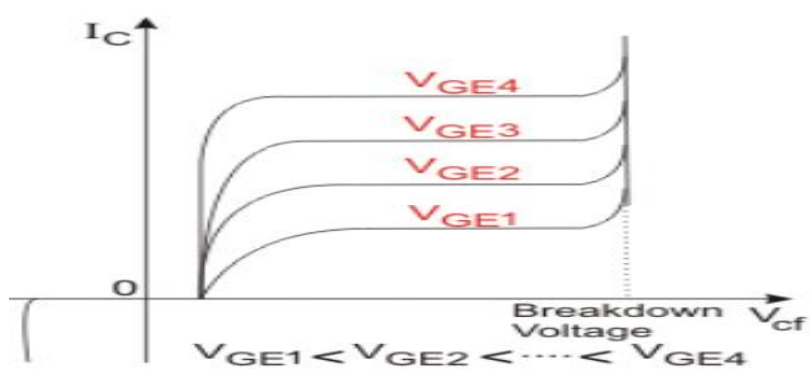


Figure : 1.26. V-I Characteristics of IGBT

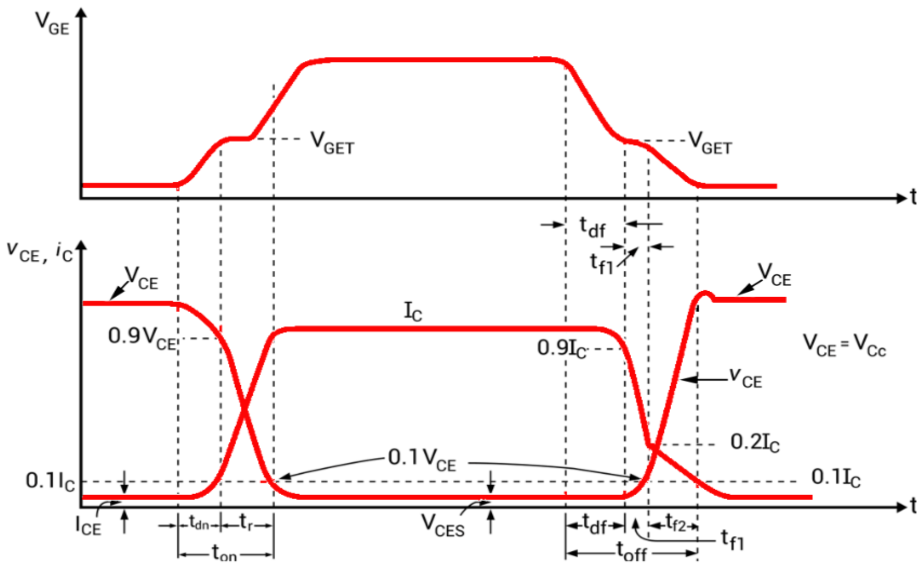


Figure : 1.27. Switching Characteristics of IGBT

$$t_{on} = t_{dn} + t_r \quad ; \quad t_{off} = t_{df} + t_{f1} + t_{f2}$$

Turn-ON:

The voltage V_{GE} is normally negative. It is made into positive to turn-on IGBT.As gate voltage is increased, V_{GE} increases. When $V_{GE} = V_{GE(th)}$ the collector current I_C starts to flow.Time taken for V_{GE} to rise and reach $V_{GE(th)}$ (or) The time for I_C to start increasing is called as "turn-on delay time t_{dn}".After $V_{GE(th)}$, the collector current I_C starts to increase. The time for I_C to rise and reach its max value is called as "rise time" for current(t_{ri}).When I_C reaches its max value, IGBT is in its ON state. When a device is in its ON state, it is said to be short circuited and so the voltage across it is equal to zero.Therefore when IGBT is ON, the V_{CE} voltage starts reducing to a value nearly equal to zero. Here it falls to a value V_{CES}(saturated value) or $V_{CE(ON)}$.This time taken for voltage V_{CE} to start to fall and reach its saturated value V_{CES} is called as "fall time for voltage(t_{fv})".Therefore the turn-on time $t_{ON} = t_{dn} + t_{ri} + t_{fv}$ These time delays are due to two reasons.Gate-Collector capacitance will increase in MOSFET portion of IGBT at low V_{CE}.PNP transistor portion of IGBT travels (or) moves to the ON state more slowly than the MOSFET portion of IGBT.

Turn OFF:

IGBT is turned OFF by removing the gate voltage.When Gate voltage V_G is reduced, V_{GE} starts to fall and V_{CE} starts to increase.Turn-off delay time(t_{df}) is the time between the V_{GE} starts to decrease and the V_{CE} starts to increase.At the end of t_{df}, the V_{CE} starts to increase and reaches its max value. The time taken for V_{CE} to rise and reach its full value is called as rise time for voltage(t_{rv}).As V_{GE} decreases and reaches $V_{GE(th)}$ the drain current reduces to zero. Time interval t_{fi1} is the fall time for current. It is the turn-off interval of the MOSFET section of IGBT.Here the current I_C is not zero, but a small current flows due to the stored charge in n_{--} drift region. This is the internal BJT current.This tailing of current (due to BJT internal current) takes place during the interval t_{fi2}. It is the turn-off interval of the BJT section of IGBT.

Merits

- Voltage controlled Device
- Less On state loss
- High switching frequency
- No commutation circuit
- Gate has full control over operation.
- Flat temperature coefficient

Demerits of IGBT

- Static charge problem
- Costlier than BJT and MOSFET

Thyristors – Silicon Controlled Rectifiers (SCR's)

A silicon controlled rectifier or semiconductor-controlled rectifier is a four-layer solid state current- controlling device. The name "silicon controlled rectifier" is General

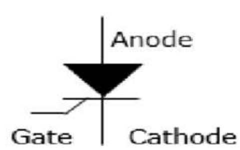


Figure: 1.28. Symbol of thyristor

Electric's trade name for a type of thyristor. SCRs are mainly used in electronic devices that require control of high voltage and power. This makes them applicable in medium and high AC power operations such as motor control function. An SCR conducts when a gate pulse is applied to it, just like a diode. It has four layers of semiconductors that form two structures namely; NPNP or PNPN. In addition, it has three junctions labeled as J1, J2 and

J3 and three terminals (anode, cathode and a gate). An SCR is diagrammatically represented as shown below.

The anode connects to the P-type, cathode to the N-type and the gate to the P-type as shown below.

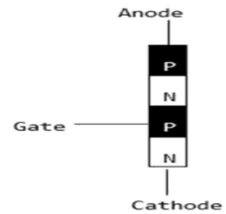


Figure: 1.29. Structure of thyristor

In an SCR, the intrinsic semiconductor is silicon to which the required dopants are infused. However, doping a PNPN junction is dependent on the SCR application.

Modes of Operation in SCR

- OFF state (forward blocking mode) − Here the anode is assigned a positive voltage, the gate is assigned a zero voltage (disconnected) and the cathode is assigned a negative voltage. As a result, Junctions J1 and J3 are in forward bias while J2 is in reverse bias. J2 reaches its breakdown avalanche value and starts to conduct. Below this value, the resistance of J1 is significantly high and is thus said to be in the off state.
- ON state (conducting mode) − An SCR is brought to this state either by increasing the potential difference between the anode and cathode above the avalanche voltage or by applying a positive signal at the gate. Immediately the SCR starts to conduct, gate voltage is no longer needed to maintain the ON state and is, therefore, switched off by−
    - Decreasing the current flow through it to the lowest value called holding current
    - Using a transistor placed across the junction.
- Reverse blocking − This compensates the drop in forward voltage. This is due to the fact that a low doped region in P1 is needed. It is important to note that the voltage ratings of forward and reverse blocking are equal.

Characteristics of Thyristor

A thyristor is a four layer 3 junction p-n-p-n semiconductor device consisting of at least three p-n junctions, functioning as an electrical switch for high power operations. It has three basic terminals, namely the anode, cathode and the gate mounted on the semiconductor layers of the device. The symbolic diagram and the basic circuit diagram for determining the characteristics of thyristor is shown in the figure below,

V-I Characteristics of a Thyristor

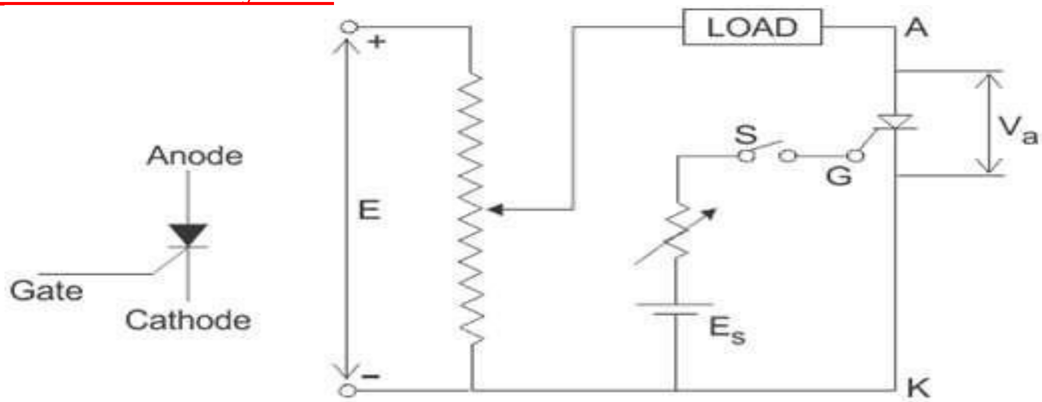


Figure: 1.30. Circuit diagram for characteristics of SCR

From the circuit diagram above we can see the anode and cathode are connected to the supply voltage through the load. Another secondary supply E_s is applied between the gate and the cathode terminal which supplies for the positive gate current when the switch S is closed. On giving the supply we get the required V-I characteristics of a thyristor show in the figure below for anode to cathode voltage $V_a$and anode current I_a as we can see from the circuit diagram. A detailed study of the characteristics reveal that the thyristor has three basic modes of operation, namely the reverse blocking mode, forward blocking (off-state) mode and forward conduction (on-state) mode. Which are discussed in great details below, to understand the overall characteristics of a thyristor.

Reverse Blocking Mode of Thyristor

Initially for the reverse blocking mode of the thyristor, the cathode is made positive with respect to anode by supplying voltage E and the gate to cathode supply voltage E_s is detached initially by keeping switch S open. For understanding this mode we should look into the fourth quadrant where the thyristor is reverse biased.

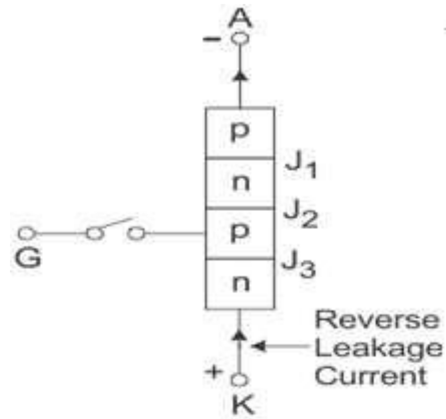


Figure: 1.31. Reverse blocking mode of SCR

Here Junctions J_1 and J_3 are reverse biased whereas the junction $J_2$is forward biased. The behavior of the thyristor here is similar to that of two diodes are connected in series with reverse voltage applied across them. As a result only a small leakage current of the order of a few µAmps flows. This is the reverse blocking mode or the off-state, of the thyristor. If the reverse voltage is now increased, then at a particular voltage, known as the critical breakdown voltage V_{BR}, an avalanche occurs at J_1 and J_3 and the reverse current increases rapidly. A large current associated with V_{BR} gives rise to more losses in the SCR, which results in heating. This may lead to thyristor damage as the junction temperature may exceed its permissible temperature rise. It should, therefore, be ensured that maximum working reverse voltage across a thyristor does not exceed V_{BR}. When reverse voltage applied across a thyristor is less than V_{BR}, the device offers very high impedance in the reverse direction. The SCR in the reverse blocking mode may therefore be treated as open circuit.

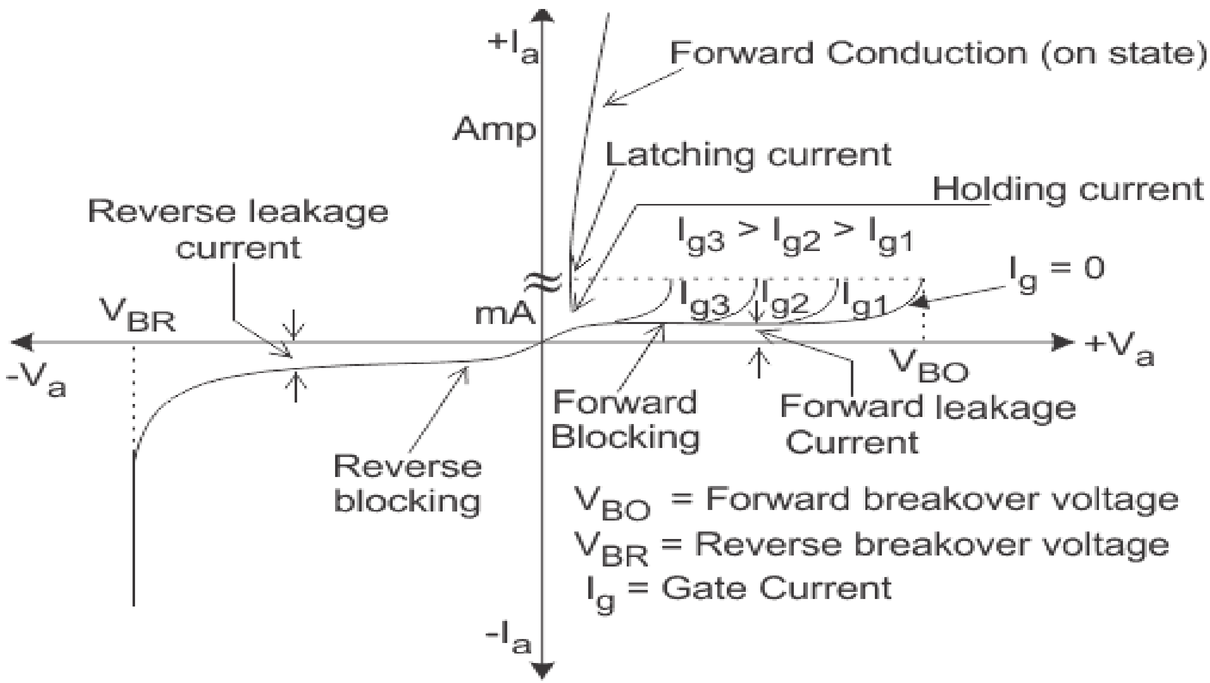


Figure: 1.32. V- I characteristics of SCR

Forward Blocking Mode

Now considering the anode is positive with respect to the cathode, with gate kept in open condition. The thyristor is now said to be forward biased as shown the figure below.

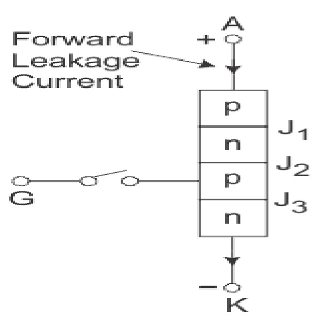


Figure: 1.33. Forward connection of SCR

As we can see the junctions $J_1$and J_3 are now forward biased but junction J_2goes into reverse biased condition. In this particular mode, a small current, called forward leakage current is allowed to flow initially as shown in the diagram for characteristics of thyristor. Now, if we keep on increasing the forward biased anode to cathode voltage.

In this particular mode, the thyristor conducts currents from anode to cathode with a very small voltage drop across it. A thyristor is brought from forward blocking mode to forward conduction mode by turning it on by exceeding the forward break over voltage or by applying a gate pulse between gate and cathode. In this mode, thyristor is in on-state and behaves like a closed switch. Voltage drop across thyristor in the on state is of the order of 1 to 2 V depending beyond a certain point, then the reverse biased junction J_2 will have an avalanche breakdown at a voltage called forward break over voltage V_{B0} of the thyristor. But, if we keep the forward voltage less than V_{BO}, we can see from the characteristics of thyristor, that the device offers high impedance. Thus even here the thyristor operates as an open switch during the forward blocking mode.

Forward Conduction Mode

When the anode to cathode forward voltage is increased, with gate circuit open, the reverse junction J_2 will have an avalanche breakdown at forward break over voltage V_{BO} leading to thyristor turn on. Once the thyristor is turned on we can see from the diagram for characteristics of thyristor, that the point M at once shifts toward N and then anywhere between N and K. Here NK represents the forward conduction mode of the thyristor.

SCR Turn off 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.

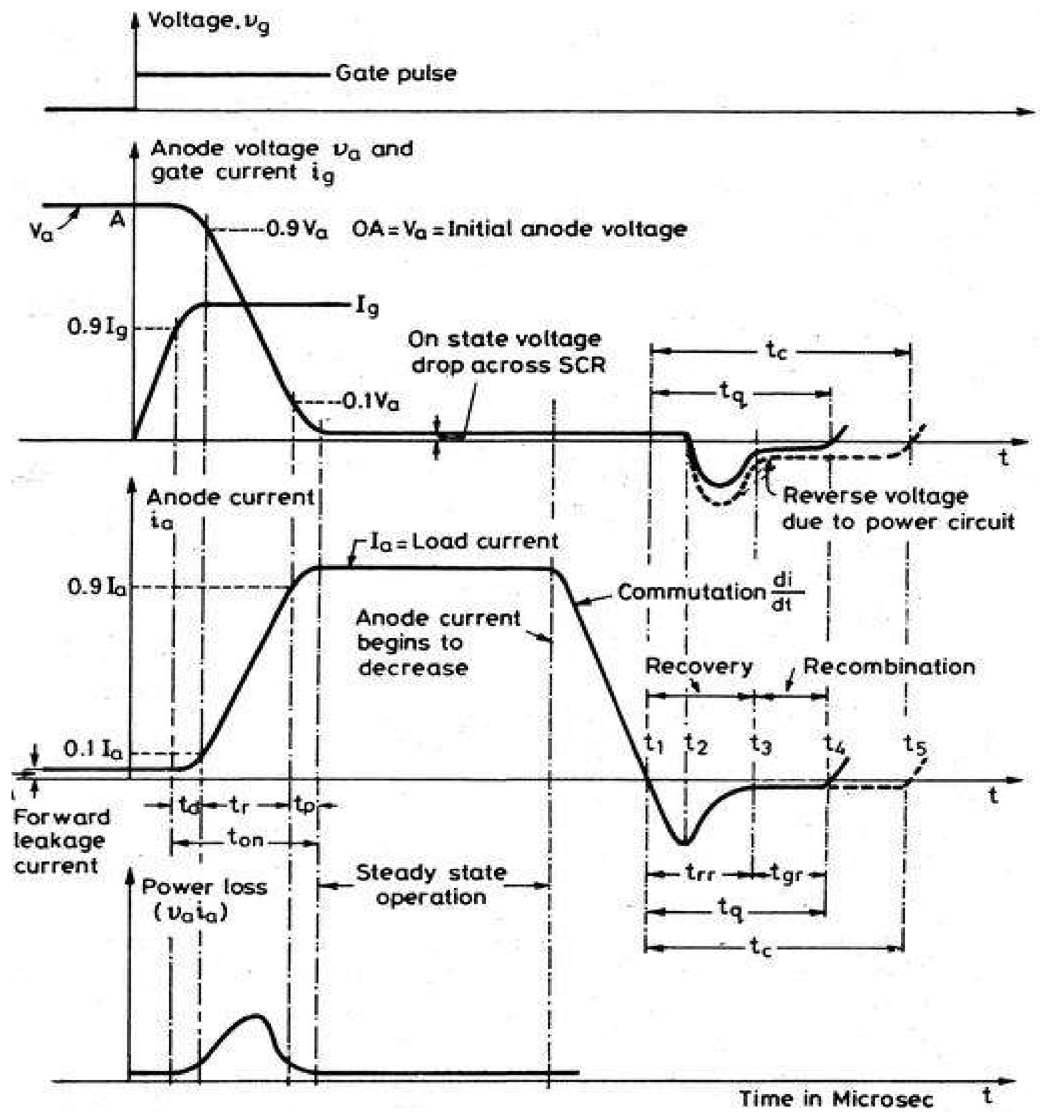


Figure: 1. 22. Dynamic characteristics of SCR

Hence , during the time t_3 to t_4, the recombination of charges takes place and at the instant t_4, junction J_2 completely recovers. This time is called gate recovery time t_{gr}.

- From the figure the turn OFF time is the time interval between the $t_4$and t_1. Generally, this time varies from 10 to 100 microseconds. This turn OFF time t_q is applicable to the individual SCR.
- The time required by the commutation circuit to apply the reverse voltage to commutate the SCR is called the circuit turn OFF time (t_c). For a safety margin or reliable commutation, this t_c must be greater than the t_q otherwise commutation failure occurs.

- The SCRs which have slow turn OFF time as in between 50 to 100 microseconds are called as converter grade SCRs. These are used in phase controlled rectifiers, cyclo-converters, AC voltage regulators etc.
- The SCRs which have fast turn OFF time as in between 3 to 50 microseconds are inverter grade SCRs. These are costlier compared to converter grade and are used in choppers, force commutated converters and inverters.

Turn OFF mechanism

Turning OFF an SCR means bringing the SCR from conducting state to blocking state. To turn off an SCR two things are to be done.(1) Reduce the anode current below its holding current level. (2) Application of reverse voltage.When the anode current is zero, if we apply forward voltage to the SCR, the device will not be able to block this forward voltage due to the fact that excess charge carriers are still at the junctions, so the device will start conducting even when the gate signal is not applied. In order to avoid this, reverse biasing of SCR is done to remove the excess charge carriers from all four layers. The turn OFF time is defined as the time from the instant the anode current becomes zero to the instant SCR reaches its forward blocking ability. Turn off time $t_{OFF} = t_{rr} + t_{gr}$ trr = Reverse recovery time tgr =Gate recovery time Reverse recovery process is the removal of excessive charge carries from the top and bottom layers of SCR. At t_1; current $I_A = 0$ After t_1; I_A build up in the reverse direction, due to the charge carriers stored in the four layers. Reverse recovery current removes the excessive carriers from junctions J_1 and J_3 during the time t_1 to t_3. (Reverse recovery current flows due sweeping out of holes from top p-layer and electrons from bottom n layer)

Reverse Recovery Time (t_{rr}):-

It is the time taken for the removal of excessive carriers from top and bottom layer of SCR. At t_2: When nearly 60% of charges are removed from the outer two layers, the reverse recovery current decreases. This decaying causes a reverse voltage to be applied across the SCR. At t_3 all excessive carriers from J_1 and J_3 is removed. The reverse voltage across SCR removes the excessive carriers from junction J_2. Gate recovery process is the removal of excessive carriers from J_2 junction by application of reverse voltage. Time taken for removal of trapped charges from J_2 is called gate recovery time(t_{gr}). At t_4 all the carriers are removed and the device moves to the forward blocking mode.

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

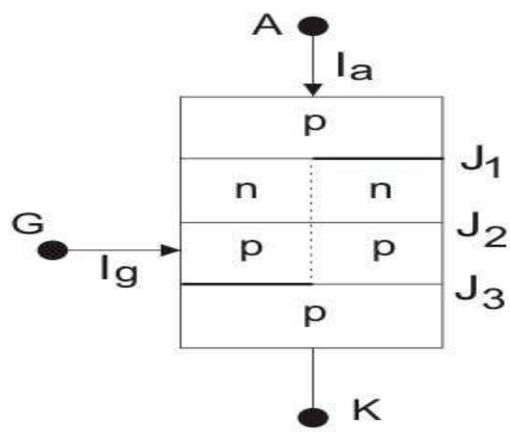


Figure: 1.34.a. Two transistor structure of SCR

This is a pnpn thyristor. If we bisect it through the dotted line then we will get two transistors i.e. one pnp transistor with J_1 and J_2 junctions and another is with J_2 and J_3 junctions as shown in figure below.

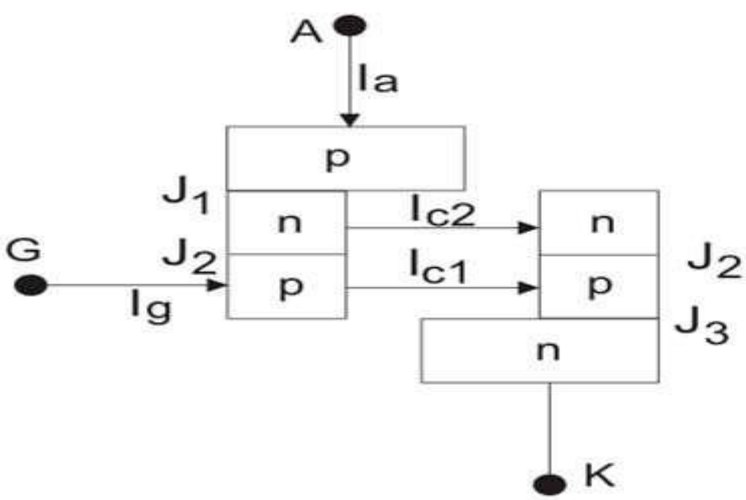


Figure: 1. 34.b. Two transistor structure of SCR

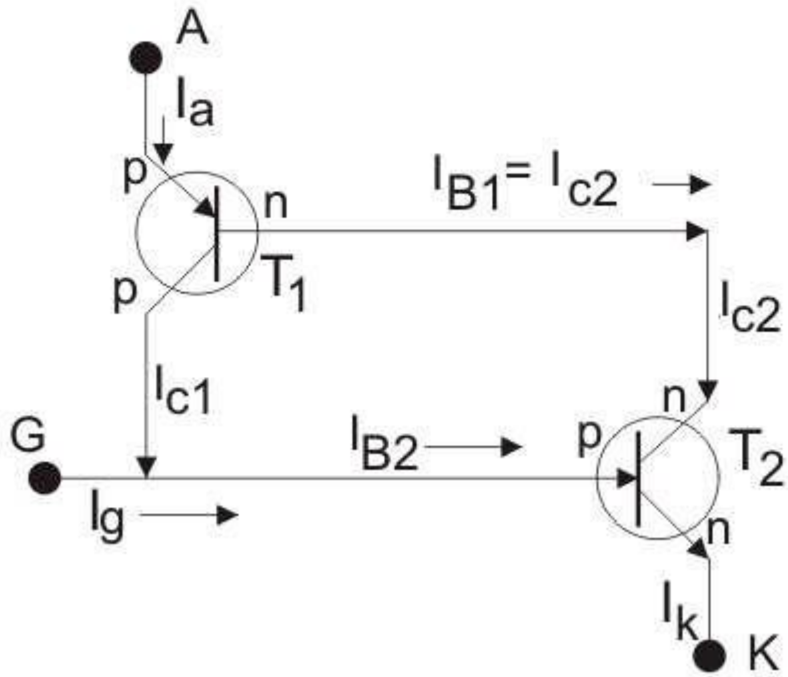


Figure: 1. 35. Two transistors connection of SCR

When the transistors are in off state, the relation between the collector current and emitter current is shown.Here, I_C is collector current, I_E is emitter current, I_{CBO} is forward leakage current, α is common base

forward current gain and relationship between I_C and I_B is $I_C = \beta I_B$ Where, I_B is base current and β is common emitter forward current gain. Let's for transistor T_1 this relation holds

$$I_{C1} = \alpha_1 I_a + I_{CBO1} \ldots . (i)$$

And that for transistor T_2

$$I_{C2} = \alpha_2 I_k + I_{CBO2} \ldots . (ii) \ again \ I_{C2} = \beta_2 I_{B2}$$

Now, by the analysis of two transistors model we can get anode current,

$$I_a = I_{C1} + I_{C2} \ \ [applying \ KCL]$$

From equation (i) and (ii), we get,

$$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 I_k + I_{CBO2} \ldots\ldots (iii)$$

If applied gate current is I_g then cathode current will be the summation of anode current and gate current i.e. $I_k = I_a + I_g$

By substituting this value of I_k in (iii) we get,

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

From this relation we can assure that with increasing the value of $(\alpha_1 + \alpha_2)$towards unity, corresponding anode current will increase. Now the question is how $(\alpha_1 + \alpha_2)$increasing. Here is the explanation using **two transistor model of SCR**. At the first stage when we apply a gate current I_g, it acts as base current of T_2 transistor i.e. $I_{B2} = I_g$ and emitter current i.e. $I_k = I_g$ of the T,$_2$ transistor. Hence establishment of the emitter current gives rise $\alpha_2$as

$$\alpha_2 = \frac{I_{CBO1}}{I_g}$$

Presence of base current will generate collector current as

$$I_{C2} = \beta_2 \times I_{B2} = \beta_2 I_g$$

This I_{C2} is nothing but base current I_{B1} of transistor T,$_1$, which will cause the flow of collector current,

$$I_{C2} = \beta_1 \times I_{B1} = \beta_1 \beta_2 I_g$$

I_{C1} and I_{B1} lead to increase I_{C1} as

$$I_a = I_{C1} + I_{B1}$$

And hence, α_1 increases. Now, new base current of T_2 is

$$I_g + I_{C1} = (1 + \beta_1\beta_2)I_g,$$

This will lead to increase emitter current

$$I_k = I_q + I_{C1}$$

and as a result α_2 also increases and this further increases

$$I_{C2} = \beta_2(1 + \beta_1\beta_2)I_g.$$

$$I_{B1} = I_{C2}$$

,

As α_1 again increases. This continuous positive feedback effect increases $(\alpha_1 + \alpha_2)$towards unity and anode current tends to flow at a very large value. The value current then can only be controlled by external resistance of the circuit.

Turn ON methods / Methods of Turning ON

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

(a) 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 (even when gate is open)

(b) 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.

(c) 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

(d) 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.
- If voltage across the device is V, the charge by Q and capacitance by C then, $i_c = dQ/dt$

  $Q = CV$

  $i_c = d(CV)/dt$

  $= CdV/dt + dC/dt$; as $dC/dt = 0$

  $i_c = CdV/dt$
- Therefore when the rate of change of voltage across the device becomes large, the device may turn ON, even if the voltage across the device is small.

(e) 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.

- Three types of signals are used for gate triggering.

DC gate triggering:-

- A DC voltage of proper polarity is applied between gate and cathode (Gate terminal is positive with respect to Cathode).
- When applied voltage is sufficient to produce the required gate Current, the device starts conducting.
- One drawback of this scheme is that both power and control circuits are DC and there is no isolation between the two.
- Another disadvantage is that a continuous DC signal has to be applied. So gate power loss is high.

2. AC Gate Triggering:-

- Here AC source is used for gate signals.
- This scheme provides proper isolation between power and control circuit.
- Drawback of this scheme is that a separate transformer is required to step down ac supply.
- There are two methods of AC voltage triggering namely (i) R Triggering (ii) RC triggering.

(i) Resistance triggering

The following circuit shows the resistance triggering.

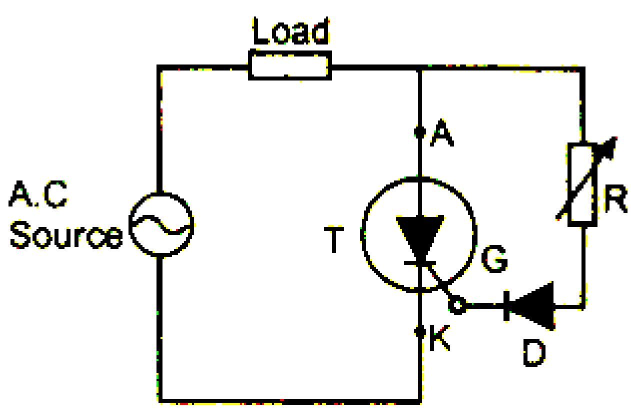


Figure: 1. 36. Resistance triggering circuit of SCR

- In this method, the variable resistance R is used to control the gate current.
- Depending upon the value of R, when the magnitude of the gate current reaches the sufficient value (latching current of the device) the SCR starts to conduct.
- The diode D is called as blocking diode. It prevents the gate cathode junction from getting damaged in the negative half cycle.

- By considering that the gate circuit is purely resistive, the gate current is in phase with the applied voltage.
- By using this method we can achieve maximum firing angle up to90°.

(ii) RC Triggering

The following circuit shows the resistance-capacitance triggering.

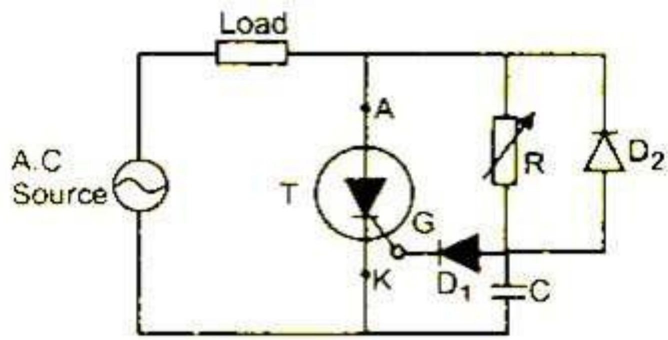


Figure: 1. 37. Resistance Capacitance triggering circuit of SCR

- By using this method we can achieve firing angle more than90°.
- In the positive half cycle, the capacitor is charged through the variable resistance R up to the peak value of the applied voltage.
- The variable resistor R controls the charging time of the capacitor.
- Depends upon the voltage across the capacitor, when sufficient amount of gate current will flow in the circuit, the SCR starts to conduct.
- In the negative half cycle, the capacitor C is charged up to the negative peak value through the diode D2.
- Diode D1 is used to prevent the reverse break down of the gate cathode junction in the negative half cycle.

3. Pulse Gate Triggering

- In this method the gate drive consists of a single pulse appearing periodically (or) a sequence of high frequency pulses.
- This is known as carrier frequency gating.
- A pulse transformer is used for isolation.
- The main advantage is that there is no need of applying continuous signals, so the gate losses are reduced.

Advantages of pulse train triggering

- Low gate dissipation at higher gate current.
- Small gate isolating pulse transformer
- Low dissipation in reverse biased condition is possible. So simple trigger circuits are possible in some cases
- When the first trigger pulse fails to trigger the SCR, the following pulses can succeed in latching SCR.
- Triggering inductive circuits and circuits having back emf's.

Turn off methods of SCR / Commutation Techniques

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.

When the SCR is turned OFF by reducing forward current to zero there exist excess charge carriers in different layers. To regain the forward blocking state of an SCR, these excess carriers must be recombined. Therefore, this recombination process is accelerated by applying a reverse voltage across the SCR. 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.

Forced Commutation

In case of DC circuits, there is no natural current zero to turn OFF the SCR. In such circuits, forward current must be forced to zero with an external circuit to commutate the SCR hence named as forced commutation.

This commutating circuit consists of components like inductors and capacitors called as commutating components. These commutating components cause to apply a reverse voltage across the SCR that immediately bring the current in the SCR to zero. Based on the manner in which the zero current achieved and arrangement of the commutating components, forced commutation is classified into different types such as class A, B, C, D, and E. This commutation is mainly used in chopper and inverter circuits.

Class A Commutation

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.

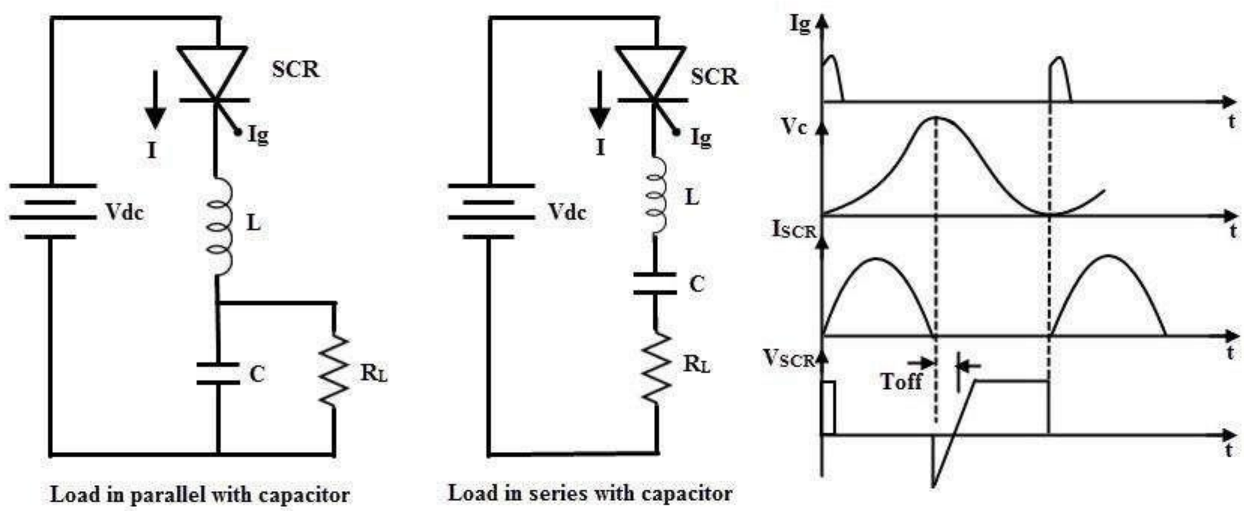


Figure: 1. 38. Class A Commutation circuit and waveforms

The value of load resistance and commutating components are so selected that they forms a under damped resonant circuit to produce natural zero. When the thyristor or SCR is triggered, the forward currents start flowing through it and during this the capacitor is charged. Once the capacitor is fully charged (more than the supply source voltage) the SCR becomes reverse biased and hence the commutation of the device. The capacitor discharges through the load resistance to make ready the circuit for the next cycle of operation. The time for switching OFF the SCR depends on the resonant frequency which further depends on the L and C components.This method is simple and reliable. For high frequency operation which is in the range above 1000 Hz, this type of commutation circuits is preferred due to the high values of L and C components.

Class B Commutation

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.

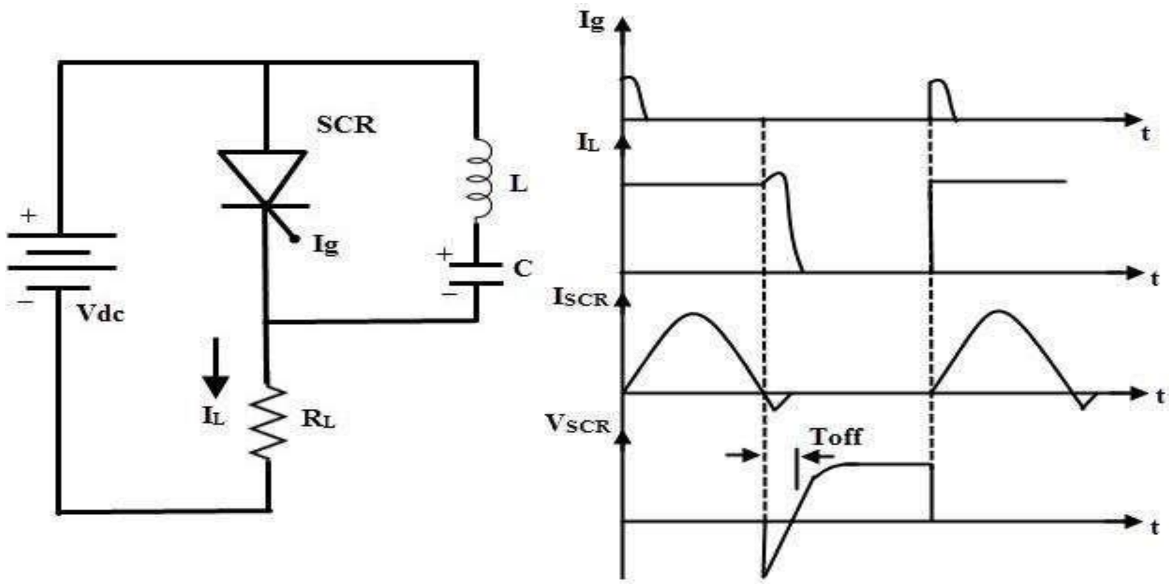


Figure: 1. 39. Class B Commutation circuit and waveforms

When the DC supply is applied to the circuit, the capacitor charges with an upper plate positive and lower plate negative up to the supply voltage E. When the SCR is triggered, the current flows in two directions, one is through E+ – SCR – R – E- and another one is the commutating current through L and C components.

Once the SCR is turned ON, the capacitor is starts discharging through C+ – L – T – C-. When the capacitor is fully discharged, it starts charging with a reverse polarity. Hence a reverse voltage applied across the SCR which causes the commutating current IC to oppose load current IL.

When the commutating current Ic is higher than the load current, the SCR will automatically turn OFF and the capacitor charges with original polarity.

In the above process, the SCR is turned ON for some time and then automatically turned OFF for some time. This is a continuous process and the desired frequency of ON/OFF depends on the values of L and C. This type of commutation is mostly used in chopper circuits.

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.

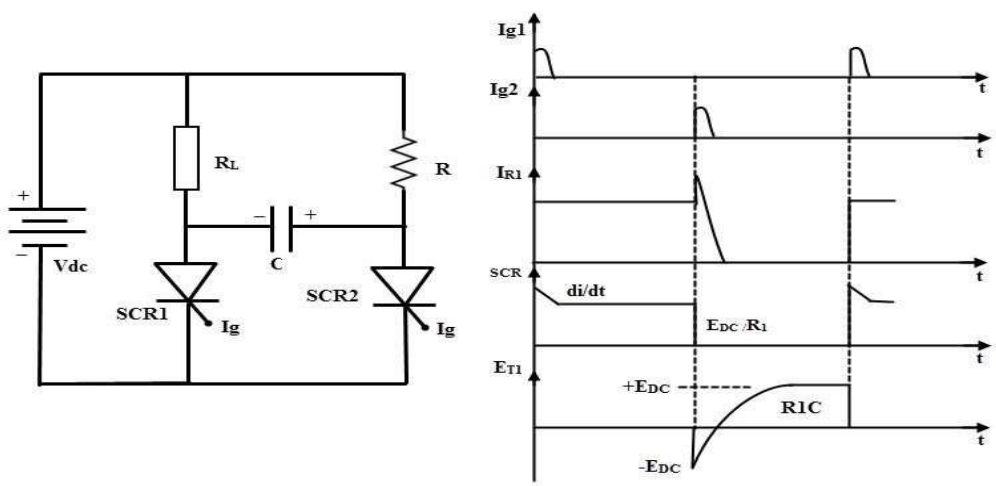


Figure: 1. 40. Class C Commutation circuit and waveforms

Initially, both SCRs are in OFF state so the capacitor voltage is also zero. When the SCR1 or main SCR is triggered, current starts flowing in two directions, one path is E+ – R1 – SCR1 – E- and another path is the charging current E+ – R2- C+ – C- SCR1 – E-. Therefore, the capacitor starts charging up to the value of E.

When the SCR2 is triggered, SCR is turned ON and simultaneously a negative polarity is applied across the SCR1. So this reverse voltage across the SCR1 immediately causes to turn OFF the SCR1. Now the capacitor starts charging with a reverse polarity through the path of E+ – R1- C+ – C- SCR2 – E-. And again, if the SCR 1 is triggered, discharging current of the capacitor turns OFF the SCR2. This commutation is mainly used in single phase inverters with a centre-tapped transformers. The Mc Murray Bedford inverter is the best example of this commutation circuit. This is a very reliable method of commutation and it is also useful even at frequencies below 1000Hz.

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.

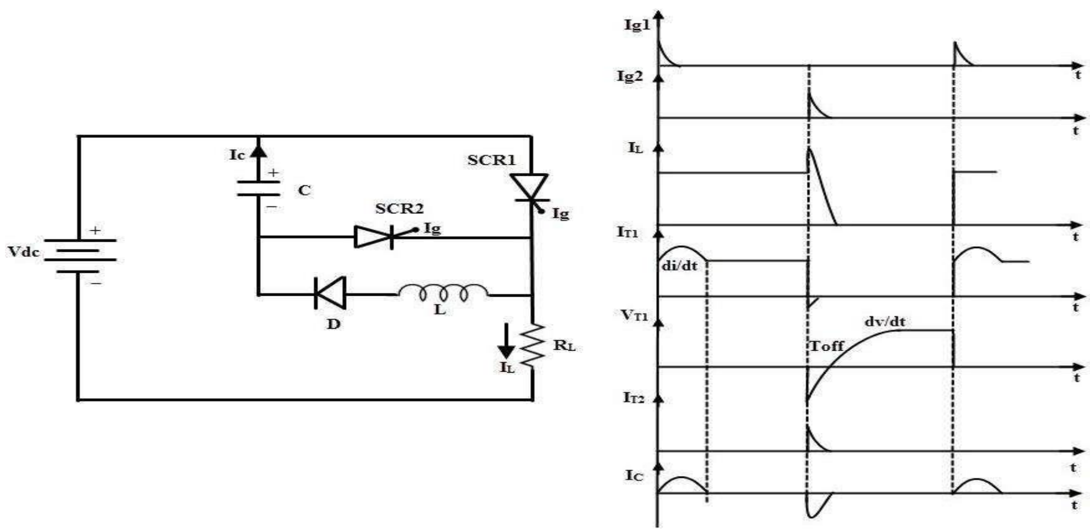


Figure: 1. 41. Class D Commutation circuit and waveforms

When the supply voltage E is applied, both SCRs are in OFF state and hence the capacitor voltage is zero. In order to charge the capacitor, SCR2 must be triggered first. So the capacitor charges through the path E+ – C+ – C- – SCR2- R- E. When the capacitor is fully charged the SCR2 becomes turned OFF because no current flow through the SCR2 when capacitor is charged fully. If the SCR1 is triggered, the current flows in two directions; one is the load current path E+ – SCR1- R- E- and another one is commutation current path C+ – SCR1- L- D- C.

As soon as the capacitor completely discharges, its polarities will be reversed but due to the presence of diode the reverse discharge is not possible. When the SCR2 is triggered capacitor starts discharging through C+ – SCR2- SCR1- C-. When this discharging current is more than the load current the SCR1 becomes turned OFF.

Again, the capacitor starts charging through the SCR2 to a supply voltage E and then the SCR2 is turned OFF. Therefore, both SCRs are turned OFF and the above cyclic process is repeated. This commutation method is mainly used in inverters and also used in the Jones chopper circuit.

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.

If the SCR need to be commutated, pulse duration equal to the turn OFF time of the SCR is applied. When the SCR is triggered, load current flows through the pulse transformer. If the pulse is applied to the primary of the pulse transformer, an emf or voltage is induced in the secondary of the pulse transformer.

This induced voltage is applied across the SCR as a reverse polarity and hence the SCR is turned OFF. The capacitor offers a very low or zero impedance to the high frequency pulse.

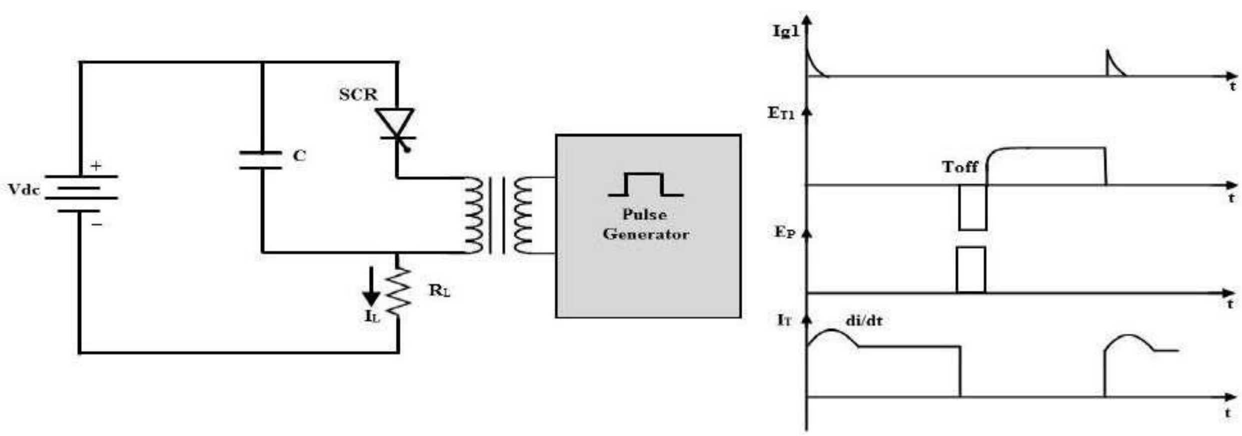


Figure: 1. 42. Class E Commutation circuit and waveforms

Class F / 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.

This method of commutation is also called as source commutation, or line commutation, or class F commutation. This commutation is possible with line commutated inverters, controlled rectifiers, cyclo-converters and AC voltage regulators because the supply is the AC source in all these converters.

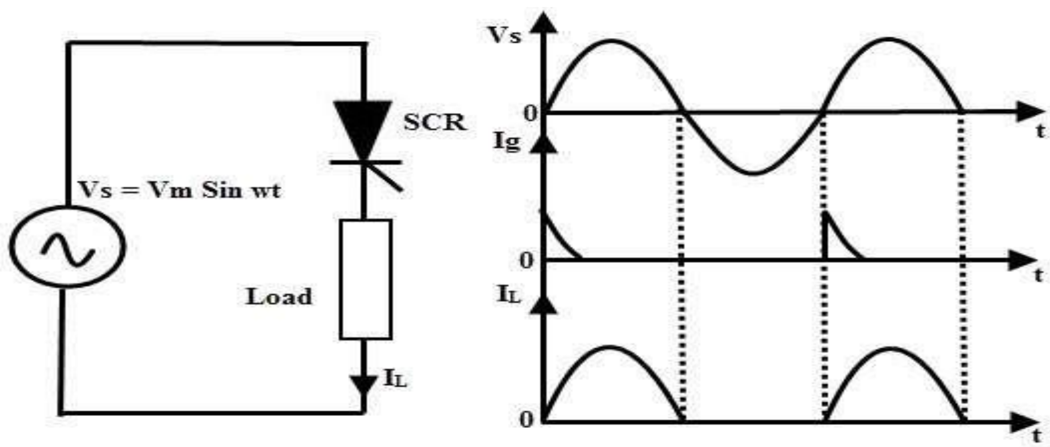


Figure: 1. 43. Class F / Natural Commutation circuit and waveforms

AC Gate Triggering for 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.
- The SCR remains ON until the anode current is equal to the holding current of the SCR. And it will switch OFF when the voltage applied is zero. So the load current is zero as the SCR acts as open switch.
- The diode protects the gate drive circuit from reverse gate voltage during the negative half cycle of the input. And Resistance R1 limits the current flowing through the gate terminal and its value is such that the gate current should not exceed the maximum gate current.
- It is the simplest and economical type of triggering but limited for few applications due to its disadvantages.
- In this, the triggering angle is limited to 90 degrees only. Because the applied voltage is maximum at 90 degrees so the gate current has to reach minimum gate current value somewhere between zero to 90degrees.

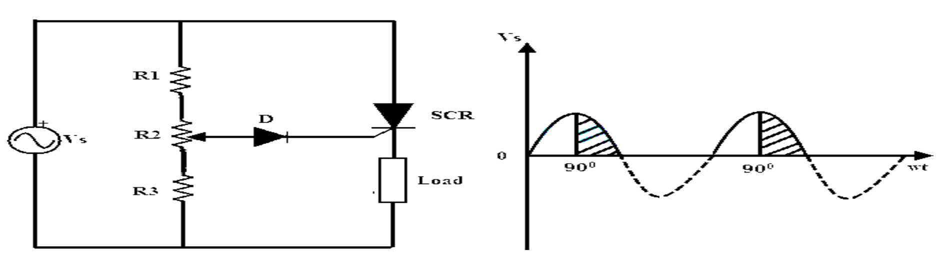


Figure: 1. 44. R Firing circuit for SCR and corresponding waveforms

Resistance Capacitacne (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.
- During the negative half cycle of the input signal, capacitor charges with lower plate positive through diode D2 up to the maximum supply voltage Vmax. This voltage remains at -Vmax across the capacitor till supply voltage attains zero crossing.
- During the positive half cycle of the input, the SCR becomes forward biased and the capacitor starts charging through variable resistance to the triggering voltage value of the SCR.
- When the capacitor charging voltage is equal to the gate trigger voltage, SCR is turned ON and the capacitor holds a small voltage. Therefore the capacitor voltage is helpful for triggering the SCR even after 90 degrees of the input waveform.
- In this, diode D1 prevents the negative voltage between the gate and cathode during the negative half cycle of the input through diode D_2.

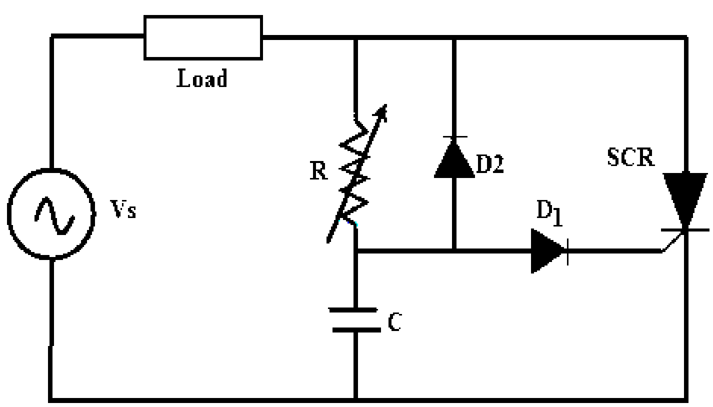


Figure: 1. 46. R Firing circuit for SCR

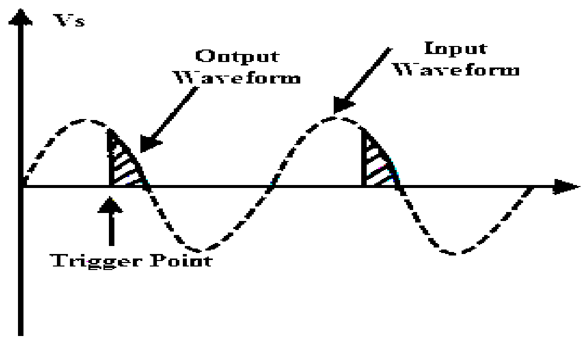


Figure: 1. 47. R Firing circuit waveforms of SCR

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.
- The pulse output at the base terminal 1 is used to turn ON the SCR at predetermined time intervals.

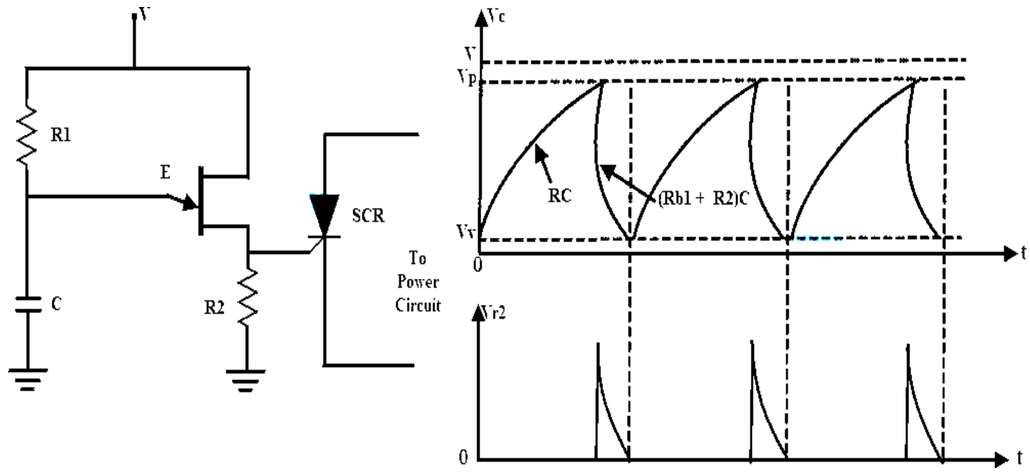


Figure: 1. 48. UJT Firing circuit for SCR and corresponding

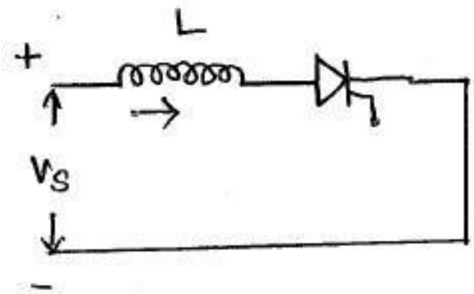
SCR PROTECTION

For reliable operation of SCR, it should be operated within the specific ratings. SCRs are very delicate devices and so they must be protected against abnormal operating conditions. Various protection of SCR are

1. di/dt Protection
2. dv/dt Protection
3. Over voltage Protection
4. OverCurrent Protection.

di/dt Protection

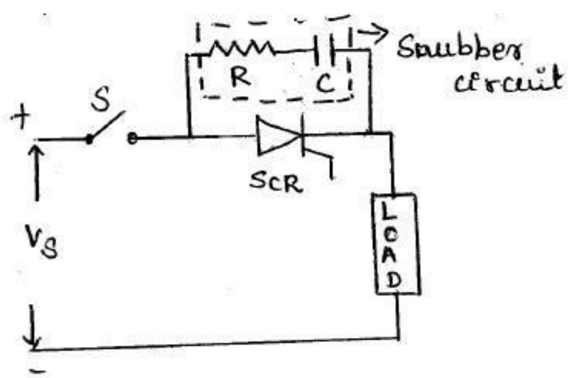
di/dt is the rate of change of current in a device. When SCR is forward biased and is turned ON by the gate signal, the anode current flows. The anode current requires some time to spread inside the device. (Spreading of charge carriers)But if the rate of rise of anode current(di/dt) is greater than the spread velocity of charge carriers then local hot spots is created near the gate due to increased current density. This localized heating may damage the device.Local spot heating is avoided by ensuring that the conduction spreads to the whole area very rapidly. (OR) The di/dt value must be maintained below a threshold (limiting) value. This is done by means of connecting an inductor in series with the thyristor. The inductance L opposes the high di/dt variations. When the current variation is high, the inductor smooths it and protects the SCR from damage. (Though di/dt variation is high, the inductor 'L' smooths it because it takes some time to charge). $L \geq [Vs / (di/dt)]$



dv/dt Protection

We know that i_C=C.dv/dt. ie, when dv/dt is high, i_C is high.This high current(i_C) may turn ON SCR even when gate current is zero. This is called as dv/dt turn ON or false turn ON of SCR.dv/dt is the rate of charge of voltage in SCR.To protect the thyristor against false turn ON or against high dv/dt a "Snubber Circuit" is used.

Snubber Circuit:-



The snubber Circuit is a series combination of resistor 'R' and capacitor 'C'.They are connected across the thyristor to be protected.The capacitor 'C' is used to limit the dv/dt across the SCR.The resistor 'R' is used to limit high discharging current through the SCR.When switch S is closed, the capacitor 'C' behaves as a short-circuit.Therefore voltage across SCR is zero.As time increases, voltage across 'C' increases at a slow rate.Therefore dv/dt across 'C' and SCR is less than maximum dv/dt rating of the device.The capacitor charges to full voltage Vs; after which the gate is triggered, and SCR is turned ON and high current flows through SCR.As di/dt is high, it may damage the SCR.To avoid this, the resistor R in series with 'C' will limit the magnitude of di/dt.The technique of 'snubbing' can apply to any switching circuit, not only to thyristor/triac circuits.The rate of rise of turn-off voltage is determined by the time constant R_LC. Where R_L is the circuit minimum load resistance, for instance the cold resistance of a heater or lamp, the winding resistance of a motor or the primary resistance of a transformer.

Overvoltage Protection

Overvoltage may result in false turn ON of the device (or) damage the device.SCR is subjected to internal and external over voltage. Internal Overvoltage. The reverse recovery current of the SCR decays at a very fast rate. ie, high di/dt. So a voltage surge is produced whose magnitude is L(di/dt). External Overvoltage. These are caused by the interruption of current flow in the inductive circuit and also due to lightning strokes on the lines feeding the SCR systems. The effect of overvoltage is reduced by using Snubber circuits and Non-Linear Resistors called Voltage Clamping Devices.

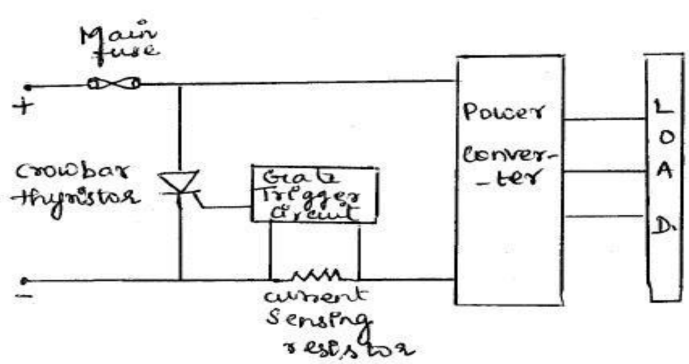
Voltage Clamping Device:

It is a non-linear resistor called as VARISTOR (VARIable resiSTOR) connected across the SCR.The resistance of varistor will decrease with increase in voltage.During normal operation, varistor has high Resistance and draws only small leakage current.When high voltage appears, it operates in low resistance region and the surge energy is dissipated across the resistance by producing a virtual short-circuit across the SCR.

Over Current Protection

In an SCR due to over-current, the junction temperature exceeds the rated value and the device gets damaged.Over-current is interrupted by conventional fuses and circuit breakers.The fault current must be interrupted before the SCR gets damaged and only the faulty branches of the network should be isolated.Circuit breaker has long tripping time. So it is used for protecting SCR against continuous over loads (or) against surge currents of long duration.Fast acting current limiting fuse is used to protect SCR against large surge currents of very short duration.

Electronic Crowbar Protection



SCR has high surge current ability.SCR is used in electronic crowbar circuit for over-current protection of power converter. In this protection, an additional SCR is connected across the supply which is known as 'Crowbar SCR'. Current sensing resistor detects the value of converter current. If it exceeds preset value, then gate trigger circuits turn ON the crowbar SCR. So the input terminals are short-circuit by SCR and thus it bypass the converter over current. After some time the main fuse interrupts the fault current.

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 (**di/dt** or **dv/dt**) and over voltage during turn-on and turn-off. These are placed across the semiconductor devices for protection as well as to improve the performance. Static **dv/dt** is a measure of the ability of a thyristor to retain a blocking state under the influence of a voltage transient. These are also used across the relays and switches to prevent arcing.

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

Similarly when the transition is from OFF to ON state, due to uneven distribution of the current through the area of the switch overheating will takes place and eventually it will be burned. Here also snubber is necessary to reduce the current at starting by making an alternate path.

Snubbers in switching mode provides one or more of the following functions

- Shape the load line of a bipolar switching transistor to keep it in its safe operating area.
- Reducing the voltages and currents during turn-ON and turn-OFF transient conditions.

- Removes energy from a switching transistor and dissipate the energy in a resistor to reduce junction temperature.
- Limiting the rate of change of voltage and currents during the transients.
- Reduce ringing to limit the peak voltage on a switching transistor and lowering their frequency.

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.

I = Vo/Rs and I = C dv/dt

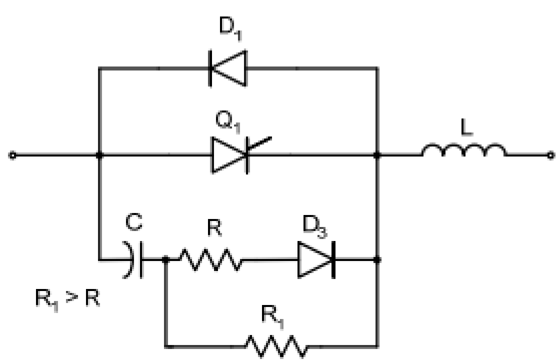


Figure: 1. 29. Forward-Polarized RC Snubber Circuit

For an appropriate forward-polarized RC snubber circuit a thyristor or a transistor is connected with an anti-parallel diode. R will limit the forward **dv/dt** and R1 limits the discharge current of the capacitor when transistor Q1 is turned on. These are used as overvoltage snubbers to clamp the voltage.

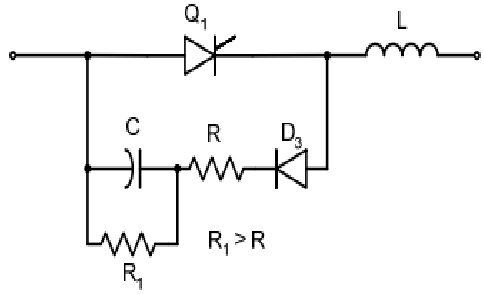


Figure: 1. 30. Reverse Polarized RC Snubber Circuit

Reverse polarized snubber circuit can be used to limit the reverse **dv/dt**. R1 will limit the discharge current of the capacitor.

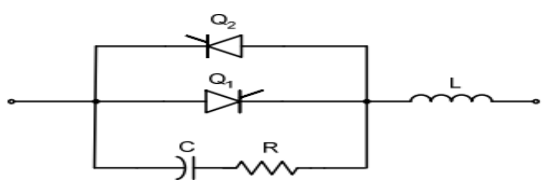


Figure: 1. 31. An un-polarized snubber circuit

An un-polarized snubber circuit is used when a pair of switching devices is used in anti-parallel. For determining the resistor and capacitor values a simple design technique can be used. For this an optimum design is needed. Hence a complex procedure will be used. These can be used to protect and thyristors.

Capacitors selection

Snubber capacitors are subjected to high peak and RMS currents and high **dv/dt**. An example is turn-on and turn-off current spikes in a typical RCD snubber capacitor. The pulse will have high peak and RMS amplitudes. The snubber capacitor has to meet two requirements. First, the energy stored in the snubber capacitor must be greater than the energy in the circuit's inductance. Secondly, the time constant of snubber circuits should me small compared to shortest on time expected, usually 10% of the on time. By allowing the resistor to be effective in the ringing frequency this capacitor is used to minimize the dissipation at switching frequency. The best design is selecting the impedance of the capacitor is same that of resistor at the ringing frequency.

Resistors selection

It is important that R in the RC snubber, have low self inductance. Inductance in R will increase the peak voltage and it will tend to defeat the purpose of the snubber. Low inductance will also be desirable for R in snubber but it is not critical since the effect of a small amount of inductance is to slightly increase the reset time of C and it will reduce the peak current in switch at turn-on. The normal choice of R is usually the carbon composition or metal film. The resistor power dissipation must be independent of the resistance R because it dissipates the energy stored in the snubber capacitor in each transition of voltage in the capacitor. If we select the resistor as that the characteristic impedance, the ringing is well damped.

When comparing the Quick design to optimum design, the required snubber resistor's power capability will be reduced. Usually the "Quick" design is completely adequate for final design. Going to the "Optimum" approach is only if power efficiency and size constraints dictate the need for optimum design.

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Question Bank

Unit I Power Semiconductor Devices			
	Part A	**CO**	**L**
1.	Discover the reverse recovery time of a diode from its switching characteristics	CO1	L4
2.	Justify how gate pulse can make a SCR conducting?	CO1	L5
3.	Justify why commutation is required in SCR?	CO1	L5
4.	Validate why snubber circuit is needed in SCR?	CO1	L5
5.	Distinguish the GTO and SCR for DC chopper application.	CO1	L4
6.	Classify the different turn on methods for SCR.	CO1	L2
7.	Distinguish Latching and holding current?	CO1	L4
8.	Classify the different commutation techniques for SCR.	CO1	L2
9.	Interpret the di/dt and dv/dt triggering of SCR?	CO1	L2
10.	Distinguish BJT and MOSFET with respect to switching losses and switching speed?	CO1	L4
11.	Classify the turn on methods of SCR?	CO1	L2
12.	Classify the Commutation methods of SCR?	CO1	L2
	Part B	**CO**	**L**
1.	Analyze the input, output and switching characteristics of power BJT from that identify the region of operation & different time periods.	CO1	L4
2.	Explain different turn on methods for a thyristor, Justify which method is suitable for industrial application.	CO1	L5
3.	Explain with necessary plots and discuss the switching characteristics of IGBT from that identify the different time periods.	CO1	L5
4.	Justify why commutation is required in SCR? Explain class B commutation and sketch and examine its different time periods.	CO1	L4
5.	Justify why protection circuits are required in SCR? Explain in detail about the di/dt and dv/dt protection with neat sketch.	CO1	L4
6.	Explain in detail about the UJT and ramp pedestal triggering of SCR with neat sketch and distinguish their merits and demerits.	CO1	L5
7.	Analyze the input, output and switching characteristics of power MOSFET from that identify the region of operation & different time periods.	CO1	L4
8.	Explain in detail about the R and RC triggering of SCR with neat sketch and distinguish their merits and demerits.	CO1	L5

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DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

UNIT – II
POWER ELECTRONICS – SEE1305

Phase controlled rectifiers

Principle of phase controlled converter operation - Single phase half wave converter - Semi converter - Full converter with R, RL and RLE load - Freewheeling diode - Inverter operation of Full converter - Three phase Semi converter and Full converter with RL load.

UNIT II

Phase Controlled Rectifier

Phase control technique – Single phase Line commutated converters

Unlike diode rectifiers, PCRs or phase-controlled rectifiers has an advantage of regulating the output voltage. The diode rectifiers are termed as uncontrolled rectifiers. When these diodes are switched with Thyristors, then it becomes phase control rectifier. The o/p voltage can be regulated by changing the firing angle of the Thyristors. The main application of these rectifiers is involved in speed control of DC motor.

What is a Phase Controlled Rectifier?

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

The phase controlled rectifier is classified into two types based on the type of i/p power supply. And each kind includes a semi, full and dual converter.

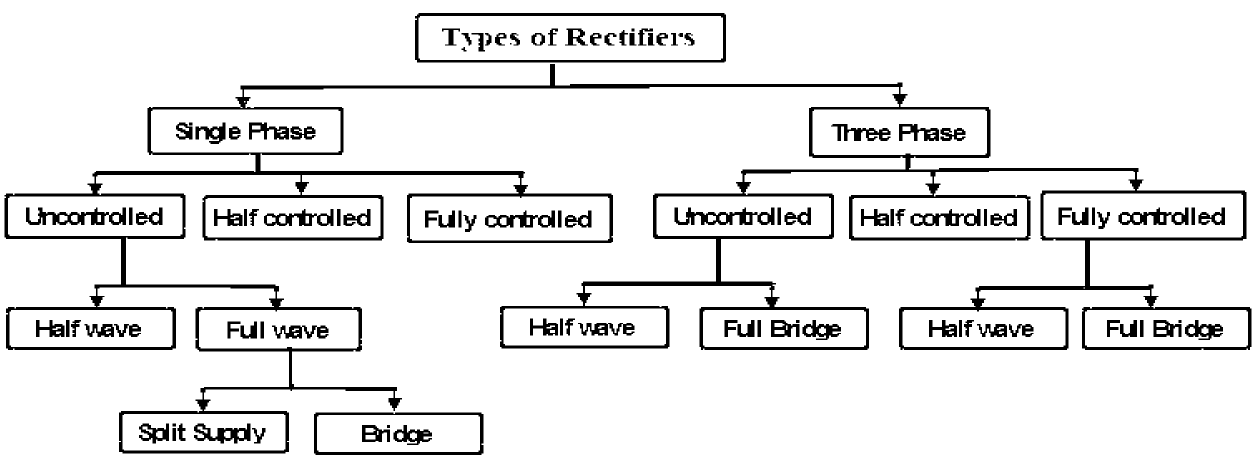

Figure: 2.1. Classification of rectifiers

Single-phase Controlled Rectifier

This type of rectifier which works from single phase AC input power,

Half wave Controlled Rectifier : This type of rectifier uses a single Thyristor device to provide output control only in one half cycle of input AC supply, and it offers low DC output.

Full wave Controlled Rectifier : This type of rectifier provides higher DC output

- Full wave controlled rectifier with a center tapped transformer requires two Thyristors.
- Full wave bridge controlled rectifiers do not need a center tapped transformer

Three-phase Controlled Rectifier

This type of rectifier which works from three phase AC input power supply

- A semi converter is a one quadrant converter that has one polarity of o/p voltage and current.
- A full converter is a a two quadrants converter that has polarity of o/p voltage can be either +ve or –ve but, the current can have only one polarity that is either +ve or-ve.
- Dual converter works in four quadrants – both o/p voltage and o/p current can have both the polarities.

Operation of Single Phase Half wave Controlled Rectifier

The basic working principle of a Phase controlled rectifier circuit is explained using a single phase half wave SCR circuit with a RL load resistive shown in the following circuit.

A single phase half wave Thyristor converter circuit is used to convert AC to DC power conversion. The input AC supply is attained from a transformer to offer the required AC supply voltage to the Thyristor converter based on the o/p DC voltage required. In the above circuit, the primary and secondary AC supply voltages are denoted with VP and VS.

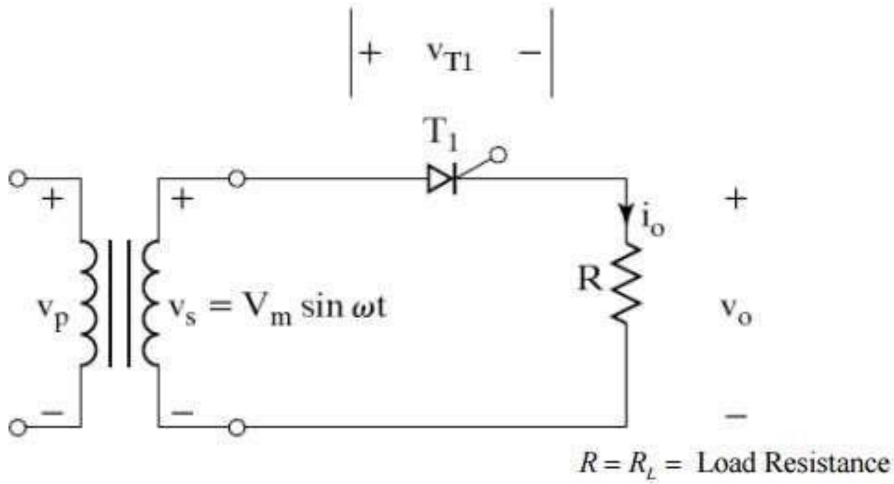

Figure: 2.2. Single phase half wave rectifier circuit

During the +ve half cycle of i/p supply when the upper end of the transformer secondary winding is at a + ve potential with respect to the lower end, the Thyristor is in a forward biased state. The thyristor is activated at a delay angle of ωt =α, by applying an appropriate gate trigger pulse to the gate terminal of thyristor. When the thyristor is activated at a delay angle of ωt =α, the thyristor behaviors and assuming a perfect thyristor. The thyristor acts as a closed switch and the i/p supply voltage acts across the load when it conducts from ωt =α to π radians For a purely resistive load, the load current io that flows when the thyristor T1 is on, is given by the expression.

$$\mathbf{Io = V_o / RL, \text{ for } \alpha \leq \omega t \leq \pi}$$

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).

Operation of Half wave converter with R and RL load

As shown in figure below primary of transformer is connected to ac mains supply with which SCR becomes forward bias in positive half cycle. T1 is triggered at an angle α, T1 conducts and voltage is applied across R.

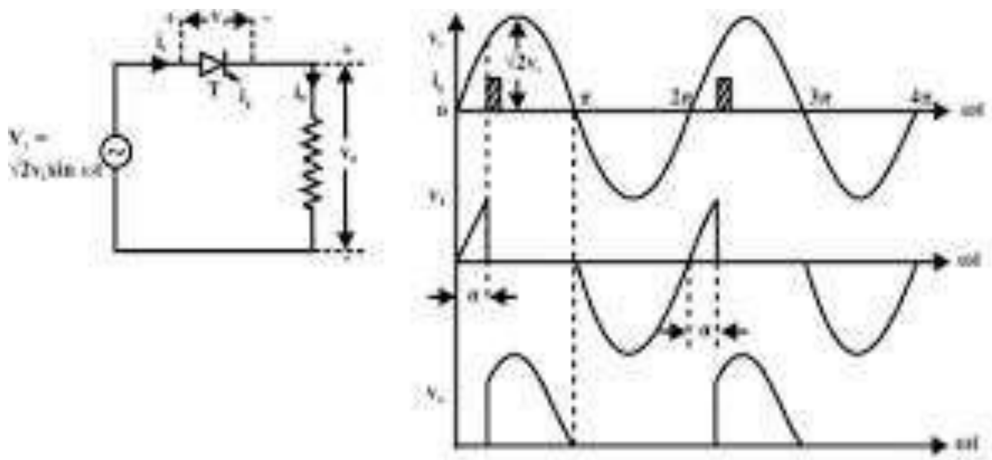

Figure: 2.3 Single phase half wave rectifier with R load with waveforms

The load current i_0 flows through 'R' the waveforms for voltage & current are as shown above. As load is resistive, Output current is given as,

$$I_O = \frac{V_O}{R}$$

Hence shape of output current is same as output voltage As T1 conducts only in positive half cycle as it is reversed bias in negative cycle. The Average output voltage is given as,

$$V_0(Avg) = \frac{1}{T}\int_0^T V_0(wt)\, dwt$$

Area under one cycle.Therefore, T=2π , Vo(ωt) = Vm sinωt from α to π and for rest of the period $V_o(\omega t) = 0$

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

$$P_0(Avg) = \frac{V_0^2(Avg)}{R}$$

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

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

Power transferred to load,

Thus, power and voltage can be controlled by firing angle.

Single Phase Half Wave Controlled Rectifier with RL load

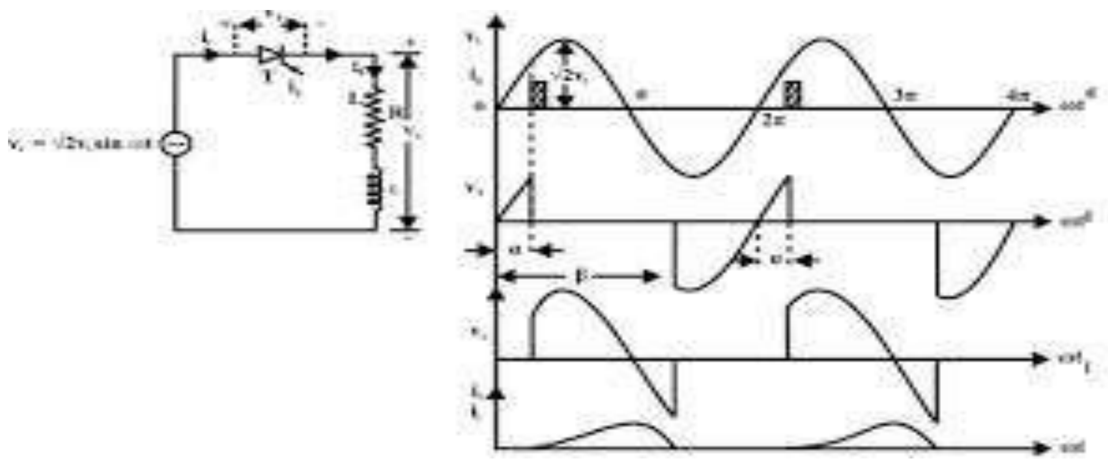

Figure: 2.4 Single phase half wave rectifier with RL load with waveforms

Figure above shows the single phase half wave rectifier with RL Load.

- Loads L= Coil inductance
    - R= Resistance of coil.
- In positive half cycle, SCR starts conduction at firing angle"α".
- Drop across SCR is small & neglected so output voltage is equal to supply voltage.
- Due to 'R_L' load, current through SCR increases slowly.
- At 'π', supply voltage is at zero where load current is at its max value.
- In positive half cycle, inductor stores energy & that generates the voltage.
- In negative half cycle, the voltage developed across inductor, forward biases SCR & maintains its conduction.
- Basically with the property of inductance it opposes change in current.
- Output current & supply current flows in same loop, so all the time $i_o=i_s$.
- After π the energy of inductor is given to mains & there is flow of 'io'. The energy reduces as if gets
    - consumed by circuit so current also reduces.
- At 'β' energy stored in inductance is finished, hence 'i_o' becomes zero & 'T1' turns off.
- 'i_o' becomes zero from 'β' to '2π+α' hence it is discontinuous conduction.

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

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

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.

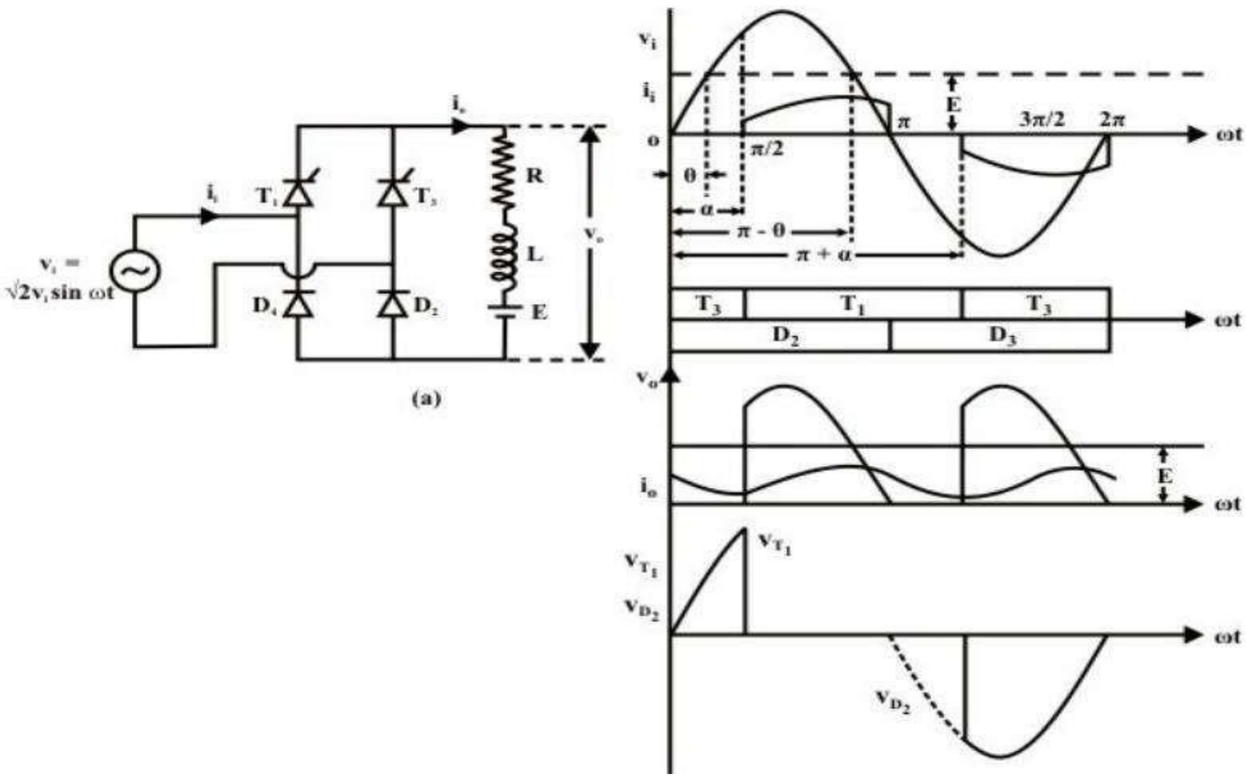

Figure : 2.5 single phase half controlled converter with RLE load

Referring to Fig T1 D2 starts conduction at $\omega t = \alpha$. Output voltage during this period becomes equal to At $\omega t = \pi$ as vi tends to go negative D4 is forward biased and the load current commutates from D2 to D4 and freewheels through D4 and T1. The output voltage remains clamped to zero till T3 is fired at $\omega t = \pi + \alpha$. The T3 D4 conduction mode continues up to $\omega t = 2\pi$. Where upon load current again free wheels through T3 and D2 while the load voltage is clamped to zero. From the discussion in the previous paragraph it can be concluded that the output voltage (hence the output current) is periodic over half the input cycle.

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

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

Single phase half controlled converter with RLE Load and freewheeling diode

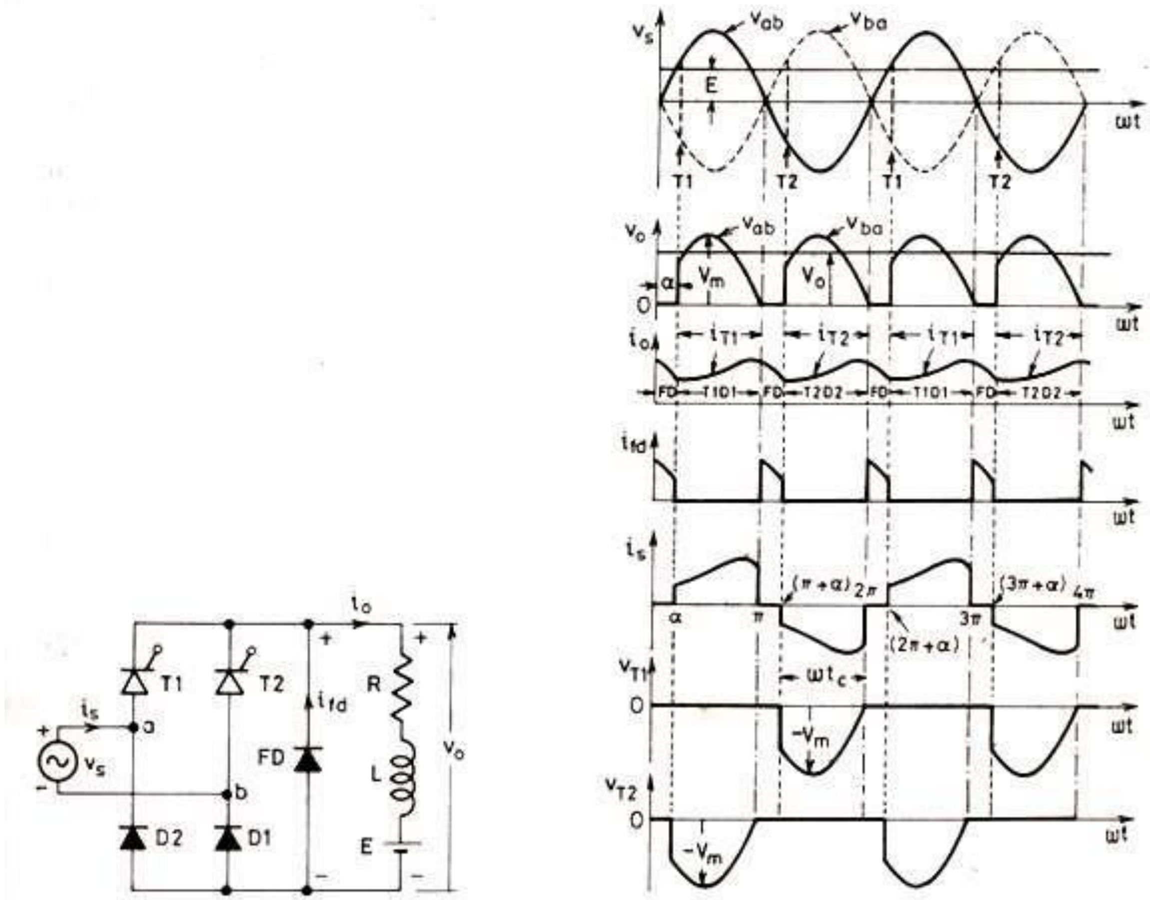

Figure: 2.6 single phase half controlled converter with RLE load and freewheeling diode

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= $V^2/W = 230^2/1000$

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

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

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

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

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

$$V_{or} = \frac{\sqrt{2}\times 230}{2\sqrt{\pi}}\left[\left(\pi - \frac{\pi}{2}\right) + \frac{1}{2}sin180\right]^{1/2} = 115\text{V}$$

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

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

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^o. 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 Wave Controlled Rectifier with 'R' load

Figure below shows the Single phase Full Wave Controlled Rectifiers with R load

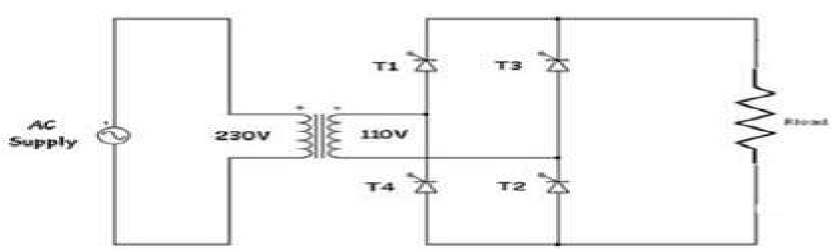

Figure: 2.7 single phase full converter circuit with R load

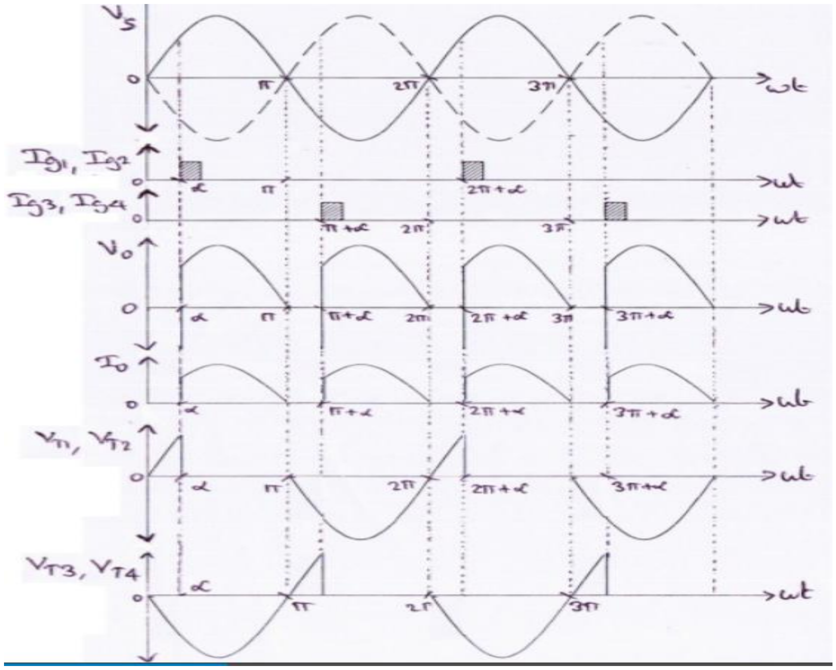

Figure: 2.8 single phase full converter circuit with R load input and output waveforms

• The single phase fully controlled rectifier allows conversion of single phase AC into DC. Normally this is used in various applications such as battery charging, speed control of DC motors and front end of UPS (Uninterruptible Power Supply) and SMPS (Switched Mode Power Supply).

• All four devices used are Thyristors. The turn-on instants of these devices are dependent on the firing signals that are given. Turn-off happens when the current through the device reaches zero and it is reverse biased at least for duration equal to the turn-off time of the device specified in the datasheet.

• In positive half cycle Thyristors T1 & T2 are fired at an angle α.

• In negative half cycle of input voltage, SCR's T3 &T4 are triggered at an angle of(π+α)
T3 & T4 becomes off at 2π.

$$V_{orms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \cdot d\omega t} \qquad V_o(avg) = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin \omega t \cdot d\omega t$$

$$V_{orms} = \frac{V_m}{\sqrt{2\pi}}\sqrt{\left[\pi - \alpha + \frac{1}{2}\sin 2\alpha\right]} \qquad V_o(avg) = \frac{V_m}{\pi}\left[1 + \cos \alpha\right].$$

Single Phase Full Wave Controlled Rectifier with 'RL' load

Figure below shows Single phase Full Wave Controlled Rectifiers with RL load.

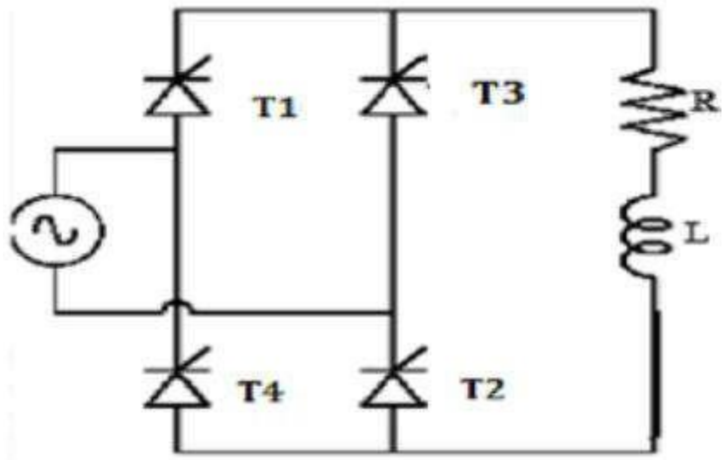

Figure: 2.9 single phase full converter circuit with RL load

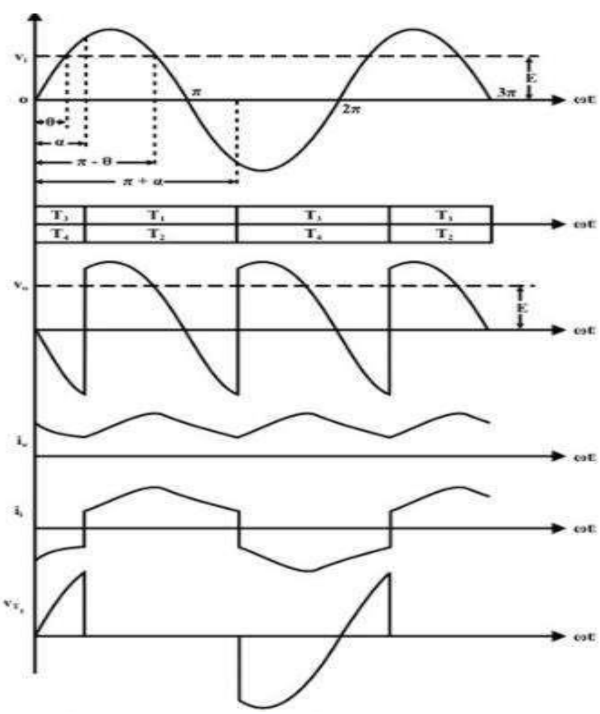

Figure: 2.10 single phase full converter circuit with RL load input and output waveforms

Operation of this mode can be divided between four modes

Mode 1 (α toπ)

- In positive half cycle of applied ac signal, SCR's T1 & T2 are forward bias & can be turned on at an angle α.
- Load voltage is equal to positive instantaneous ac supply voltage. The load current is positive, ripple free, constant and equal to Io.
- Due to positive polarity of load voltage & load current, load inductance will store energy.

Mode 2 (π toπ+α)

- At wt=π, input supply is equal to zero & after π it becomes negative. But inductance opposes any
- change through it.
- In order to maintain a constant load current & also in same direction. A self induced emf appears across
- 'L' as shown.
- Due to this induced voltage, SCR's T1 & T2 are forward bias in spite the negative supply voltage.
- The load voltage is negative & equal to instantaneous ac supply voltage whereas load current is positive.
- Thus, load acts as source & stored energy in inductance is returned back to the ac supply.

Mode 3 (π+α to 2π)

- At wt=π+α SCR's T3 & T4 are turned on & T1, T2 are reversed bias.
- Thus the process of conduction is transferred from T1,T2 toT3,T4.
- Load voltage again becomes positive & energy is stored in inductor
- T3, T4 conduct in negative half cycle from (π+α) to2π
- With positive load voltage & load current energy gets stored

Mode 4 (2π to 2π+α)

- At wt=2π, input voltage passes through zero.
- Inductive load will try to oppose any change in current if in order to maintain load current constant and in the same direction.
- Induced emf is positive & maintains conducting SCR's T3 & T4 with reverse polarity also.

- Thus VL is negative & equal to instantaneous ac supply voltage. Whereas load current continues to be positive.
- Thus load acts as source & stored energy in inductance is returned back to ac supply
- At wt=α or 2π+α, T3 & T4 are commutated and T1,T2 are turned on.

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} Vmsinwt\, d(wt) = \frac{2Vm}{\pi}\ cos\alpha$$

Single phase fully controlled converters with RLE load

The circuit diagram of a full wave bridge rectifier using thyristors in shown in figure below. It consists of four SCRs which are connected between single phase AC supply and a load.This rectifier produces controllable DC by varying conduction of all SCRs.

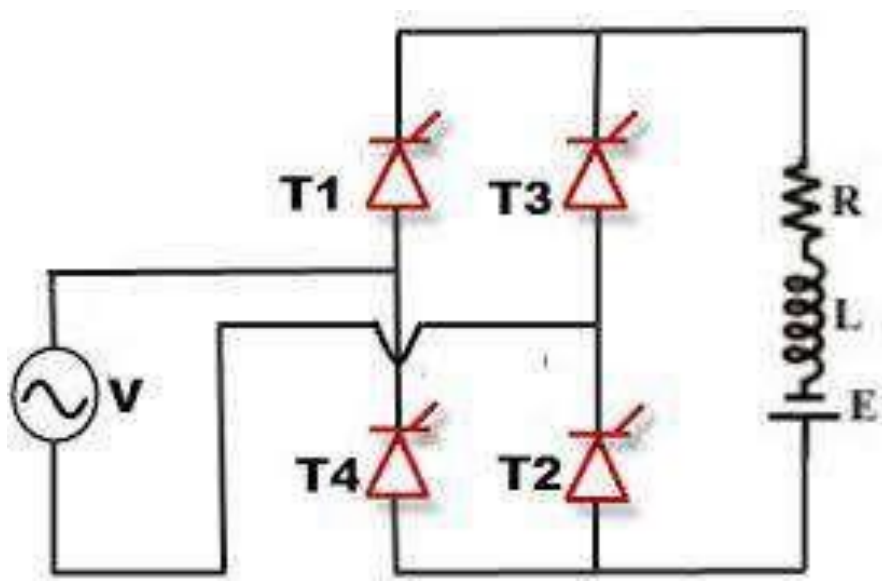

Figure: 2.11 single phase full converter circuit with RLE load

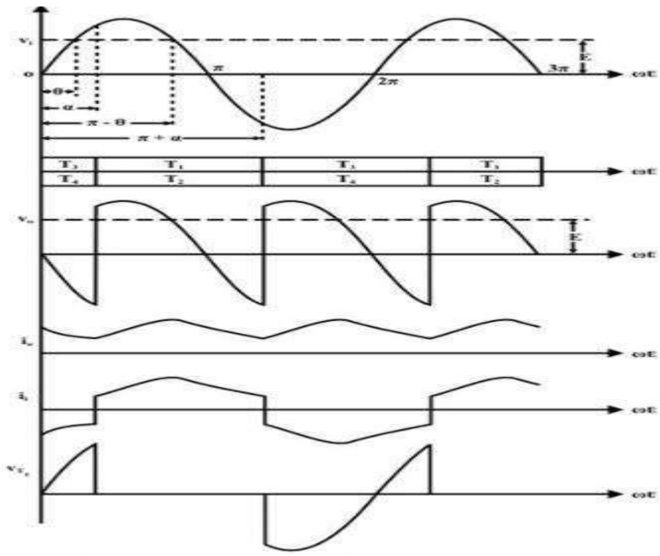

Figure: 2.12 single phase full converter circuit with RLE load input and output waveforms

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.

By varying the conduction of each thyristor in the bridge, the average output of this converter gets controlled. The average value of the output voltage is twice that of half-wave rectifier.

The average output voltage is

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} Vmsinwt\, d(wt) = \frac{2Vm}{\pi}\ cos\alpha$$

Numerical problems

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

$$\frac{2Vm}{\pi} \cos\alpha = E + I_0R$$

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

$$\alpha = 53.21^0$$

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

$$\frac{2Vm}{\pi} \cos\alpha = E + I_0R$$

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

$$\alpha = 124.1^0$$

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

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

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

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

For $\alpha = 53.21^0$ $\qquad \cos\Phi = \frac{120\times10+10^2\times0.4}{230\times10} = 0.5391$ lag

For $\alpha = 124.1^0$ $\qquad \cos\Phi = \frac{120\times10-10^2\times0.4}{230\times10} = 0.5043$ 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 60degrees

Three phase Controlled half rectifier

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

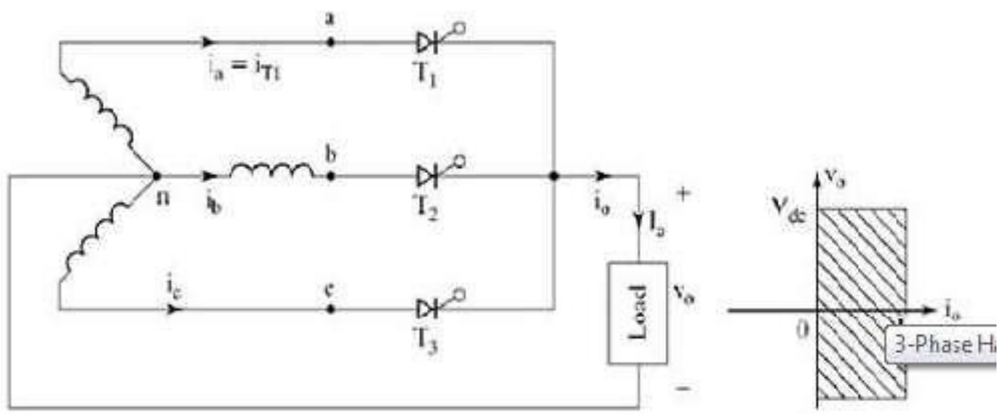

Figure: 2.13 circuit diagram three phase half wave rectifier

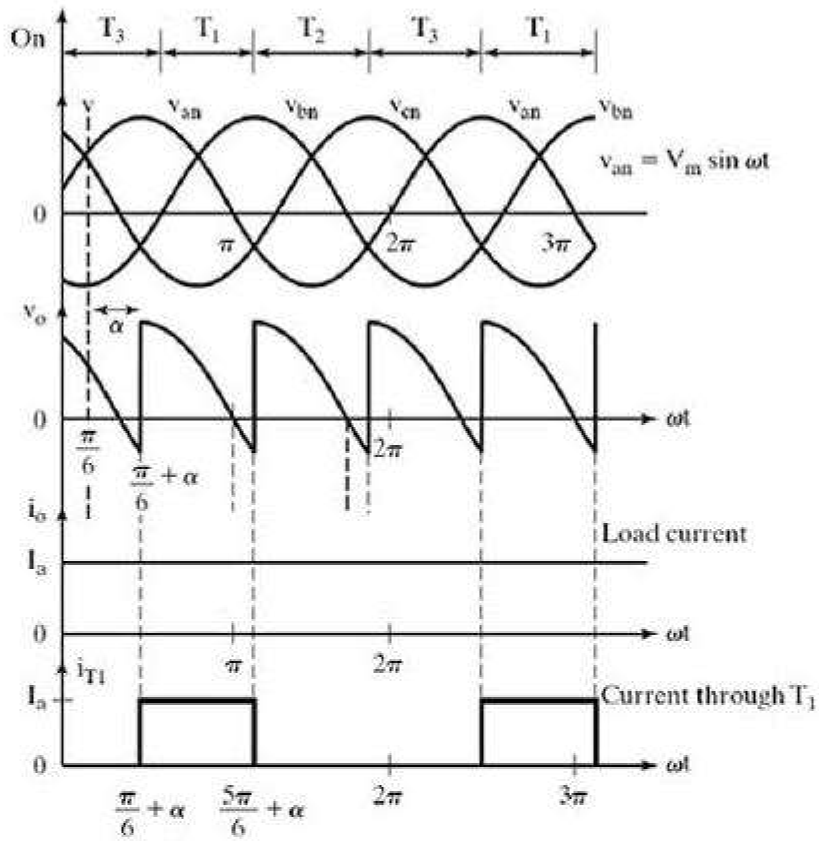

Figure: 2.14 input and output waveforms of three phase half wave rectifier

Three phase supply voltage equations

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

$V_{RN} = V_{an} = V_m$ sinwt where V_m is the maximum voltage

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

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

The **3-phase half wave converter** combines three **single phase half wave controlled rectifiers in one** single circuit feeding a common load. The thyristor T_1in series with one of the supply phase windings *'a-n'* acts as one half wave controlled rectifier The second thyristor T_2in series with the supply phase winding *'b-n'* acts as the second half wave controlled rectifier. The third thyristor T_3in series with the supply phase winding acts as the third half wave controlled rectifier. The 3-phase input supply is applied through the star connected supply transformer as shown in the figure. The common neutral point of the supply is connected to one end of the load while the other end of the load connected to the common cathode point.

When the thyristor $T_1$is triggered at $\omega t=(\prod/6 + \alpha)=(30° + \alpha)$, the phase voltage V_{an} appears across the load when T_1 conducts. The load current flows through the supply phase winding *'a-n'* and through thyristor T_1aslongasT_1conducts. When thyristor $T_2$is triggered at $\omega t=(5\prod/6\alpha)$, T_1becomes reverse biased and turns-off. The load current flows through the thyristor and through the supply phase winding *'b-n'*. When T_2conductsthephasevoltagev_{bn}appearsacrosstheloaduntilthethyristorT_3istriggered. When the thyristor $T_3$is triggered at $\omega t=(3\prod/2 + \alpha)=(270°+\alpha)$, T_2 is reversed biased and hence T_2 turns-off. The phase voltage V_{an} appears across the load when T_3conducts.When $T_1$is triggered again at the beginning of the next input cycle the thyristor T_3 turns off as it is reverse biased naturally as soon as $T_1$is triggered.

The figure shows the 3-phase input supply voltages, the output voltage which appears across the load, and the load current assuming a constant and ripple free load current for a highly inductive load and the current through the thyristorT_1.

For a purely resistive load where the load inductance ‘L = 0’ and the trigger angle $\alpha > (\prod/6)$, the load current appears as discontinuous load current and each thyristor is naturally commutated when the polarity of the corresponding phase supply voltage reverses.

The frequency of output ripple frequency for a **3-phase half wave converter** is f_s, where f_s is the input supply frequency. The **3-phase half wave converter** is not normally used in practical converter systems because of the disadvantage that the supply current waveforms contain dc components (i.e., the supply current waveforms have an average or dc value).

To derive an expression for the average output voltage of a 3-phase half wave converter for continuous load current

The reference phase voltage is $v_{RN}=v_{an}=V_m sin\omega t$. The trigger angle is measured from the cross over points of the 3-phase supply voltage waveforms. When the phase supply voltage V_{an} begins its positive half cycle at ω*t*=0, the first crossover point appears at ω*t*=(∏/6)*radians*30°.

The trigger angle α for the thyristor T_1 is measured from the cross over point at. The thyristor $T_1$is forward biased during the period ω*t*=30°to 150°, When the phase supply voltage v_{an} has higher amplitude than the other phase supply voltages. Hence T_1can be triggered between 30° to 150°. When the thyristor $T_1$is triggered at a trigger angle α, the average or dc output voltage for continuous load current is calculated using the equation

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

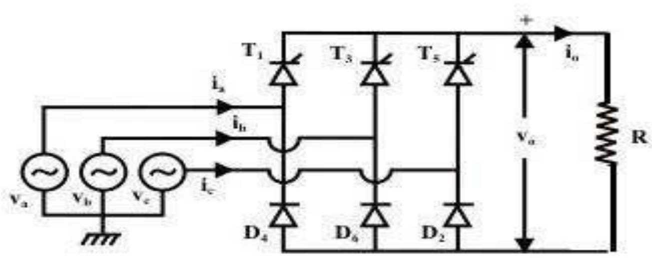

Figure: 2.15 circuit diagram three phase half controlled rectifier

Three single phase half wave converters can be connected to form a three phase half wave converter. Similarly three phase semi converter uses 3 SCRs T1, T3 & T5 and 3 diodes D2, D4&D6 In the circuit shown above when any device conducts, line voltage is applied across load. so line voltage are necessary to draw Phase shift between two line voltages is 60 degree & between two phase voltages it is 120 degree Each phase & line voltage is sine wave with the frequency of 50 Hz. R, Y, B are phase voltages with respect to 'N'.

In the case of a **three-phase half wave controlled** rectifier with resistive load, the thyristor $T_1$is triggered at ω*t=(30°+α)* and T_1 conducts up to ω*t=180°=&pron;* radians. When the phase supply voltage decreases to zero at, the load current falls to zero and the thyristor T_1 turns off. ThusT_1conductsfrom*ωt=(30°+α) to (180°).*

Three phase half wave controlled rectifier output voltage waveforms for different trigger angles with R load

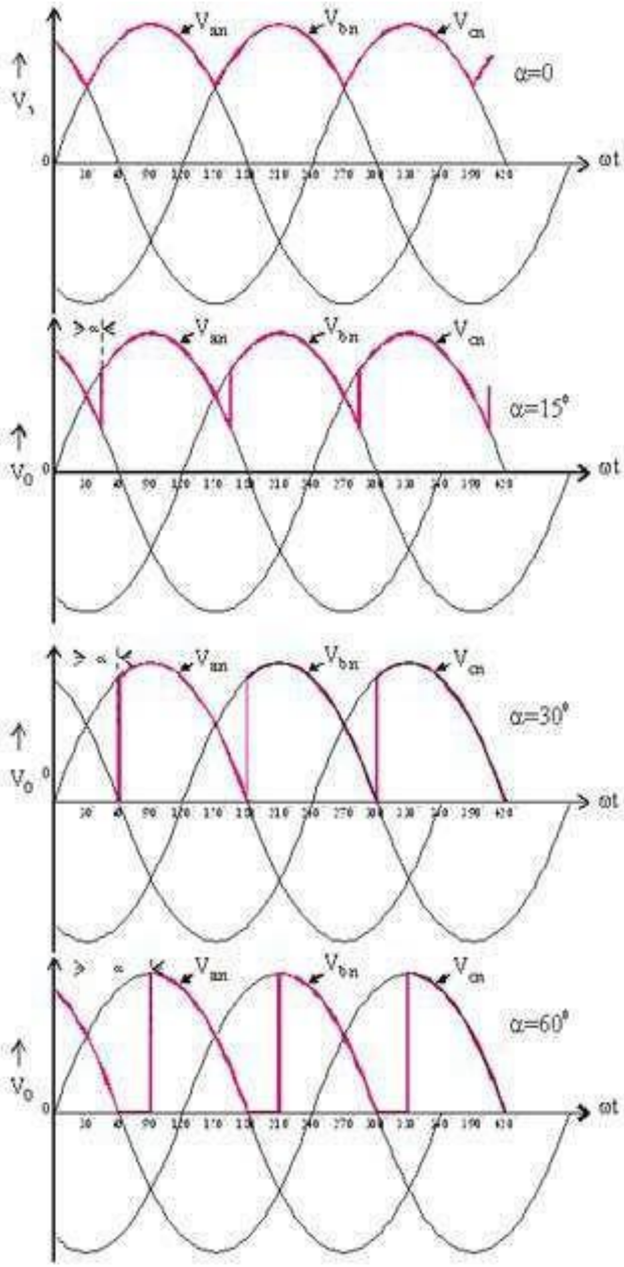

Figure: 2.16 input and output waveforms of three phase half controlled rectifier with R load

Hence the average dc output voltage for a 3-pulse converter (3-phase half wave controlled rectifier) is calculated by using the equation

$$\text{The average output voltage } V_{avg} = \frac{3}{2\pi}\int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}} \text{Vmlsinwt}\, d(wt) + \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}+\alpha} \text{Vmlsinwt}\, d(wt)$$

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

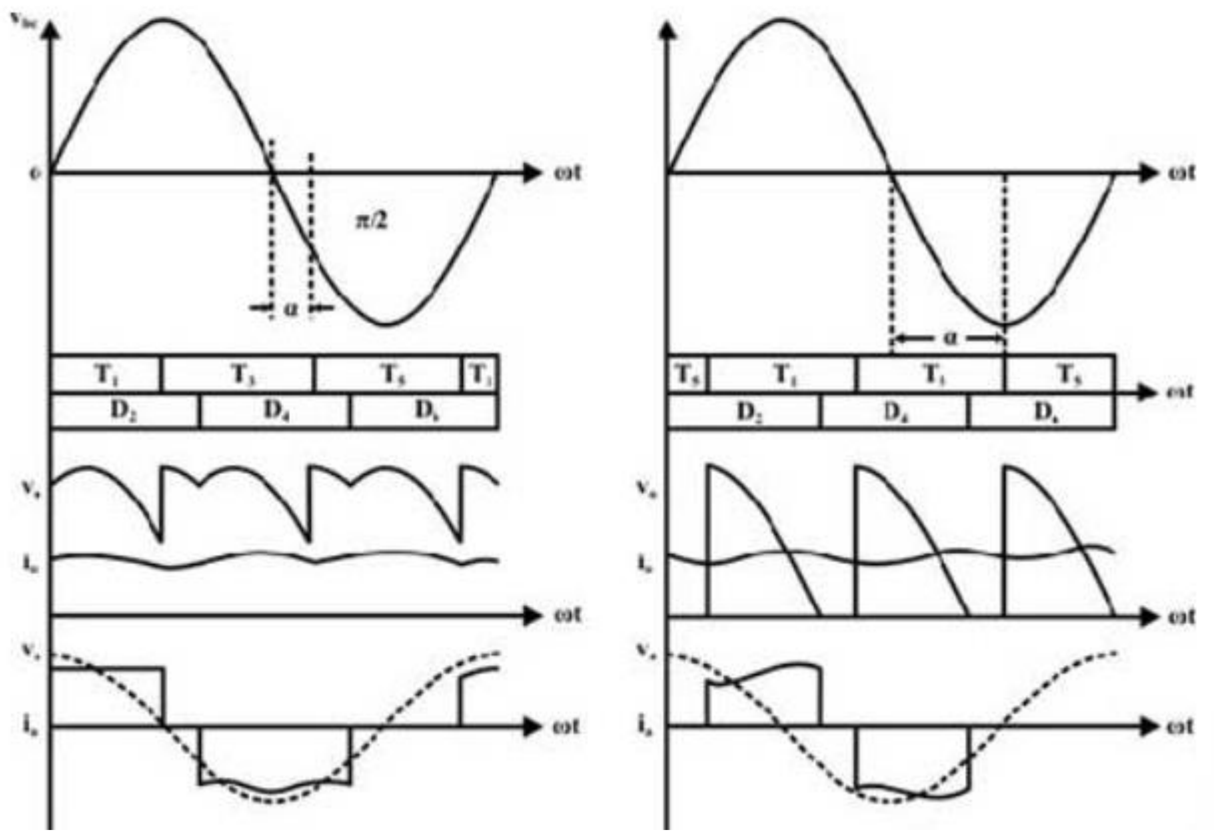

Figure: 2.17 Input and output waveforms of three phase half controlled rectifier with RL load

Numerical Problems on three phase rectifiers

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:

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

$$V_{or}^{\ 2} = \frac{3Vml^2}{4\pi}\left[\left|wt + \frac{sin2wt}{2}\right|_{-\left(\frac{\pi}{6}-\alpha\right)}^{-\frac{\pi}{6}} + \left|wt+\frac{sin2wt}{2}\right|_{-\left(\frac{\pi}{6}\right)}^{\frac{\pi}{6}+\alpha}\right]$$

$$V_{or} = \frac{Vml}{2}\sqrt{\frac{3}{\pi}}\left[\frac{2\pi}{3} + \frac{\sqrt{3}}{2}(1 + cos2\alpha\right]^{1/2}$$

For $\alpha = 30^0$

$$P = V^2/R$$

$$5000x10 = \frac{2Vs^2}{4}\frac{3}{\pi}\left[\frac{2\pi}{3} + \frac{\sqrt{3}}{2}(1 + cos60\right]$$

$V_s = 175.67V$ 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).

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

Three phase full converter is a fully controlled bridge controlled rectifier using six thyristors connected in the form of a full wave bridge configuration. All the six thyristors are controlled switches which are turned on at a appropriate times by applying suitable gate trigger signals.

The **three phase full converter** is extensively used in industrial power applications up to about 120kW output power level, where two quadrant operations is required. The figure shows a **three phase full converter** with highly inductive load. This circuit is also known as three phase full wave bridge or as a six pulse converter. The thyristors are triggered at an interval of (∏/3) radians (i.e. at an interval of 30°). The frequency of output ripple voltage is $6f_s$and the filtering requirement is less than that of **three phase semi and half wave converters**.

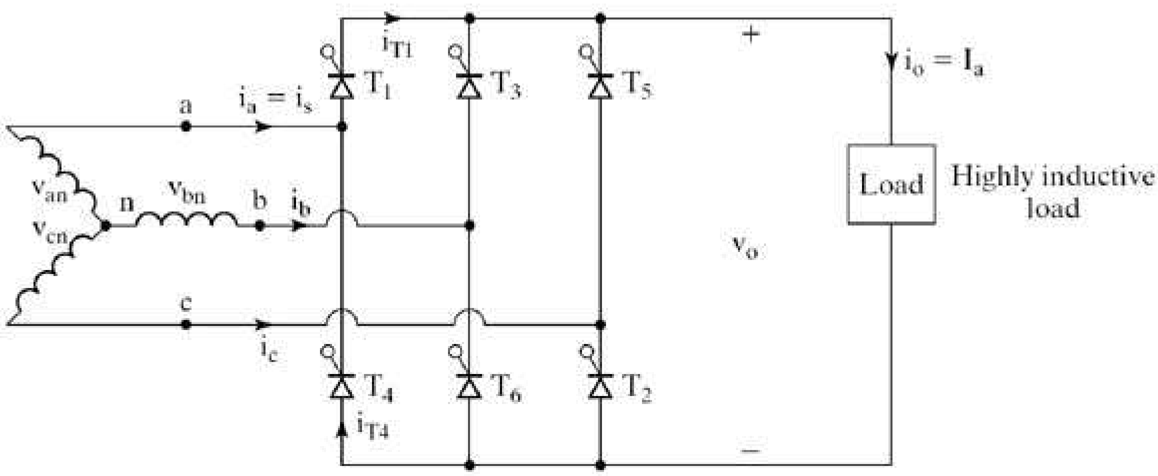

Figure: 2.18 circuit diagram three phase fully controlled rectifier with R and RL load

At ω*t=(∏/6 +α)* , thyristor is already conducting when the thyristor is turned on by applying the gating signal to the gate of . During the time period ω *t=(∏/6 +α)* to (∏/2 +α), thyristors and conduct together and the line to line supply voltage appears across the load.

At ω*t=(∏/2 +α)*, the thyristor $T_2$is triggered and T_6 is reverse biased immediately and T_6turns off due to natural commutation. During the time period ω *t=(∏/ +α) to (5∏/6+α)*,thyristors T_1 and T_2 conduct together and the line to line supply voltage appears across the load The thyristors are numbered in the circuit diagram corresponding to the order in which they are triggered. The trigger sequence (firing sequence) of the thyristors is 12, 23, 34, 45, 56, 61, 12, 23 and so on. The figure shows the waveforms of three phase input supply voltages, output voltage, the thyristor current through T_1 andT_4 the supply current through the line ‘a’.

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

$V_{RN} = V_{an} = V_m$ sinwt 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

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

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

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

To derive an expression for the average output voltage of **three phase full converter** with highly inductive load assuming continuous and constant load current.

The output load voltage consists of 6 voltage pulses over a period of 2∏ radians, hence the average output voltage is calculated as,

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

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

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

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

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

The RMS value of the output voltage is found from

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

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

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

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

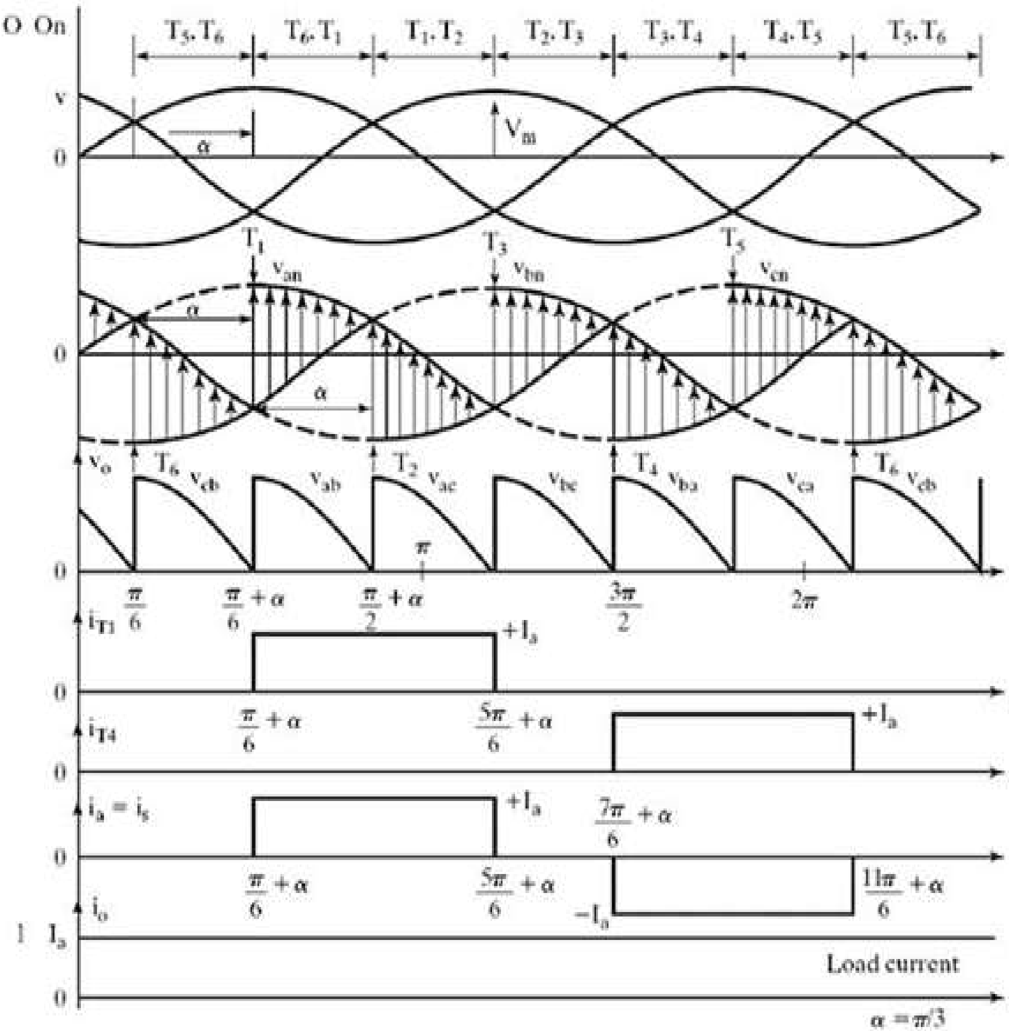

Figure: 2.19 Input and output waveforms of three phase fully controlled rectifier

Operation of three phase half wave rectifier with RLE loads

A three phase fully controlled converter is obtained by replacing all the six diodes of an uncontrolled converter by six thyristors as shown in Figure below.

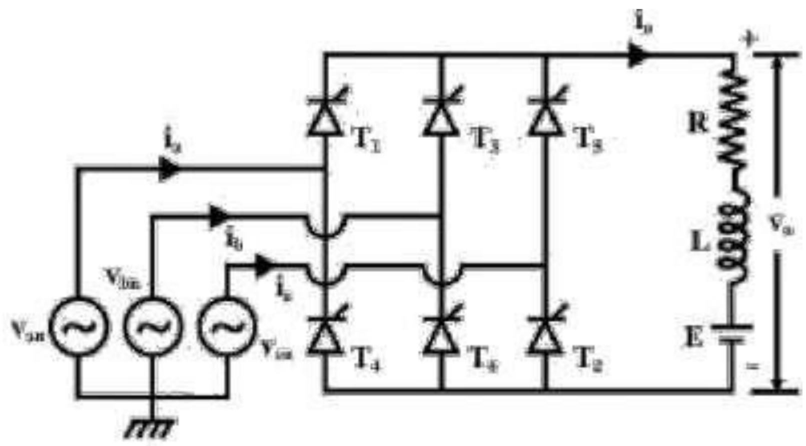

Figure: 2.20 circuit diagram of three phase fully controlled rectifier with RLE load

For any current to flow in the load at least one device from the top group (T1, T3, T5) and one from the bottom group (T2, T4, T6) must conduct. It can be argued as in the case of an uncontrolled converter only one device from these two groups will conduct.

Then from symmetry consideration it can be argued that each thyristor conducts for 120° of the input cycle. Now the thyristors are fired in the sequence T1 → T2 → T3 → T4 → T5 → T6 → T1 with 60° interval between each firing. Therefore thyristors on the same phase leg are fired at an interval of 180° and hence can not conduct simultaneously. This leaves only six possible conduction mode for the converter in the continuous conduction mode of operation. These are T1T2, T2T3, T3T4, T4T5, T5T6, T6T1. Each conduction mode is of 60° duration and appears in the sequence mentioned.

Each of these line voltages can be associated with the firing of a thyristor with the help of the conduction table-1. For example the thyristor T1 is fired at the end of T5 T6 conduction interval. During this period the voltage across T1 was vac. ThereforeT1 is fired t α angle after the positive going zero crossing of vac. similar observation can be made about other thyristors. Fig. 2.21 shows the waveforms of different variables. To arrive at the waveforms it is necessary to draw the conduction diagram which shows the interval of conduction for each thyristor and can be drawn with the help of the phasor diagram of fig.2.22. If the converter firing angle isα each thyristor is fired"α" angle after the positive going zero crossing of the line voltage with which it's firing is associated. Once the conduction diagram is drawn all other voltage waveforms can be drawn from the line voltage waveforms and from the conduction table of fig. 2.20. Similarly line currents can be drawn from the output current and the conduction diagram. It is clear from the waveforms that output voltage and current waveforms are periodic over one sixth of the input cycle. Therefore this converter is also called the "six pulse" converter. The input current on the other hand contains only odds harmonics of the input frequency other than the triplex (3rd, 9th etc.) harmonics. The next section will analyze the operation of this converter in more details.

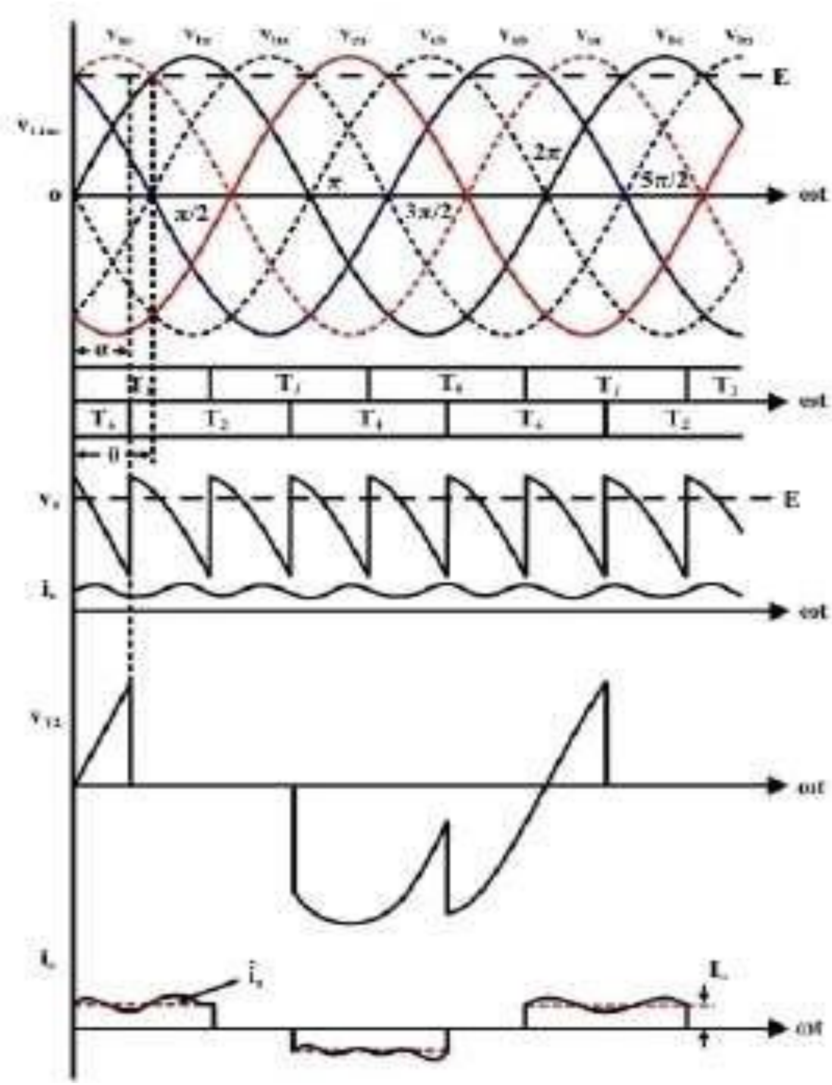

Figure: 2.21 Input and output waveforms of three phase fully controlled rectifier in rectifier mode

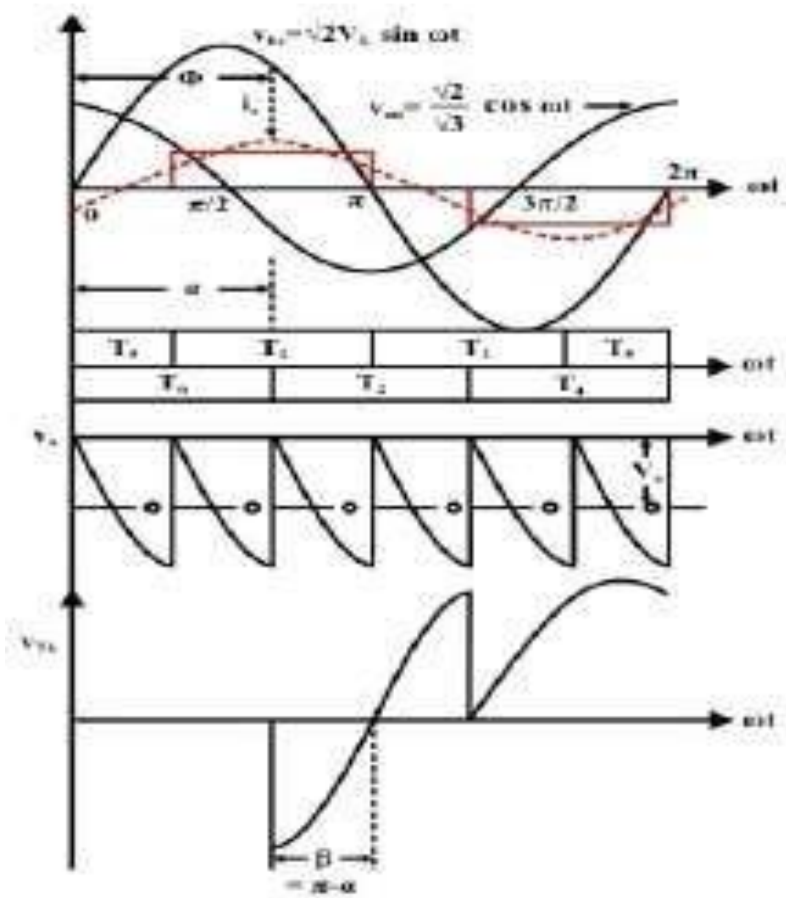

Figure: 2.22 Input and output waveforms of three phase fully controlled rectifier in inversion mode

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Question Bank

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	UNIT-II **Phase Controlled Rectifier**		
	Part A	**CO**	**L**
1.	Interpret the advantages of freewheeling diode on performance of controlled rectifiers?	CO2	L2
2.	Identify are the effects of overlap angle of controlled rectifier.	CO2	L3
4.	Distinguish circulating current mode & non circulating current mode	CO2	L2
5.	Criticize the significance of firing angle of a controlled rectifier?	CO2	L5
6.	Classify out the merits of semi converter over full converter	CO2	L2
7.	Distinguish the symmetrical and unsymmetrical semi converter	CO2	L4
8.	interpret the advantage of bridge type converter over midpoint type converter	CO2	L2
9.	Identify are the effects of extinction angle of controlled rectifier.	CO2	L4
10.	A single phase 220V full converter is triggered at a phase angle of 120 degree. When the load current is maintained at 8 A. Neglecting losses, Estimate the power fed back to the AC mains.	CO2	L5
	Part B	**CO**	**L**
1.	A single phase full converter bridge is connected to RLE load. The source voltage is 230V, 50Hz. The average load current of 10A is continuous over the working range. For R=0.4 ohm and L 2 mH, Estimate a. firing angle delay for E=120V b. firing angle delay for E= -120V	CO2	L5
2.	Examine the operation for semi converter with RL load and plot the voltage & current waveform for firing angle of 45^{o}. Also derive the average and RMS voltage.	CO2	L4
3.	Examine the operation full converter in rectification mode and inversion mode. Plot the voltage & current waveform for both cases.	CO2	L5
4.	Explain the operation of semi converter in symmetrical and unsymmetrical mode of operation with RL load. Plot the voltage & current waveform for firing angle of 60^{o}.	CO2	L5
5.	Examine the operation for Bridge type full converter with RL load and plot the voltage & current waveform for firing angle of	CO2	L4

	45^o. Also derive the average and RMS voltage.		
6.	Examine the operation for semi converter with RL load and plot the voltage & current waveform for firing angle of 60^o.	CO2	L4
7.	Examine the operation for full converter with RL load and plot the voltage & current waveform for firing angle of 90^o.	CO2	L4

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DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

UNIT – III
POWER ELECTRONICS – SEE1305

DC and AC Choppers

DC - DC Chopper: Principle of operation of Step down and step up choppers - Control Strategies - One, Two and Four quadrant operation - AC - AC Chopper - Single phase AC voltage controllers with R & RL load - Multistage sequence control. Single phase step up Cycloconverters – Single Phase Step down Cycloconverters.

UNIT III

DC and AC Choppers

Introduction to AC voltage controllers (AC Choppers)

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**.

In brief, **an AC Voltage Controller** is a type of thyristor power converter which is used to convert a fixed voltage, fixed frequency ac input supply to obtain a variable voltage ac output. The RMS value of the ac output voltage and the ac power flow to the load is controlled by varying (adjusting) the trigger angle ‘α’.

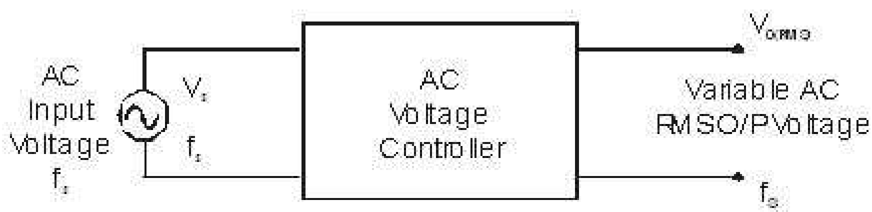


Figure: 3.1 Block diagram of AC voltage controller

Control strategies

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

- On-Off control
- Phase control

These are the two ac output voltage control techniques. In On-Off control technique, Thyristors are used as switches to connect the load circuit to the ac supply (source) for a few cycles of the input ac supply and then to disconnect it for few input cycles. The Thyristors thus act as a high speed contactor (or high speed ac switch).

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. By controlling the phase angle or the trigger angle 'α' (delay angle), the output RMS voltage across the load can be controlled. The trigger delay angle 'α' is defined as the phase angle (the value of ωt) at which the thyristor turns on and the load current begins to flow.

Thyristor **AC Voltage Controllers** use ac line commutation or ac phase commutation. Thyristors in **AC Voltage Controllers** are line commutated (phase commutated) since the input supply is ac. When the input ac voltage reverses and becomes negative during the negative half cycle the current flowing through the conducting thyristor decreases and falls to zero. Thus the ON thyristor naturally turns off, when the device current falls to zero.

Phase control Thyristors which are relatively inexpensive, converter grade Thyristors which are slower than fast switching inverter grade Thyristors are normally used. For applications up-to 400Hz, if TRIACS are available to meet the voltage and current ratings of a particular application, TRIACS are more commonly used.

Due to AC line commutation or natural commutation, there is no need of extra commutation circuitry or components and the circuits for **AC Voltage Controllers** are very simple. Due to the nature of the output waveforms, the analysis, derivations of expressions for performance parameters are not simple, especially for the phase controlled **AC Voltage Controllers** with RL load. But however most of the practical loads are of the RL type and hence RL-load should be considered in the analysis and design of **AC Voltage Controllers** circuits.

Type of ac voltage controllers

The ac voltage controllers are classified into two types based on the type of input ac supply applied to the circuit.

- Single Phase AC Voltage Controllers
- Three Phase AC Voltage Controllers

Single Phase AC Controllers operate with single phase ac supply voltage of 230V RMS at 50Hz in our country. **Three Phase AC Controllers** operate with 3 phase ac supply of 400V RMS at 50Hz supply frequency.

Performance parameters of AC voltage controllers

- RMS Output (Load) Voltage

$$V_{O(RMS)} = \left[\frac{n}{2\pi(n+m)} \int_0^{2\pi} V_m^2 \sin^2 \omega t . d(\omega t) \right]^{1/2}$$

$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}} \sqrt{\frac{n}{(m+n)}} = V_{i(RMS)} \sqrt{k} = V_S \sqrt{k}$$

$$V_{O(RMS)} = V_{i(RMS)} \sqrt{k} = V_S \sqrt{k}$$

Where $V_S = V_{i(RMS)}$ = RMS value of input supply voltage.

- Duty Cycle

$$k = \frac{t_{ON}}{T_O} = \frac{t_{ON}}{(t_{ON} + t_{OFF})} = \frac{nT}{(m+n)T}$$

Where, $k = \frac{n}{(m+n)}$ = duty cycle (d).

- RMS Load Current

$$I_{O(RMS)} = \frac{V_{O(RMS)}}{Z} = \frac{V_{O(RMS)}}{R_L}; \quad \text{for a resistive load } Z = R_L.$$

- Output AC (Load) Power

$$P_O = I^2_{O(RMS)} \times R_L$$

- Input Power Factor

$$PF = \frac{P_O}{VA} = \frac{\text{output load power}}{\text{input supply volt amperes}} = \frac{P_O}{V_S I_S}$$

$$PF = \frac{I^2_{O(RMS)} \times R_L}{V_{i(RMS)} \times I_{in(RMS)}}; \qquad I_S = I_{in(RMS)} = \text{RMS input supply current.}$$

The input supply current is same as the load current $I_{in} = I_O = I_L$

Hence, RMS supply current = RMS load current; $I_{in(RMS)} = I_{O(RMS)}$.

$$PF = \frac{I^2_{O(RMS)} \times R_L}{V_{i(RMS)} \times I_{in(RMS)}} = \frac{V_{O(RMS)}}{V_{i(RMS)}} = \frac{V_{i(RMS)}\sqrt{k}}{V_{i(RMS)}} = \sqrt{k}$$

$$PF = \sqrt{k} = \sqrt{\frac{n}{m+n}}$$

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

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.

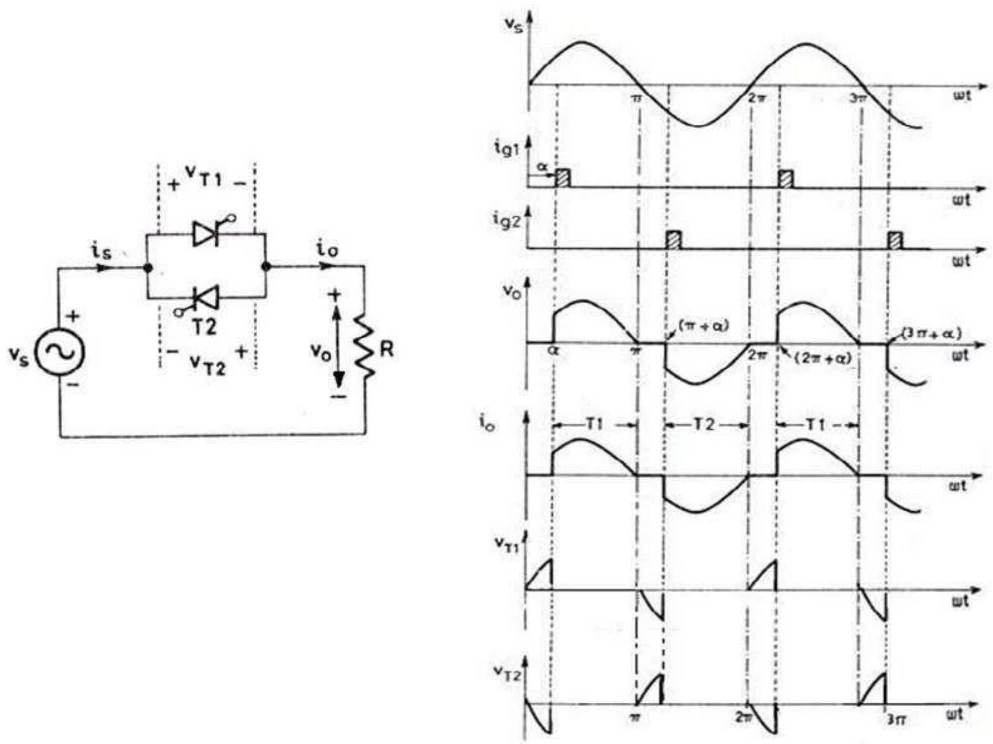


Figure: 3.2 Circuit diagram and output waveforms of AC voltage controller with R load

Fig. 3.2 illustrates the operation of the AC voltage controller with a resistive load. The devices is triggered at a phase-angle 'α' in each cycle. The current follows the voltage wave shape in each half and extinguishes itself at the zero crossings of the supply voltage. In the two-SCR topology, one SCR is positively biased in each half of the supply voltage. There is no scope for conduction overlap of the devices. A single pulse is sufficient to trigger the controlled devices with a resistive load. In the diode-SCR topology, two diodes are forward biased in each half. The SCR always receives a DC voltage and does not distinguish the polarity of the supply. It is thus always forward biased. The bi-directional TRIAC is also forward biased for both polarities of the supply voltage.

The RMS voltage V_{rms} decides the power supplied to the load. It can be computed as,

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

Power Factor

The power factor of a nonlinear deserves a special discussion. Fig. 2.35 shows the supply voltage and the non-sinusoidal load current. The fundamental load/supply current lags the supply voltage by the φ1, 'Fundamental Power Factor' angle. Cosφ1 is also called the 'Displacement Factor'. However this does not account for the total reactive power drawn by the system. This power factor is in spite of the actual load being resistive! The reactive power is drawn also y the trigger-angle dependent harmonics. Now

$$power \quad factor = \frac{average \quad power}{apparent \quad voltamperes} = \frac{P}{VI_L}$$
$$= \frac{VI_{L1} \cos \phi_1}{VI_L}$$
$$distortion \quad factor = \frac{I_{L1}}{I_L}$$

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

With inductive loads the operation of the PAC is illustrated in Fig 2. 36. 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. The devices would fail to conduct when they are intended to, as they do not have the supply voltage forward biasing them when the trigger pulse arrives. A single pulse trigger will work till the trigger angle $\alpha > \varphi$, where φ is the power factor angle of the inductive load. A train of pulses is required here. The output voltage is controllable only between triggering angles φ and 180°. The load current waveform is further explained in Fig. 26.6. The current is composed of two components. The first is the steady state component of the load current, i_{ss} and the second, i_{tr} is the transient component.

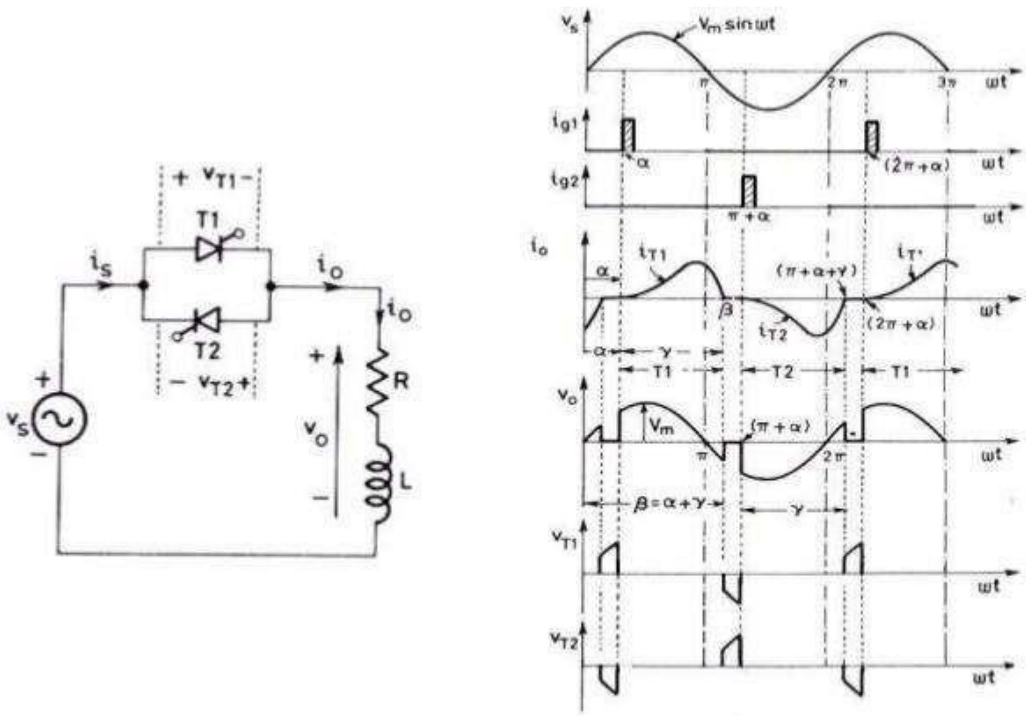


Figure: 3.3 Circuit diagram and output waveforms of AC voltage controller with RL load

With an inductance in the load the distinguishing feature of the load current is that it must always start from zero. However, if the switch could have permanently kept the load connected to the supply the current would have become a sinusoidal one phase shifted from the voltage by the phase angle of the load, φ. This current restricted to the half periods of conduction is called the 'steady-state component' of load current i_{ss}. The 'transient component' of load current i_{tr}, again in each half cycle, must add up to zero with this i_{ss} to start from zero. This condition sets the initial value of the transient component to that of the steady state at the instant that the SCR/TRIAC is triggered. When a device is in conduction, the load current is governed by the equation

$$L\, {di}/{dt} + Ri = v_s$$

$$i_{load} = \frac{\sqrt{2}V}{Z}\left[\ \sin(\omega t - \phi) + \sin(\alpha - \phi)\, e^{-\frac{R}{L}\left(\alpha/\omega - t\right)}\ \right]$$

Since at t = 0, $i_{load} = 0$ and supply voltage $v_s = \sqrt{2}V\sin\omega t$ the solution is of the form the instant when the load current extinguishes is called the extinction angle β. It can be inferred that there would be no transients in the load current if the devices are triggered at the power factor angle of the load. The load current I that case is perfectly sinusoidal.

Cycloconverters

The **Cycloconverter** has been traditionally used only in very high power drives, usually above one megawatt, where no other type of drive can be used. Examples are cement tube mill drives above 5 MW, the 13 MW German-Dutch wind tunnel fan drive, reversible rolling mill drives and ship propulsion drives. The reasons for this are that the traditional **Cycloconverter** requires a large number of thyristors, at least 36 and usually more for good motor performance, together with a very complex control circuit, and it has some performance limitations, the worst of which is an output frequency limited to about one third the input frequency.

Figure 3.4 Block diagram of Cycloconverters

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 3.4. It is important to keep the non-conducting thyristor bank off at all times, otherwise the mains could be shorted via the two thyristor banks, resulting in waveform distortion and possible device failure from the shorting current. A major control problem of the **Cycloconverter** is how to swap between banks in the shortest possible time to avoid distortion whilst ensuring the two banks do not conduct at the same time. A common addition to the power circuit that removes the requirement to keep one bank off is to place a centre tapped inductor called a circulating current inductor between the outputs of the two banks. Both banks can now conduct together without shorting the mains. Also, the circulating current in the inductor keeps both banks operating all the time, resulting in improved output waveforms. This technique is not often used, though, because the circulating current inductor tends to be expensive and bulky and the circulating current reduces the power factor on the input.

In a **1-φ Cycloconverter,** the output frequency is less than the supply frequency. These converters require natural commutation which is provided by AC supply. During positive half cycle of supply, Thyristors P1 and N2 are forward biased. First triggering pulse is applied to P1 and hence it starts conducting.

As the supply goes negative, P1 gets off and in negative half cycle of supply, P2 and N1 are forward biased. P2 is triggered and hence it conducts. In the next cycle of supply, N2 in positive half cycle andN1 in negative half cycle are triggered. Thus, we can observe that here the output frequency is 1/2 times the supply frequency.

Operation Principles

The following sections will describe the operation principles of the **Cycloconverter** starting from the simplest one, **single-phase to single-phase (**1Φ -1Φ) **Cycloconverter.**

Single-phase to Single-phase (1Φ -1Φ) Cycloconverter

To understand the operation principles of **Cycloconverters**, the single-phase to single- phase **Cycloconverter** (Fig. 3.5) should be studied first. This converter consists of back-to-back connection of two full-wave rectifier circuits. Fig 3.5 shows the operating waveforms for this converter with a resistive load.

Zero Firing angle, i.e. thyristors act like diodes. Note that the firing angles are named as αP for the positive converter and αN for the negative converter. The input voltage, Vs is an ac voltage frequency, fi as shown in Fig. 3.5. For easy understanding assume that all the thyristors are fired at α=0°

Consider the operation of the **Cycloconverter** to get one-fourth of the input frequency at the output. For the first two cycles of Vs, the positive converter operates supplying current to the load. It rectifies the input voltage; therefore, the load sees 4 positive half cycles as seen in Fig.3.5. In the next two cycles, the negative converter operates supplying current to the load in the reverse direction. The current waveforms are not shown in the figures because the resistive load current will have the same waveform as the voltage but only scaled by the resistance. Note that when one of the converters operates the other one is disabled, so that there is no current circulating between the two rectifiers.

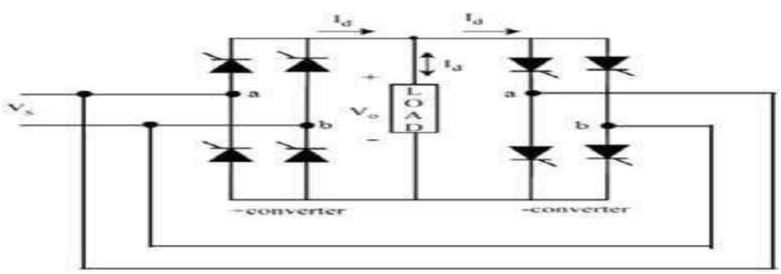


Figure 3.5 circuit diagram of Cycloconverter

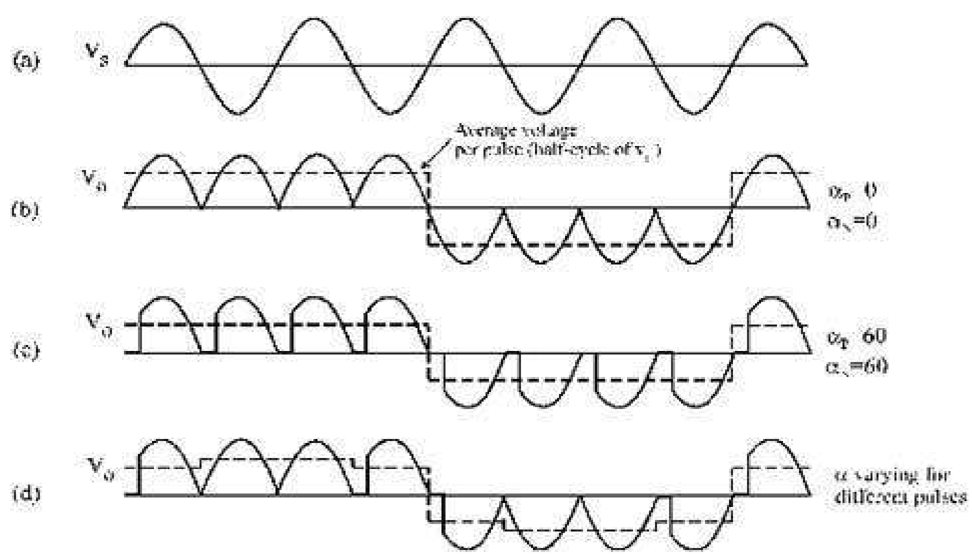


Figure 3.5 Input and output waveforms of cycloconverter

<u>Single phase midpoint Cycloconverters</u>

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, $f_o > f_i$.

In case of step-down cyclo-converter, the output frequency is limited to a fraction of input frequency, typically it is below 20Hz in case 50Hz supply frequency. In this case, no separate commutation circuits are needed as SCRs are line commutated devices. But in case of step-up cyclo-converter, forced commutation circuits are needed to turn OFF SCRs at desired frequency. Such circuits are relatively very complex. Therefore, majority of cyclo - converters are of step-down type that lowers the frequency than input frequency.

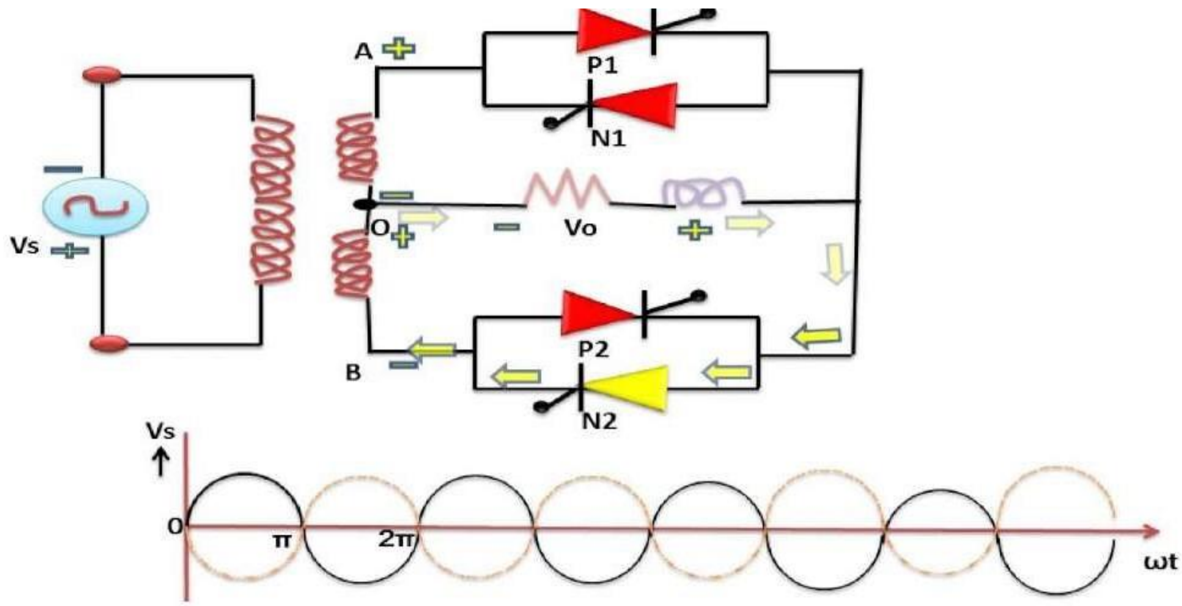


Figure 3.6 circuit diagram of midpoint cycloconverter

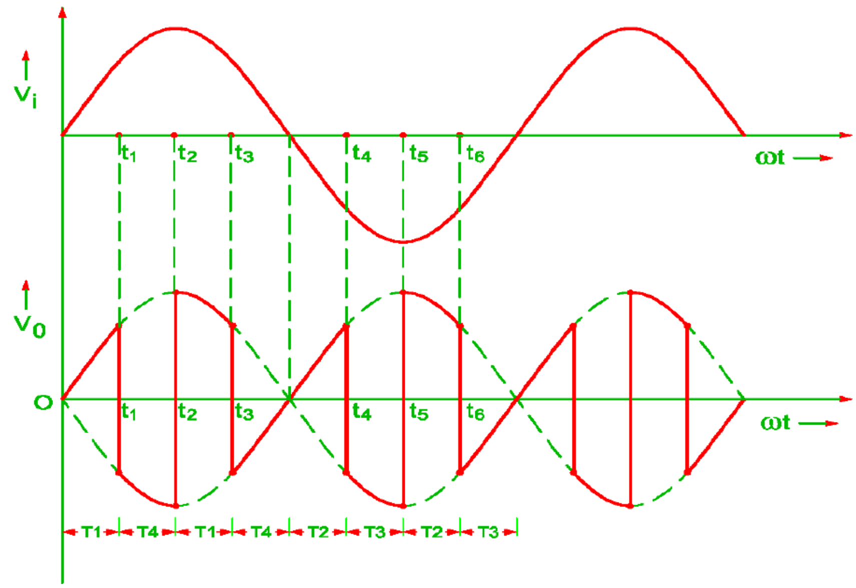


Figure 3.7 Input and output waveforms of midpoint cycloconverter

It consists of single phase transformer with mid tap on the secondary winding and four thyristors. Two of these thyristors P1, P2 are for positive group and the other two N1, N2 are for the negative group. Load is connected between secondary winding midpoint 0 and the load terminal. Positive directions for output voltage and output current are marked in figure 3.6

In figure 3.6 during the positive half cycle of supply voltage terminal a is positive with respect to terminal b. therefore in this positive half cycle, both p1 and N2 are forward biased from wt= 0 to Π. As such SCR P1 is turned on at wt = 0 so that load voltage is positive with terminal A and 0 negative. Now the load voltage is positive. At instant t1 P1 is force commutated and forward biased thyristor N2 is turned on so that load voltage is negative with terminal 0 and A negative. Now the load voltage is negative. Now N2 is force commutated and P1 is turned on the load voltage is positive this is a continuous process and will get step up cycloconverter output

Bridge configuration of single phase Cycloconverter

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.

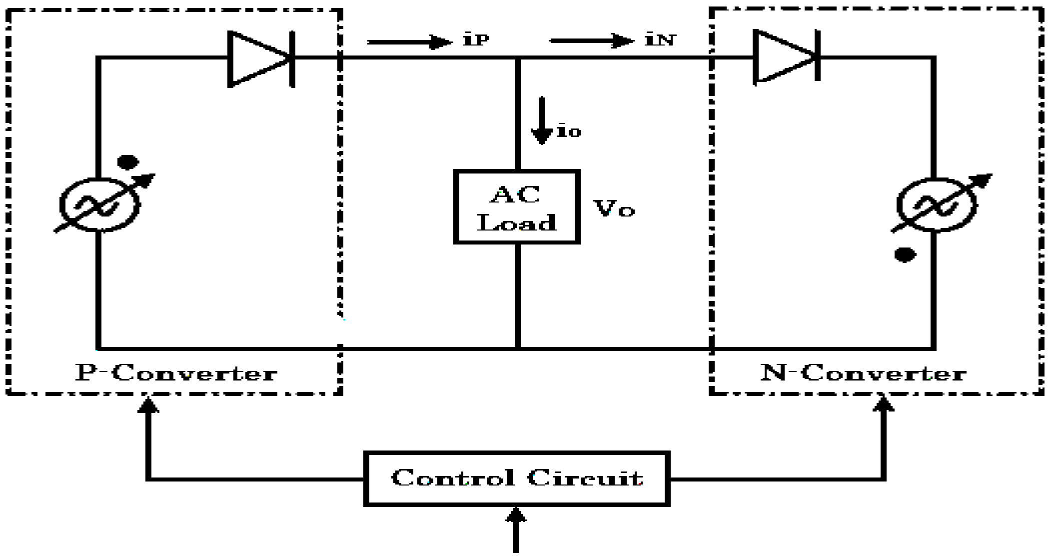


Figure 3.8 Block diagram of bridge type Cycloconverter

If the firing angles of individual converters are modulated continuously, each converter produces same sinusoidal voltages at its output terminals. So the voltages produced by these two converters have same phase, voltage and frequency. The average power produced by the cyclo-converter can flow either to or from the output terminals as the load current can flow freely to and from the load through the positive and negative converters. Therefore, it is possible to operate the loads of any phase angle (or power factor), inductive or capacitive through the cyclo-converter circuit.

Due to the unidirectional property of load current for each converter, it is obvious that positive converter carries positive half-cycle of load current with negative converter remaining in idle during this period. Similarly, negative converter carries negative half cycle of the load current with positive converter remaining in idle during this period, regardless of the phase of current with respect to voltage. This means that each converter operates both in rectifying and inverting regions during the period of its associated half cycles. The figure below shows ideal output current and voltage waveforms of a cyclo-converter for lagging and leading power factor loads. The conduction periods of positive and negative converters are also illustrated in the figure.

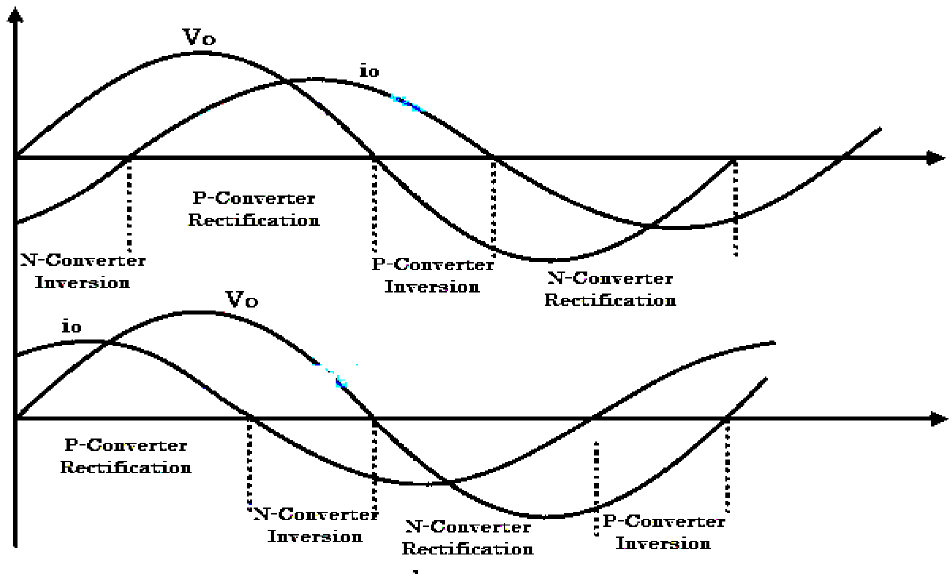


Figure 3.9 Cycloconverter waveforms

The positive converter operates whenever the load current is positive with negative converter remaining in idle. In the same manner negative converter operates for negative half cycle of load current. Both rectification and inversion modes of each converter are shown in figure. This desired output voltage is produced by regulating the firing angle to individual converters.

Single-phase to single-phase cyclo-converters

These are rarely used in practice; however, these are required to understand fundamental principle of cyclo-converters. It consists of two full-wave, fully controlled bridge thyristors, where each bridge has 4 thyristors, and each bridge is connected in opposite direction (back to back) such that both positive and negative voltages can be obtained as shown in figure below. Both these bridges are excited by single phase, 50 Hz AC supply.

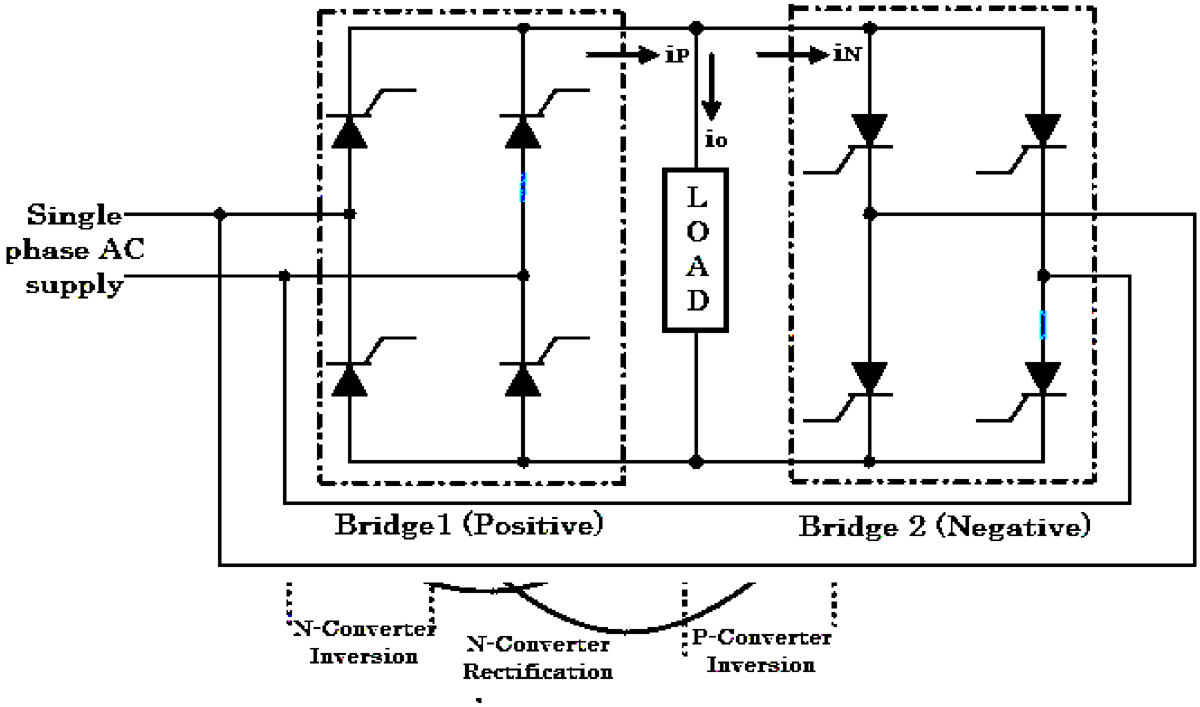


Figure 3.10 Circuit diagram of bridge type cycloconverter

During positive half cycle of the input voltage, positive converter (bridge-1) is turned ON and it supplies the load current. During negative half cycle of the input, negative bridge is turned ON and it supplies load current. Both converters should not conduct together that cause short circuit at the input.

To avoid this, triggering to thyristors of bridge-2 is inhibited during positive half cycle of load current, while triggering is applied to the thyristors of bridge-1 at their gates. During negative half cycle of load current, triggering to positive bridge is inhibited while applying triggering to negative bridge. By controlling the switching period of thyristors, time periods of both positive and negative half cycles are changed and hence the frequency. This frequency of fundamental output voltage can be easily reduced in steps, i.e., 1/2, 1/3, 1/4 and soon.

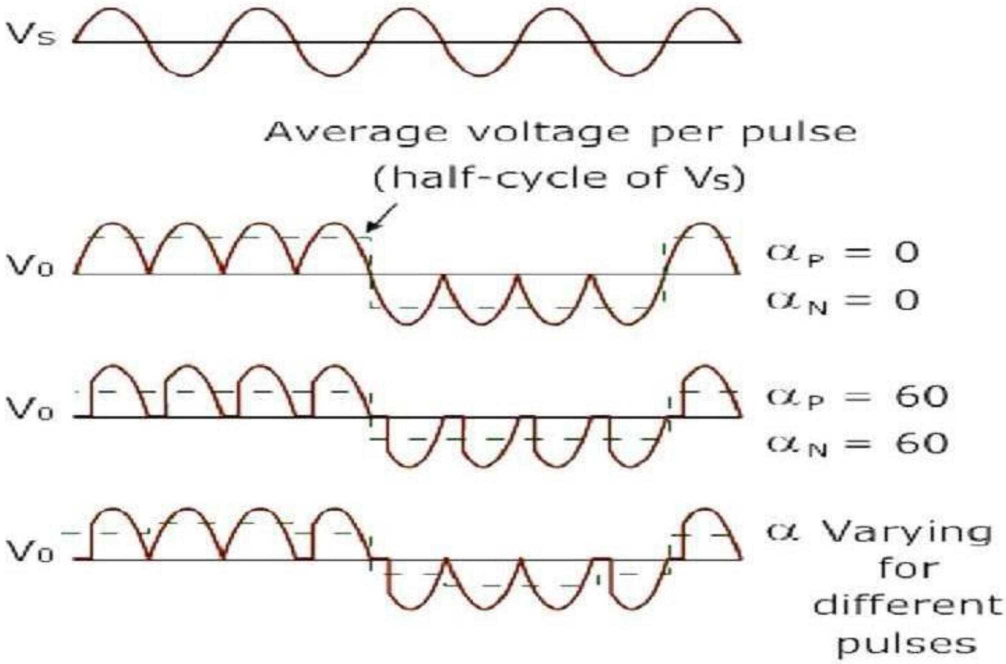


Figure 3.10 Input and output waveforms of bridge type Cycloconverter

The above figure shows output waveforms of a cyclo-converter that produces one-fourth of the input frequency. Here, for the first two cycles, the positive converter operates and supplies current to the load. It rectifies the input voltage and produce unidirectional output voltage as we can observe four positive half cycles in the figure. And during next two cycles, the negative converter operates and supplies load current. Here current waveforms are not shown because it is a resistive load in where current (with less magnitude) exactly follows the voltage.

Here one converter is disabled if another one operates, so there is no circulating current between two converters. Since the discontinuous mode of control scheme is complicated, most cyclo-converters are operates on circulating current mode where continuous current is allowed to flow between the converters with a reactor. This circulating current type cyclo-converter can be operated on with both purely resistive (R) and inductive (R-L) loads.

DC Chopper

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.

Symbol of a Chopper

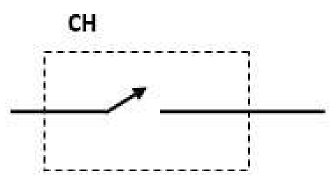


Figure: 3.11 symbol of chopper

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

In this post we shall look upon both the ways of varying the duty cycle. Duty Cycle is the ratio of 'On Time' to 'Time Period of a pulse'. Time Ratio Control: As the name suggest, here the time ratio (i.e. the duty cycle ratio Ton/T) is varied. This kind of control can be achieved using 2 ways:

- Pulse Width Modulation (PWM)
- Frequency Modulation Control (FMC)

Pulse Width Modulation (PWM)

In this technique, the time period is kept constant, but the 'On Time' or the 'OFF Time' is varied. Using this, the duty cycle ratio can be varied. Since the ON time or the 'pulse width' is getting changed in this method, so it is popularly known as Pulse width modulation.

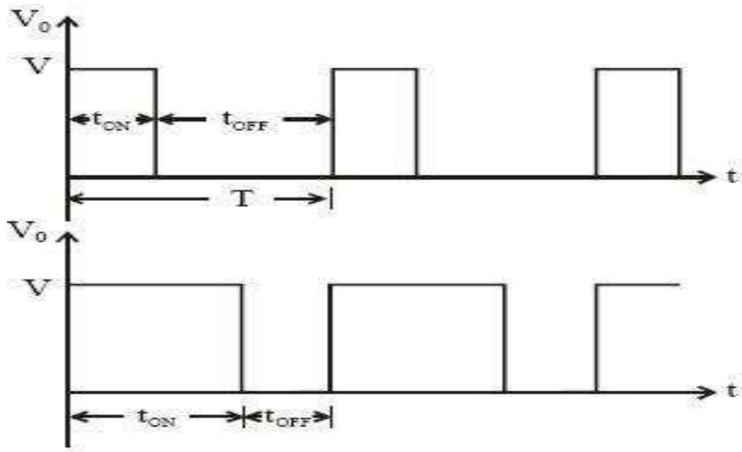


Figure: 3.12 pulse width modulation waveforms

Frequency Modulation Control (FMC)

In this control method, the 'Time Period' is varied while keeping either of 'On Time' or 'OFF time' as constant. In this method, since the time period gets changed, so the frequency also changes accordingly, so this method is known as frequency modulation control.

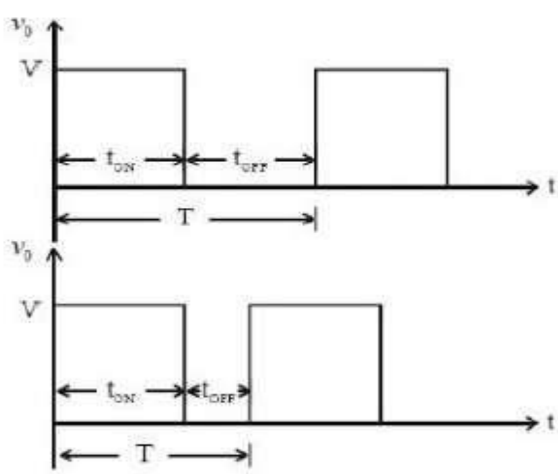


Figure: 3.13 Frequency modulation waveforms

Current Limit Control

As is obvious from its name, in this control strategy, a specific limit is applied on the current variation. In this method, current is allowed to fluctuate or change only between 2 values i.e. maximum current (I max) and minimum current (I min). When the current is at minimum value, the chopper is switched ON. After this instance, the current starts increasing, and when it reaches up to maximum value, the chopper is switched off allowing the current to fall back to minimum value. This cycle continues again and again.

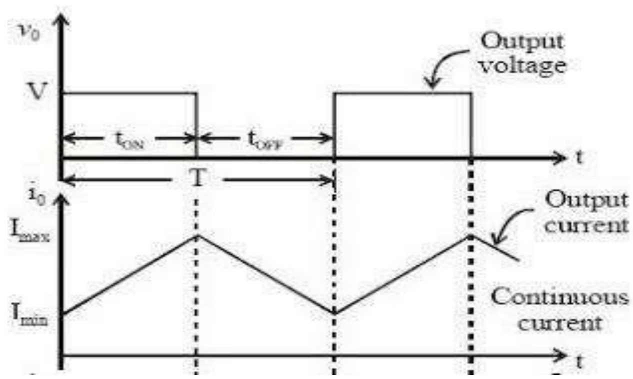


Figure: 3.14 current limit control waveforms

Classification of DC 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, the converters can be classified into five classes namely :

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]

Step Down Chopper (Buck Converter)

This is also known as a buck converter. In this chopper, the average voltage output V_O is less than the input voltage V_S. When the chopper is ON, $V_O = V_S$ and when the chopper is off, $V_O = 0$

When the chopper is ON :

$$VS=(VL+V0),\ VL=VS-V0,$$

$$Ldi/dt=VS-V0,$$

$$L\Delta i/TON=Vs+V0$$

$$VS=(VL+V0),$$

$$VL=VS-V0,$$

$$Ldi/dt=VS-V0,$$

$$L\Delta i/TON=Vs+V0$$

Thus, peak-to-peak current load is given by,

$$\Delta i=\frac{Vs-V0}{L}TON$$

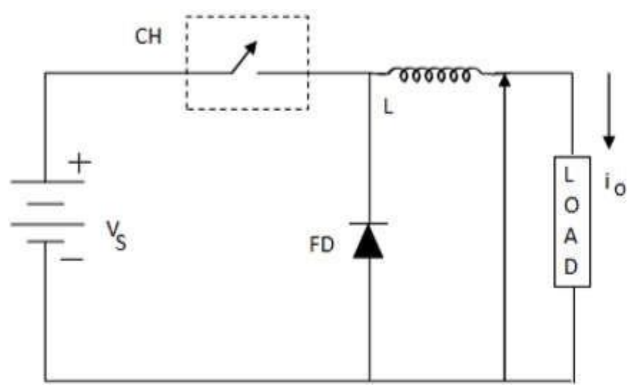
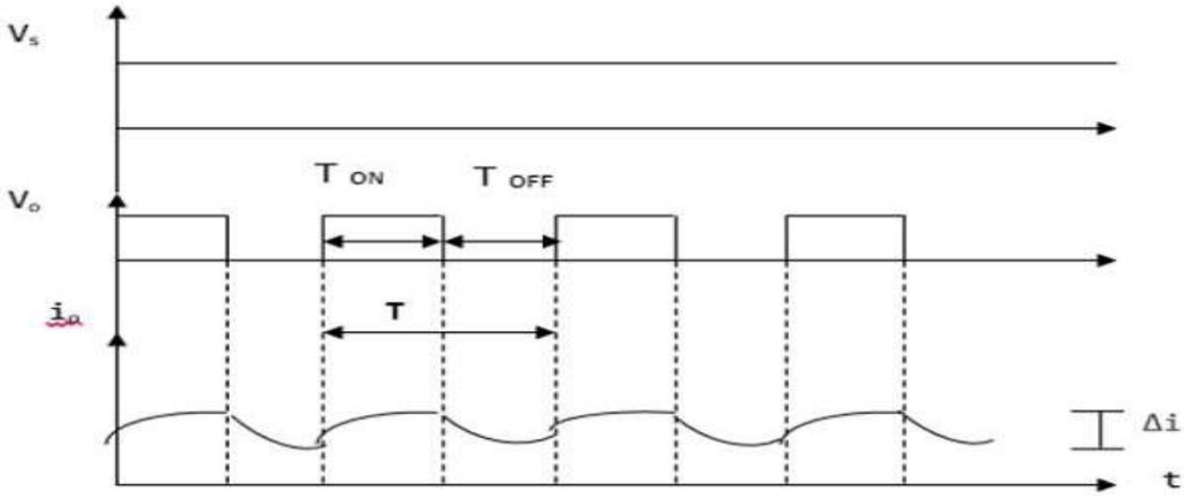


Figure: 3.15 Step down chopper



$$\frac{\quad}{L}T_{ON}=\frac{\quad}{L}T_{OFF}$$

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

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

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

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

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

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

When the chopper is OFF, polarity reversal and discharging occurs at the inductor. The current passes through the free-wheel diode and the inductor to the load. This gives,

$$L\,di/dt=V0$$

Rewritten as $L\Delta i/TOFF=V0$ $L\Delta i/TOFF=V0$ $\Delta i=V0TOFF/L$

From the above equations

The current and voltage waveforms are given below :

For a step down chopper the voltage output is always less than the voltage input. This is shown by the waveform below.

Step Up Chopper

The average voltage output (V_o) in a step up chopper is greater than the voltage input (V_s). The figure below shows a configuration of a step up chopper.

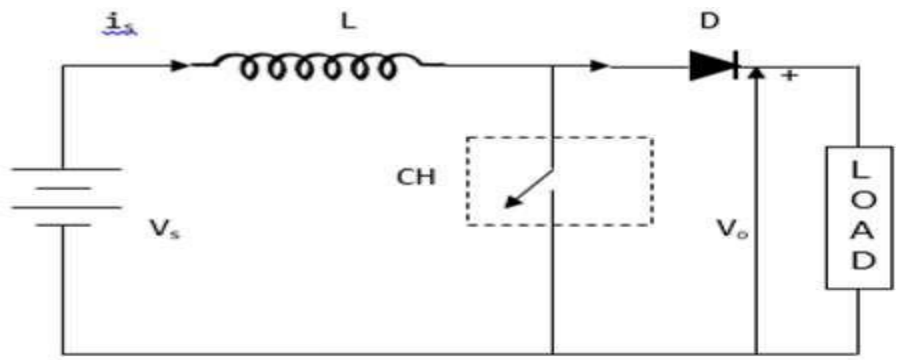


Figure: 3.17 circuit diagram of step up chopper

V_0 (average voltage output) is positive when chopper is switched ON and negative when the chopper is OFF as shown in the waveform below.

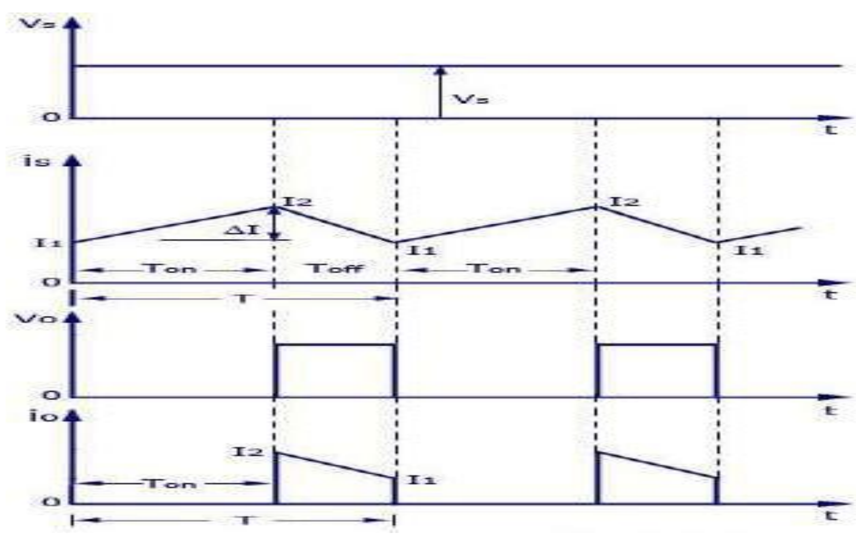


Figure: 3.18 Input and output waveforms of step up chopper

Where,

T_{ON} – time interval when chopper is ON

T_{OFF} – time interval when chopper is OFF

V_L – Load voltage

V_s – Source voltage

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

V_0 is given by −

$$V0 = \frac{1}{T}\int_0^{Ton} Vsdt$$

When the chopper (CH) is switched ON, the load is short circuited and, therefore, the voltage output for the period $\mathbf{T_{ON}}$ is zero. In addition, the inductor is charged during this time. This gives $V_S = V_L$

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

Δi = is the inductor peak to peak current. When the chopper (CH) is OFF, discharge occurs through the inductor L. Therefore, the summation of the V_s and V_L is given as follows −

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

This is also known as a buck-boost converter. It makes it possible to increase or reduce the voltage input level. The diagram below shows a buck-boost chopper

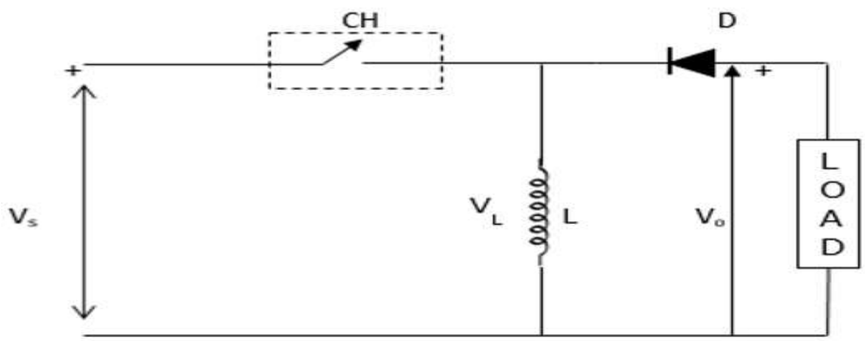


Figure: 3.19 circuit diagram of step up chopper

When the chopper is switched ON, the inductor L becomes charged by the source voltage V_s. Therefore, $V_s = V_L$.

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

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

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

When the chopper is switched OFF, the inductor's polarity reverses and this causes it to discharge through the diode and the load.

$$V0 = -VL$$

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

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

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

By comparing the above equations,

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

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

Principle of operation of class A chopper

Class A Chopper is a first quadrant 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.
- 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 step-down chopper in which power always flows form source to load.
- It is used to control the speed of dc motor.
- The output current equations obtained in step down chopper with R-L load can be used to study the performance of Class A Chopper.

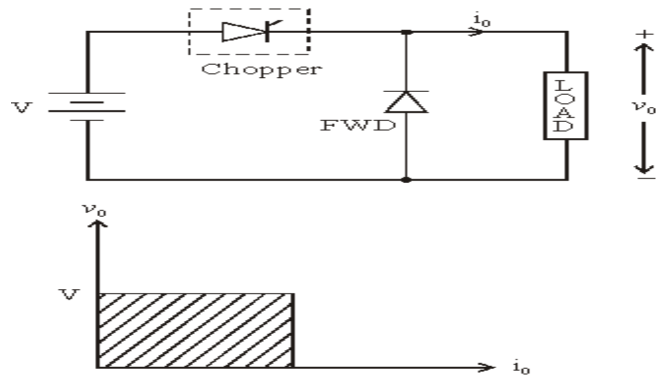


Figure: 3.20 circuit diagram and quadrant operation of Type A chopper

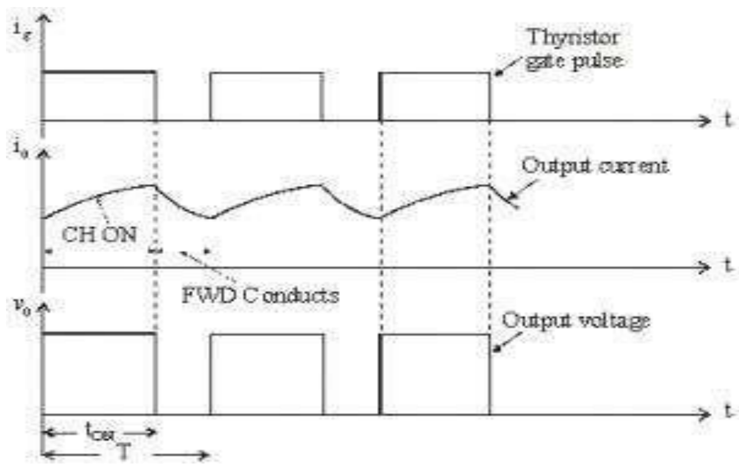


Figure: 3.21 Output voltage and current waveforms of type A chopper

Class B Chopper

- Class B Chopper is a step-up 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.

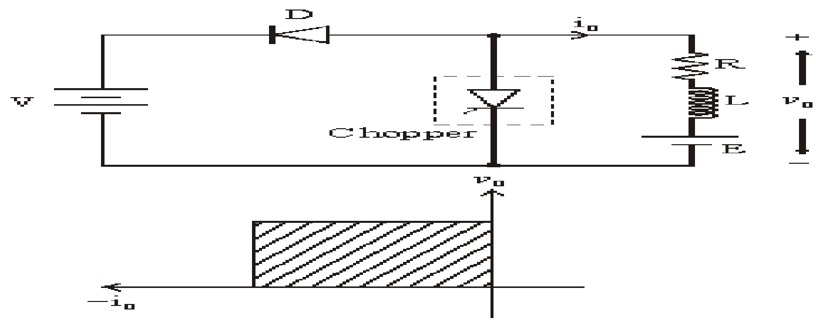


Figure: 3.22 circuit diagram and quadrant operation of Type B chopper

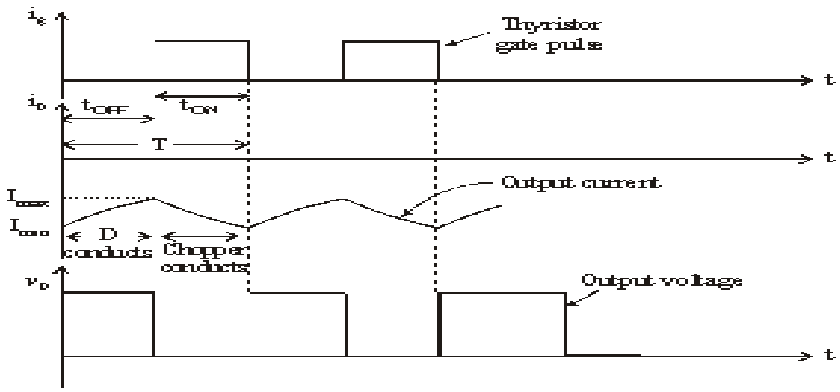


Figure: 3.23 Output voltage and current waveforms of type B

Class C chopper

- Class C Chopper can be used as a step-up or step-down chopper
- Class C Chopper is a combination of Class A and Class B Choppers.
- For first quadrant operation, CH1 is ON or D2conducts.
- For second quadrant operation, CH2 is ON or D1conducts.
- When CH1 is ON, the load current is positive.
- The output voltage is equal to ‘V’ & the load receives power from the source.
- When CH1 is turned OFF, energy stored in inductance L forces current to flow through the diode D2 and the output voltage is zero.
- Current continues to flow in positive direction.
- When CH2 is triggered, the voltage E forces current to flow in opposite direction through L and CH2.
- The output voltage is zero.
- On turning OFF CH2 , the energy stored in the inductance drives current through diode D1 and the supply
- Output voltage is V, the input current becomes negative and power flows from load to source.
- Average output voltage is positive
- Average output current can take both positive and negative values.
- Choppers CH1 & CH2 should not be turned ON simultaneously as it would result in short circuiting the supply.
- Class C Chopper can be used both for dc motor control and regenerative braking of dc motor.

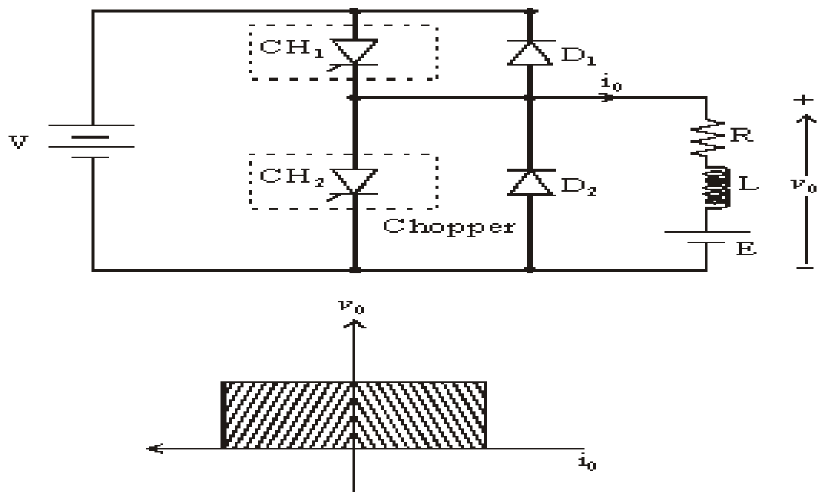


Figure: 3.24 circuit diagram and quadrant operation of Type C chopper

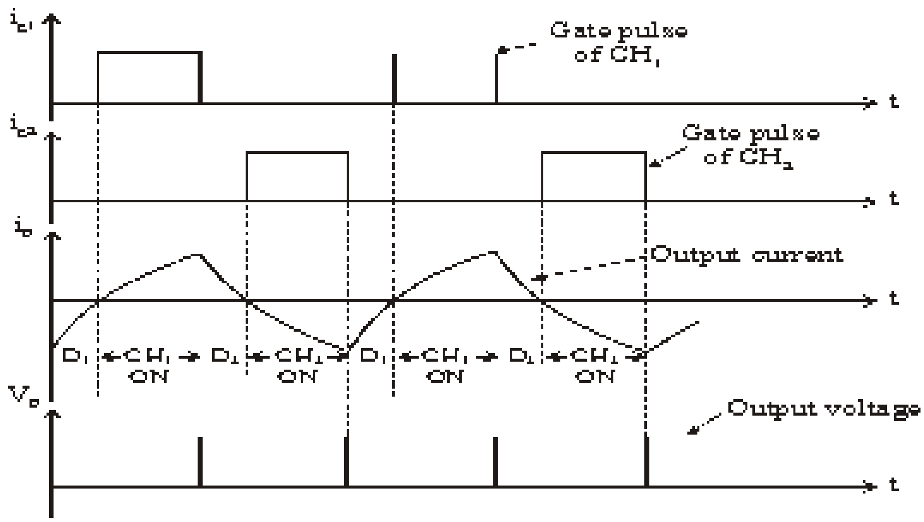


Figure: 3.25 Output voltage and current waveforms of type

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 $t_{ON} < t_{OFF}$.
- Hence the direction of load current is always positive but load voltage can be positive or negative.

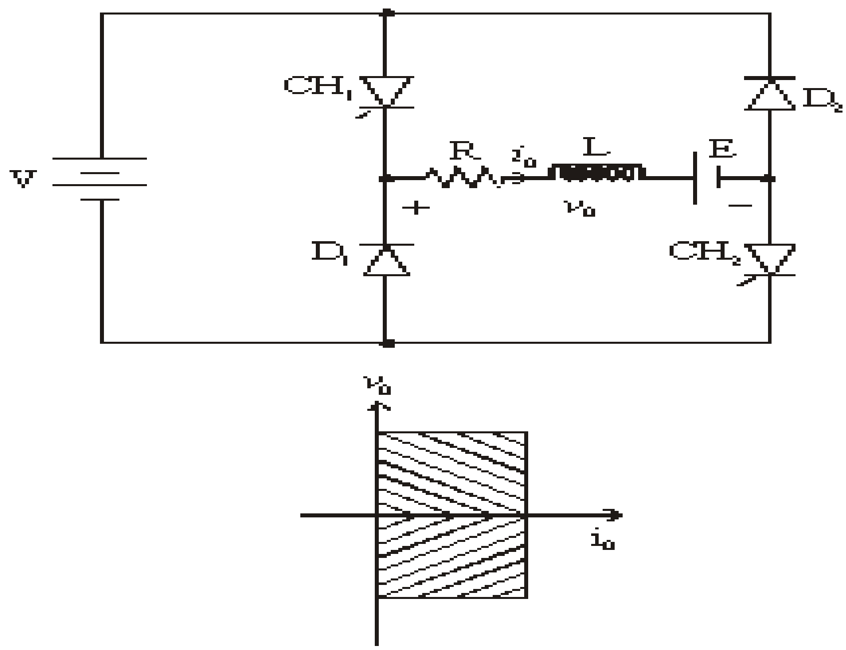


Figure: 3.26 circuit diagram and quadrant operation of Type D chopper

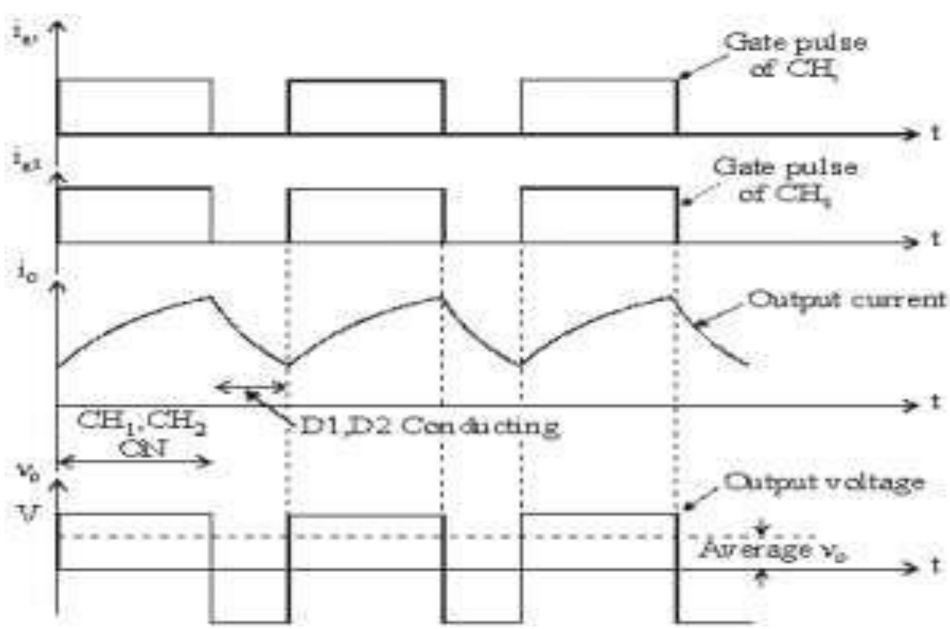


Figure: 3.27 Output voltage and current waveforms of type D chopper

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 andCH4,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 D1and D4 and the output voltage Vo = V.
- Therefore the chopper operates in second quadrant as Vo is positive but Io is negative.

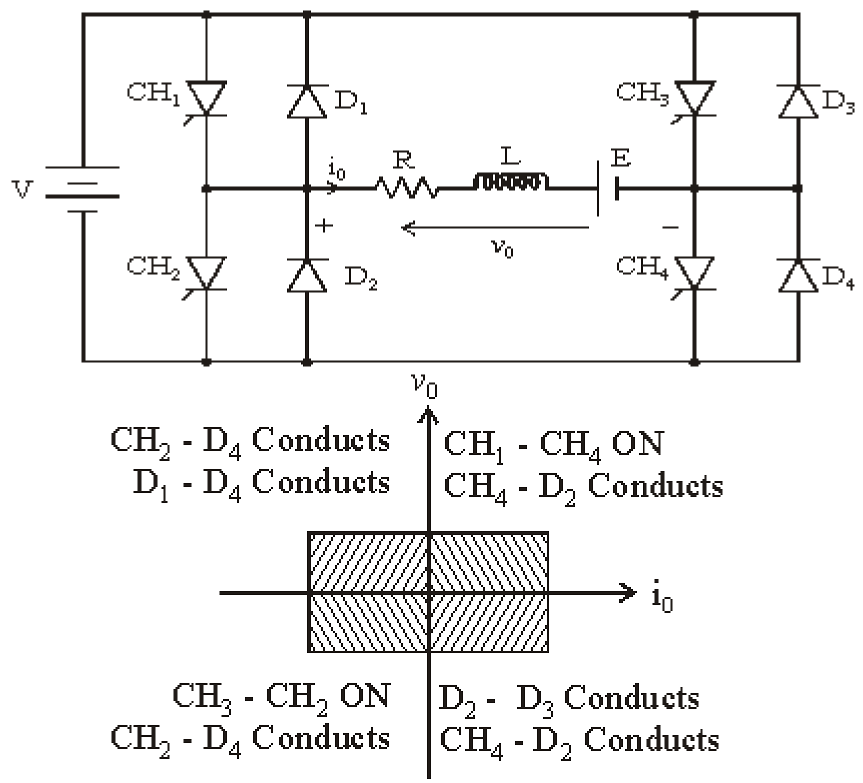


Figure: 3.28 circuit diagram and quadrant operation of Type E chopper

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:

The chopping frequency (f)

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

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

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

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

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

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

Numerical probelms

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.

   Solution:

   $I_{dc} = 30$ 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}..

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5. Rashid M.H , Power electronics hank book, Academics press publications., 2nd Edition, 2007.

Question Bank

UNIT-3 DC and AC Choppers			
	Part A	**CO**	**L**
1.	Illustrate the time ratio control in chopper circuit?	CO3	L2
2.	Criticize the significance of firing angle of a controlled rectifier?	CO3	L5
3.	Classify the applications of DC chopper	CO3	L2
4.	Justify Why forced commutation technique is required in DC choppers?	CO3	L5
5.	Illustrate current limit control in chopper circuit?	CO3	L2
6.	Illustrate current and voltage commutation in case of chopper.	CO3	L2
7.	Analyze the effect of load inductance on the load current of the DC chopper.	CO3	L4
8.	A chopper circuit is operating on TRC at a frequency of 2kHz on a 460Vsupply. If the load voltage is 350V, Estimate the conduction period of the chopper in each cycle.	CO3	L5
9.	Distinguish integral cycle control and phase angle control.	CO3	L2
10.	Justify Why half wave AC voltage regulator not used.	CO3	L5
11.	Criticize the term sequence control of ac voltage controller.		L5
12.	Interpret the negative group SCR in cyclo-converter	CO3	L2
13.	Classify the application of cyclo-converters	CO3	L2
	PART-B	**CO**	**L**
1.	Explain the working of buck converter with neat waveform and also derive the expression of output voltage of the converter.	CO3	L5
2.	With a neat power circuit diagram, explain the operation of boost converter. Draw the load voltage and load current waveforms and derive the expression for the output voltage.	CO3	L5
3.	With a neat power circuit diagram, explain the operation of buck-boost	CO3	L5

	converter. Draw the load voltage and load current waveforms and derive the expression for the output voltage.		
4.	With necessary modes of operation examine the operation of two quadrant chopper. Draw the equivalent circuit for each modes of operation.	CO3	L4
4.	With necessary modes of operation examine the operation of Four quadrant chopper Draw the equivalent circuit for each modes of operation.	CO3	L4
5.	Analyze the operation single phase AC voltage controller for RL load with appropriate waveforms.	CO3	L4
6.	Analyze the operation single phase step down cyclo converter with appropriate waveforms.	CO3	L4
7.	Examine the operation of single phase step up cyclo converter with appropriate waveforms.	CO3	L4
8.	A DC chopper has a resistive load of 20Ω and input voltage of 220V. When the chopper is ON, its voltage drop is 1.5V and chopping frequency is 10kHz. If the duty cycle is 80%, Estimate the average output voltage and the chopper ON time.	CO3	L5

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DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

UNIT – IV
POWER ELECTRONICS – SEE1305

INVERTERS

Principle of operation : Single phase half bridge & full bridge Voltage Source Inverters (VSI) – Series Inverters – Parallel Inverters - Three phase Voltage Source Inverters (120° and 180° mode) - Single phase current source inverter. PWM techniques : Single pulse PWM, Sinusoidal PWM, Modified sinusoidal PWM and Multiple PWM.

UNIT - IV

Inverters

Single Phase Half Bridge Inverter with R Load

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. Thus, for example, the primary source of input power may be utility ac voltage supply that is converted to dc by an ac to dc converter and then 'inverted' back to ac using an inverter. Here, the final ac output may be of a different frequency and magnitude than the input ac of the utility supply.

A single phase Half Bridge DC-AC inverter is shown in Figure below

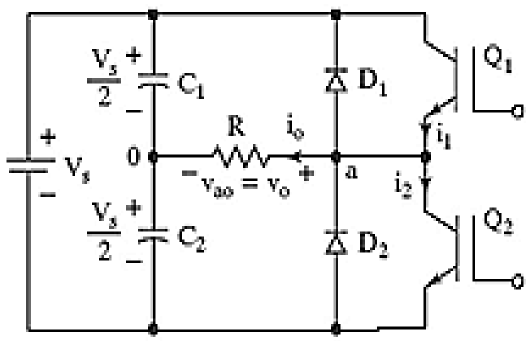

Figure: 4.1 Single phase Half Bridge inverter with R load

The analysis of the DC-AC inverters is done taking into accounts the following assumptions and conventions.

- The current entering node a is considered to be positive.
- The switches S1 and S2 are unidirectional, i.e. they conduct current in one direction.
- The current through S1 is denoted as is1 and the current through S2 is2.

The switching sequence is so design is shown in Figure below. Here, switch S1 is on for the time duration $0 \leq t \leq T1$ and the switch S2 is on for the time duration $T1 \leq t \leq T2$. When switch S1 is turned on, the instantaneous voltage across the load is $Vo = Vin/2$. When the switch S2 is only turned on, the voltage across the load is $Vo = -Vin/2$.

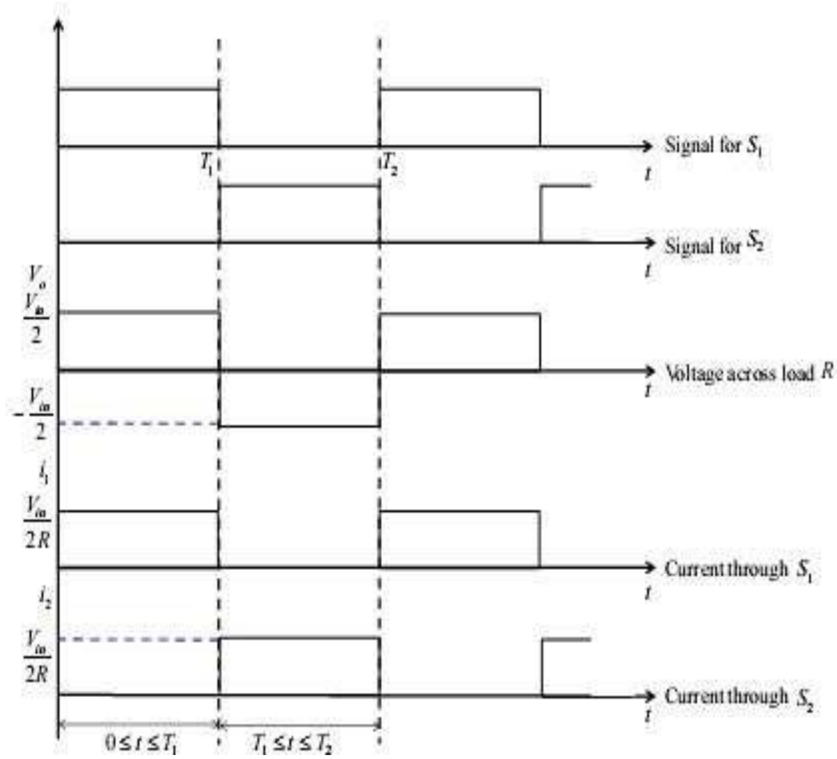

Figure: 4.2 Single phase Half Bridge DC-AC inverter output waveforms

The RMS value of output voltage v o is given by,

$$V_{o,rms} = \left(\frac{1}{T_1} \int_0^{T_1} \frac{V_{in}^2}{4} dt \right) = \frac{V_{in}}{2}$$

The instantaneous output voltage v o is rectangular in shape. The instantaneous value of v o can be expressed in Fourier series as,

$$v_o = \frac{a_o}{2} + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t)$$

Due to the quarter wave symmetry along the time axis , the values of a0 and an are zero. The value of bn is given by,

$$b_n = \frac{1}{\pi} \left[\int_{\frac{-\pi}{2}}^{0} \frac{-V_{in}}{2} d(\omega t) + \int_0^{\frac{\pi}{2}} \frac{V_{in}}{2} d(\omega t) \right] = \frac{2V_{in}}{n\pi}$$

Substituting the value of b_n from above equation, we get

$$i_L = \sum_{n=1,3,5,...}^{\infty} \frac{1}{R} \frac{2V_{in}}{n\pi} \sin(n\omega t)$$

The current through the resistor (iL) is given by,

Single Phase Half Bridge Inverter with R-L Load

The DC-AC converter with inductive load is shown in Figure below. For an inductive load, the load current cannot change immediately with the output voltage.

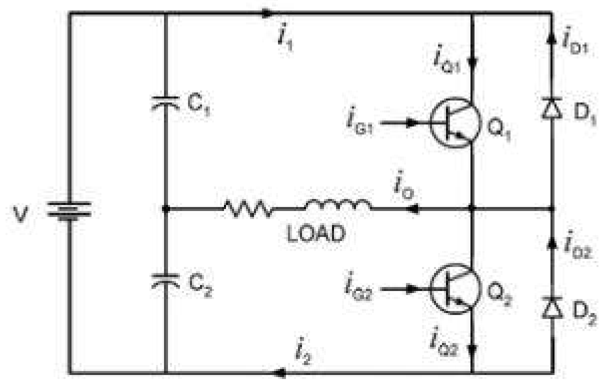

Figure: 4.3 Single phase Half Bridge inverter with RL load

The working of the DC-AC inverter with inductive load is as follow as, **Case 1:** In the time interval 0<=t<= T1 the switch S1 is on and the current flows through the inductor from points a to b. When the switch S1 is turned off (case 1) at t-T1, the load current would continue to flow through the capacitor C2 and diode D2 until the current falls to zero, as shown in Figure below.

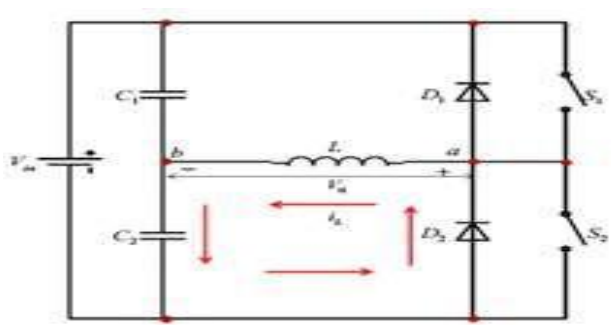

Figure: 4.4 Single phase Half Bridge inverter with L load

Case 2: Similarly, when S2 is turned off at t = T1, the load current flows through the diode D1 and capacitor C1until the current falls to zero, as shown in Figure below.

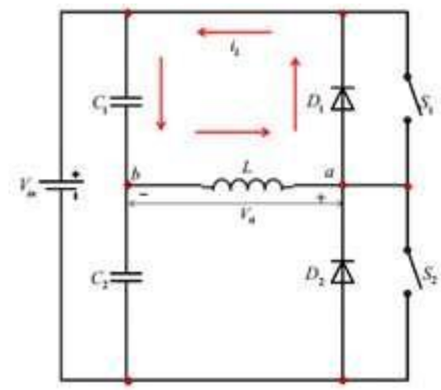

Figure: 4.5 Single phase Half Bridge inverter with L load

When the diodes D1 and D2 conduct, energy is feedback to the dc source and these diodes are known as feedback diodes. These diodes are also known as freewheeling diodes. The current for purely inductive load is given by,

$$i_L = \sum_{n=1,3,5,...}^{\infty} \frac{1}{\omega n L} \frac{2V_{in}}{n\pi} \sin\left(n\omega t - \frac{\pi}{2}\right)$$

Similarly, for the R – L load. The instantaneous load current is obtained as,

$$i_L = \sum_{n=1,3,5,...}^{\infty} \frac{2V_{in}}{n\pi\sqrt{R^2 + (n\omega L)^2}} \sin(n\omega t - \theta_n)$$

Where,

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

Single phase full bridge inverter with R Load

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.

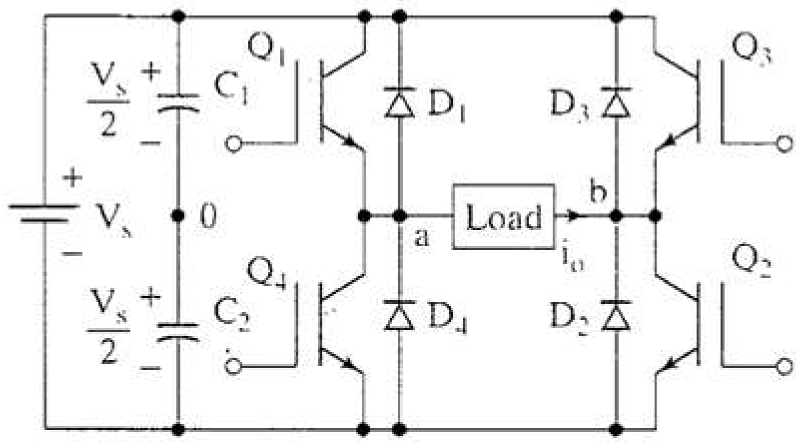

Figure: 4.6 Single phase Full Bridge inverter with R load

When the switches S1 and S2 are turned on simultaneously for a duration $0 \leq t \leq T1$, the the input voltage Vin appears across the load and the current flows from point a to b.

Q1 – Q2 ON, Q3 – Q4 OFF ==> $v_o = V_s$

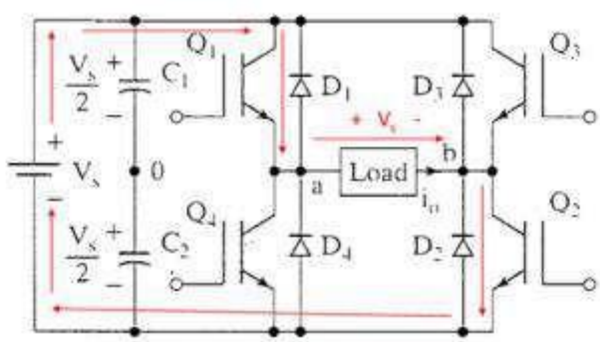

Figure: 4.7 Single phase Full Bridge inverter with R load

If the switches S3 and S4 turned on duration $T1 \leq t \leq T2$, the voltage across the load the load is reversed and the current through the load flows from point b to a.

Q1 – Q2 OFF, Q3 – Q4 ON ==> $V_o = -V_s$

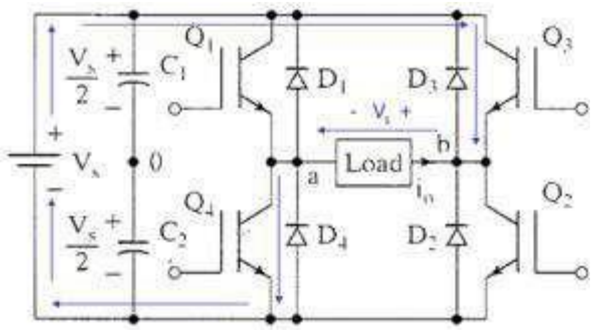

Figure: 4.8 Single phase Full Bridge inverter with R load current directions

The voltage and current waveforms across the resistive load are shown in Figure below

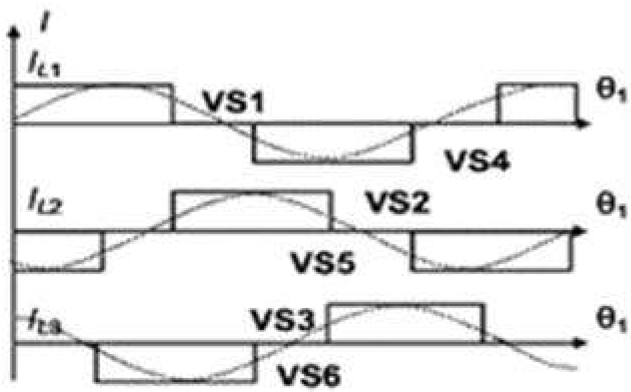

Figure: 4.9 Single phase Full Bridge Inverter waveforms

Single Phase Full Bridge Inverter for R-L load:

A single-phase square wave type voltage source inverter produces square shaped output voltage for a single-phase load. Such inverters have very simple control logic and the power switches need to operate at much lower frequencies compared to switches in some other types of inverters. The first generation inverters, using thyristor switches, were almost invariably square wave inverters because thyristor switches could be switched on and off only a few hundred times in a second. In contrast, the present day switches like IGBTs are much faster and used at switching frequencies of several kilohertz. Single-phase inverters mostly use half bridge or full bridge topologies. Power circuits of these topologies are shown in in Figure below.

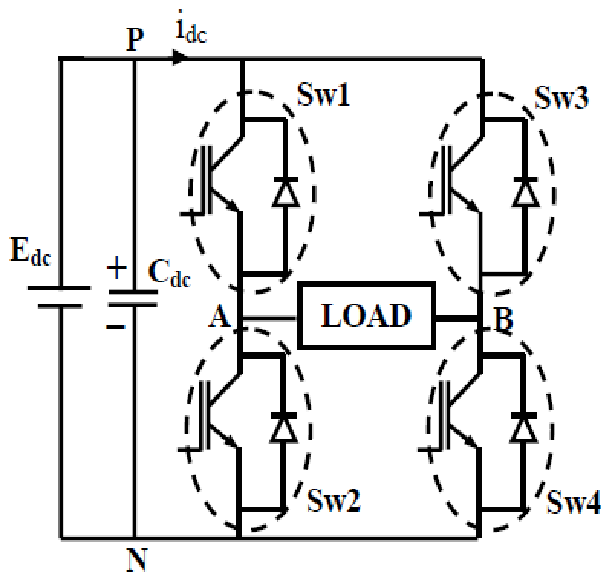

Figure: 4.10 Single phase Full Bridge Inverter with L load

The above topology is analyzed under the assumption of ideal circuit conditions. Accordingly, it is assumed that the input dc voltage (E_{dc}) is constant and the switches are lossless. In full bridge topology has two such legs. Each leg of the inverter consists of two series connected electronic switches shown within dotted lines in the figures. Each of these switches consists of an IGBT type controlled switch across which an uncontrolled diode is put in anti-parallel manner. These switches are capable of conducting bi-directional current but they need to block only one polarity of voltage. The junction point of the switches in each leg of the inverter serves as one output point for the load.

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 switches 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.

- The general configuration of a three phase DC-AC inverter is shown in **Figure.** Two types of control signals can be applied to the switches:
    - 180°conduction
    - 120°conduction

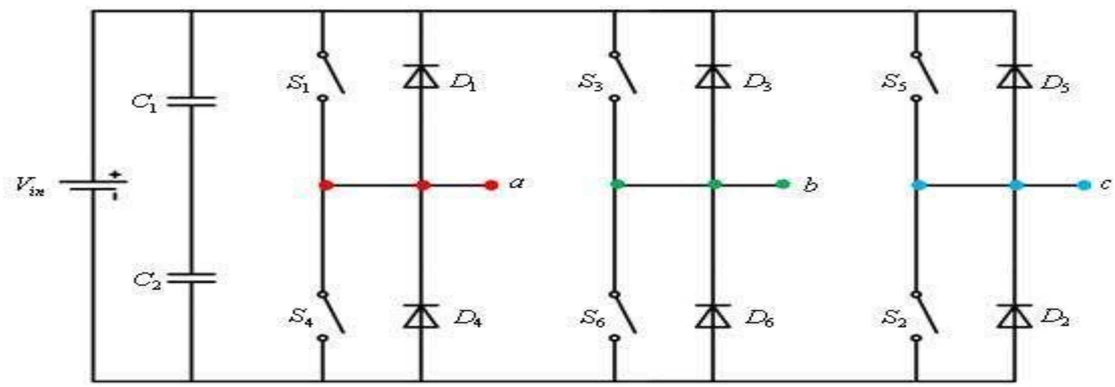

Figure: 4.15 Circuit diagram of three phase bridge inverter

180-Degree Conduction with Star Connected Resistive Load

The configuration of the three phase inverter with star connected resistive load is shown in f**igure.**
The following convention is followed:

- A current leaving a node point ***a***, ***b*** or ***c*** and entering the neutral point ***n*** is assumed to be positive.
- All the three resistances are equal, $R_a = R_b = R_c = R$.

In this mode of operation each switch conducts for 180°. Hence, at any instant of time three switches remain ***on*** . When S_1 is ***on*** , the terminal ***a*** gets connected to the positive terminal of input DC source. Similarly, when S_4 is ***on*** , terminal ***a*** gets connected to the negative terminal of input DC source. There are six possible modes of operation in a cycle and each mode is of 60° duration and the explanation of each mode is as follows:

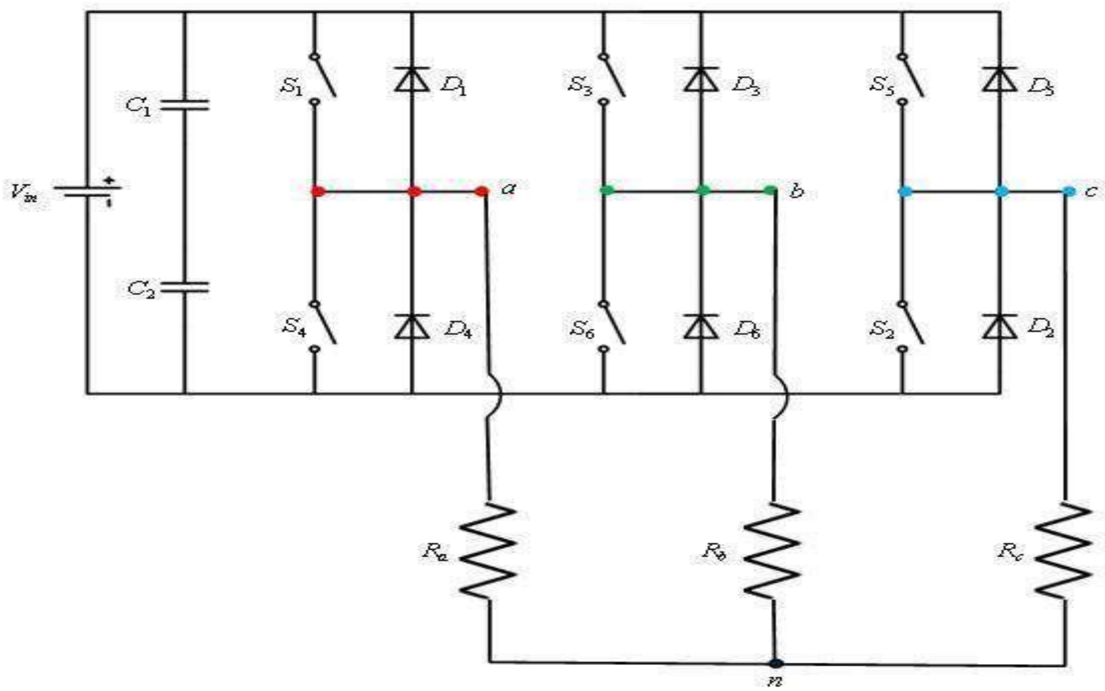

Figure: 4.16 Circuit diagram of three phase bridge inverter with star connected load

Mode 1**:** In this mode the switches S5 , S6 and S1 are turned on for time interval $0 \le \omega t \le \frac{\pi}{3}$. As a result of this the terminals a and c are connected to the positive terminal of the input DC source and the terminal b is connected to the negative terminal of the DC source. The current flow through Ra, R_b and Rc is shown in Figure 4.17 and the equivalent circuit is shown in Figure in 4.18.

$$R_{eq} = R + \frac{R}{2} = \frac{3R}{2} \qquad (1)$$

The current *i* delivered by the DC input source is

$$i = \frac{V_{in}}{R_{eq}} = \frac{2}{3}\frac{V_{in}}{R} \qquad (2)$$

The currents i_a and i_b are

$$i_a = i_c = \frac{1}{3}\frac{V_{in}}{R} \qquad (3)$$

Keeping the current convention in mind, the current $i_b$is

$$i_b = -i = -\frac{2}{3}\frac{V_{in}}{R} \qquad (4)$$

Having determined the currents through each branch, the voltage across each branch is,

$$v_{an} = v_{cn} = i_a R = \frac{V_{in}}{3};\ v_{bn} = i_b R = -\frac{2V_{in}}{3} \qquad (5)$$

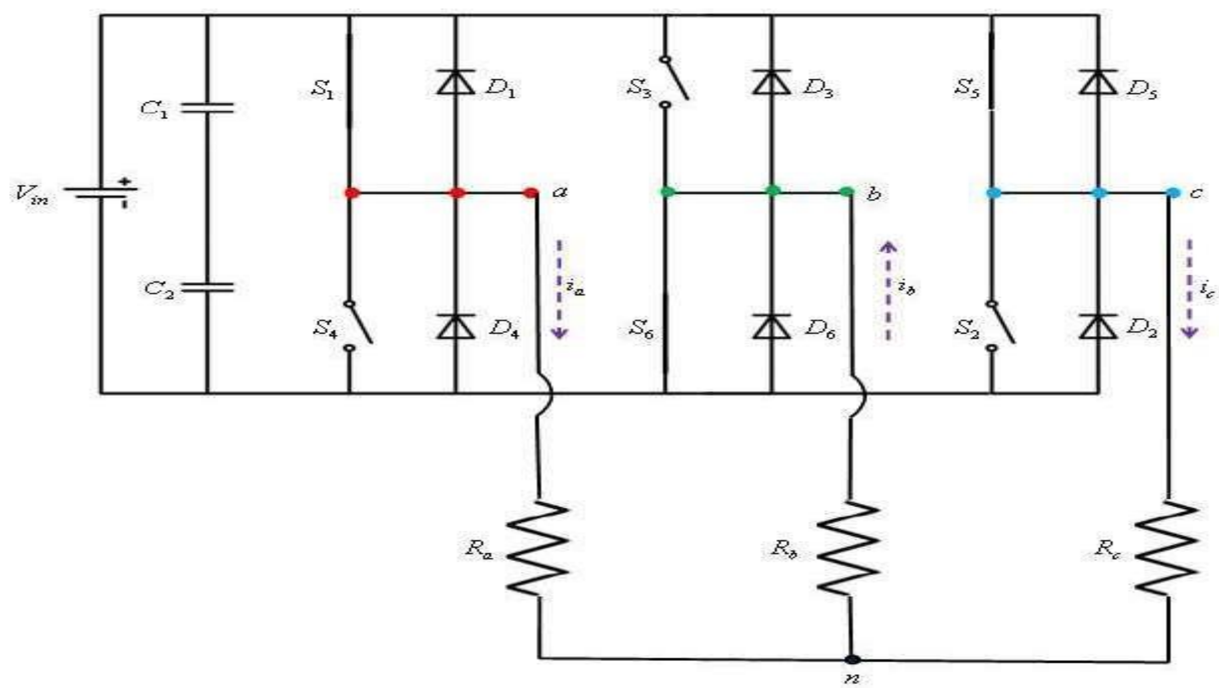

Figure: 4.17 Mode 1 operation of three phase bridge inverter with star connected load

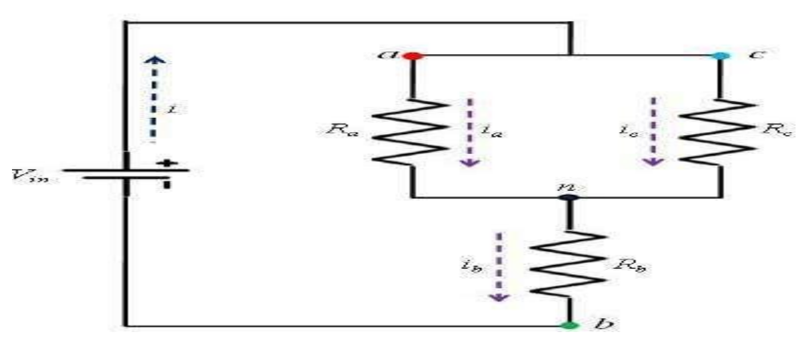

Figure: 4.18 Current flow in Mode 1 operation

Mode 2 **:** In this mode the switches S_6 , S_1 and S_2 are turned ***on*** for time interval $\frac{\pi}{3} \le \omega t \le \frac{2\pi}{3}$. The current flow and the equivalent circuits are shown in **Figure 4.19** and **Figure 4.20** respectively. Following the reasoning given for ***mode 1*** , the currents through each branch and the voltage drops are given by

$$i_b = i_c = \frac{1}{3}\frac{V_{in}}{R};\; i_a = -\frac{2}{3}\frac{V_{in}}{R} \qquad (6)$$

$$v_{bn} = v_{cn} = \frac{V_{in}}{3};\; v_{an} = -\frac{2V_{in}}{3} \qquad (7)$$

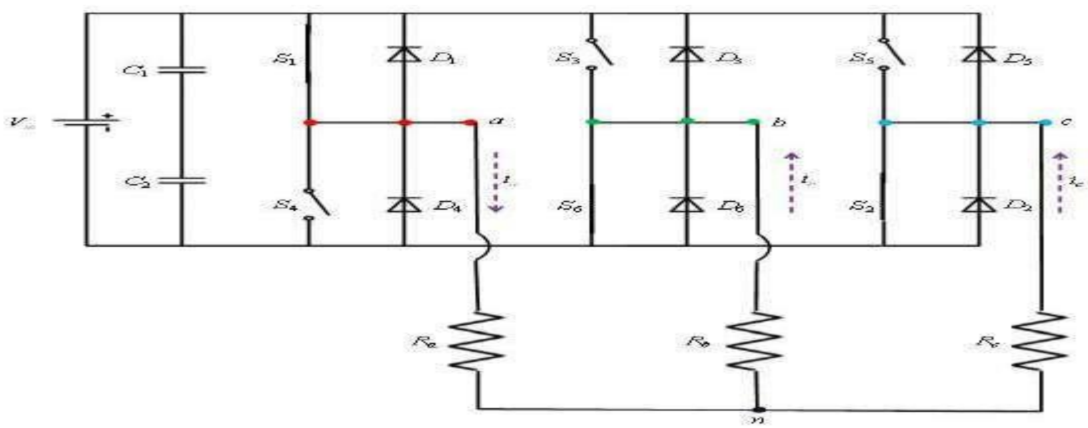

Figure: 4.19 Mode 2 operation of three phase bridge inverter with star connected load

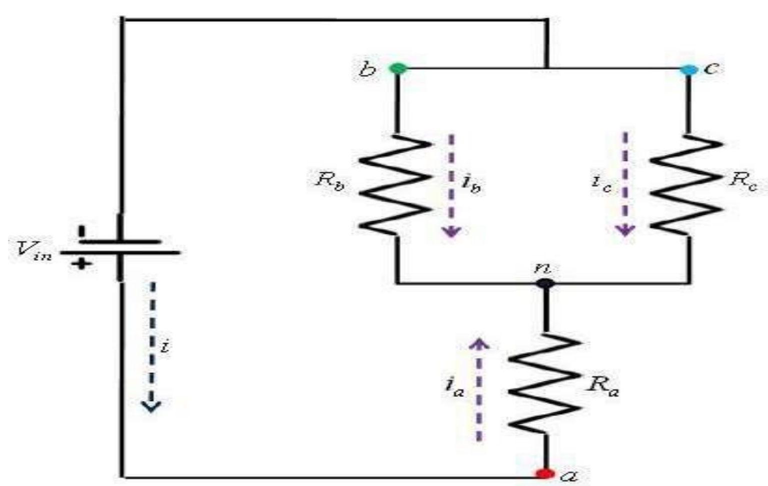

Figure: 4.20 Current flow in Mode 2 operation

Mode 3*:** In this mode the switches S_1, S_2 and S_3 are ***on for $\frac{2\pi}{3} \le \omega t \le \pi$. The current flow and the equivalent circuits are shown in **Figure 4.21** and **figure 4.22** respectively. The magnitudes of currents and voltages are:

$$i_a = i_b = \frac{1}{3}\frac{V_{in}}{R};\ i_c = -\frac{2}{3}\frac{V_{in}}{R} \quad (8)$$

$$v_{an} = v_{bn} = \frac{V_{in}}{3};\ v_{cn} = -\frac{2V_{in}}{3} \quad (9)$$

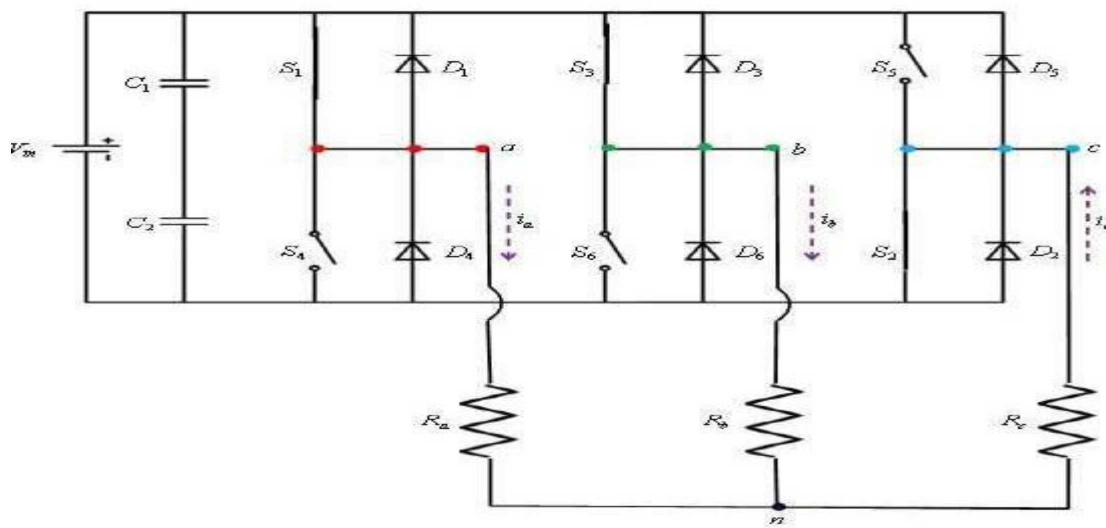

Figure: 4.21 Mode 3 operation of three phase bridge inverter with star connected load

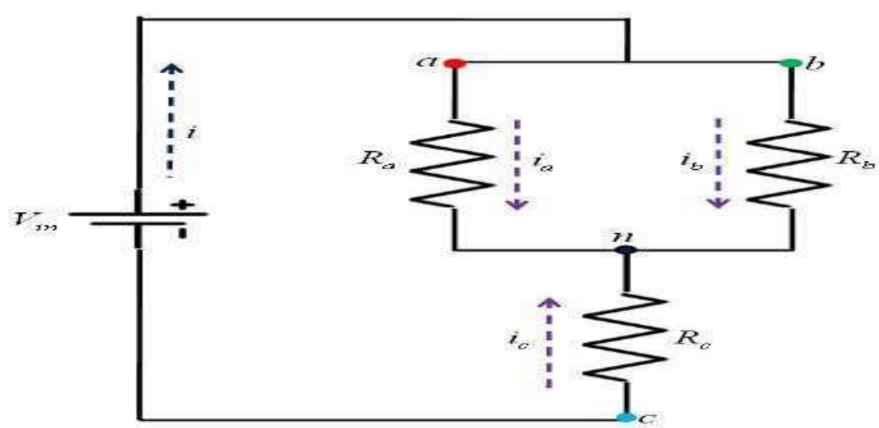

Figure: 4.22 Current flow in Mode 3 operation

For ***modes 4, 5*** and ***6*** the equivalent circuits will be same as ***modes 1, 2*** and ***3*** respectively. The voltages and currents for each mode are:

$$\left.\begin{aligned} i_a = i_c = -\frac{1}{3}\frac{V_{in}}{R};\ i_b = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{cn} = -\frac{V_{in}}{3}; V_{bn} = \frac{2V_{in}}{3} \end{aligned}\right\}$$ for ***mode 4*** (10)

$$\left.\begin{aligned} i_b = i_c = -\frac{1}{3}\frac{V_{in}}{R};\ i_a = \frac{2}{3}\frac{V_{in}}{R} \\ v_{bn} = v_{cn} = -\frac{V_{in}}{3}; V_{an} = \frac{2V_{in}}{3} \end{aligned}\right\}$$ for ***mode5*** (11)

$$\left.\begin{aligned} i_a = i_b = -\frac{1}{3}\frac{V_{in}}{R};\ i_c = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{bn} = -\frac{V_{in}}{3}; V_{cn} = \frac{2V_{in}}{3} \end{aligned}\right\}$$ for ***mode 6*** (12)

The plots of the phase voltages (v_{an}, $v_{bn}$and v_{cn}) and the currents (i_a, $i_b$and i_c) are shown in **Figure 4.23** Having known the phase voltages, the line voltages can also be determined as:

$$\begin{aligned} v_{ab} &= v_{an} - v_{bn} \\ v_{bc} &= v_{bn} - v_{cn} \\ v_{ca} &= v_{cn} - v_{an} \end{aligned}$$ (13)

The plots of line voltages are also shown in **Figure** and the phase and line voltages can be expressed in terms of Fourier series as:

$$v_{an} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1 + \sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin(n\omega t)$$
$$v_{bn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1 + \sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \frac{2n\pi}{3}\right)$$
$$v_{cn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1 + \sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \frac{4n\pi}{3}\right) \tag{14}$$

$$v_{ab} = v_{an} - v_{bn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t + \frac{n\pi}{6}\right)$$
$$v_{bc} = v_{bn} - v_{cn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t - \frac{n\pi}{2}\right)$$
$$v_{ca} = v_{cn} - v_{an} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t - \frac{7n\pi}{6}\right) \tag{15}$$

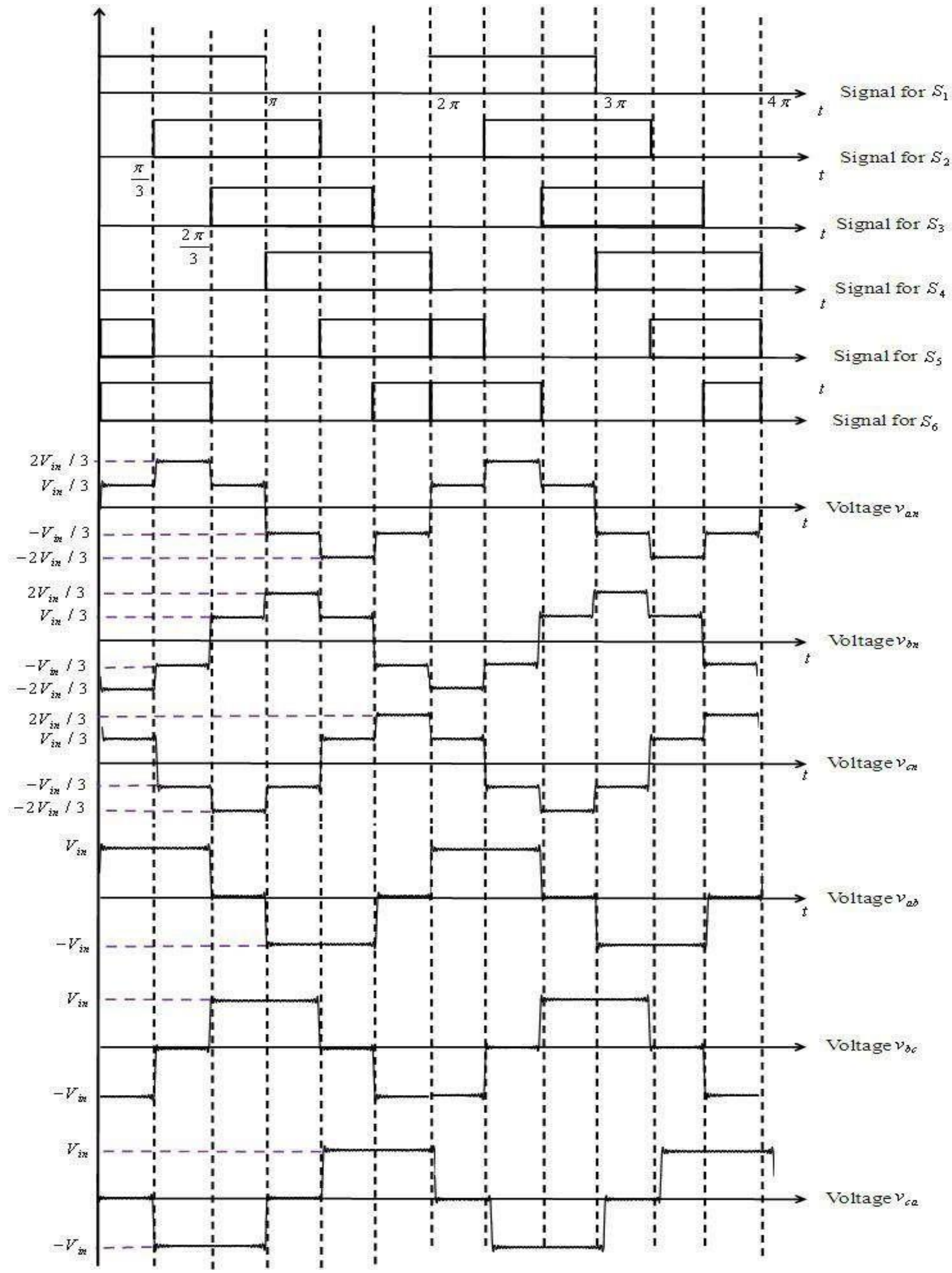

Figure: 4.23 Line and phase voltages of three phase bridge inverter

Three Phase Converters with 120 degree Conduction mode

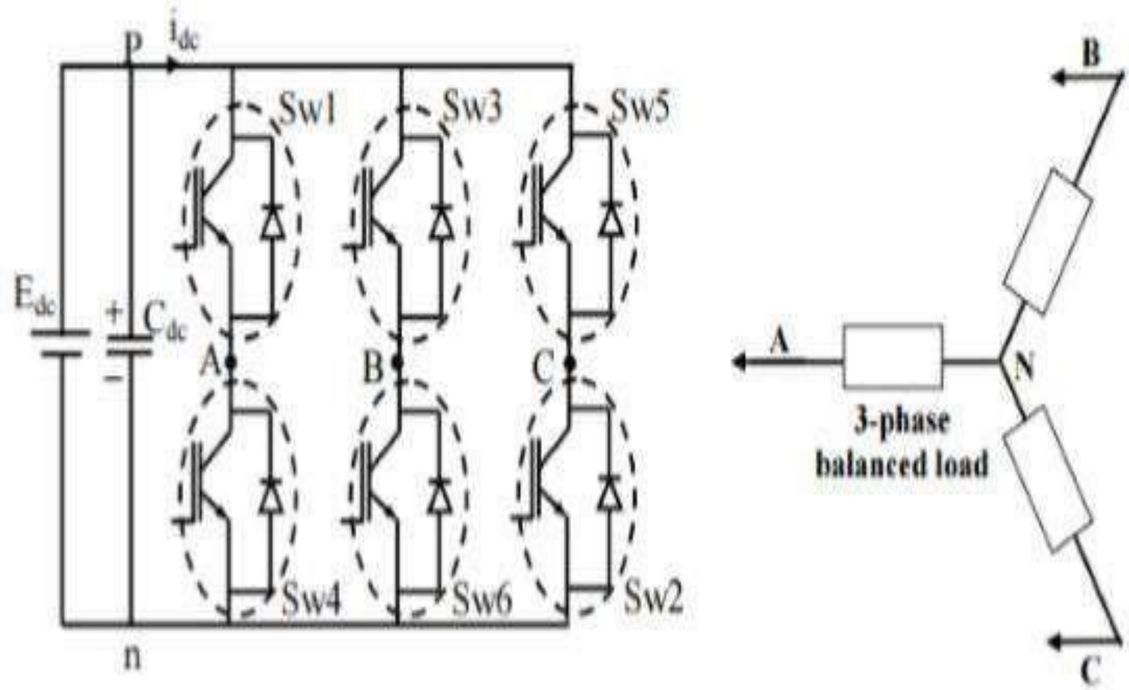

Figure: 4.24 Circuit diagram of three phase bridge inverter

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 only120°.

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 $V_{AB} = V$

$$V_{BC} = -V/2$$

$$V_{CA} = -V/2$$

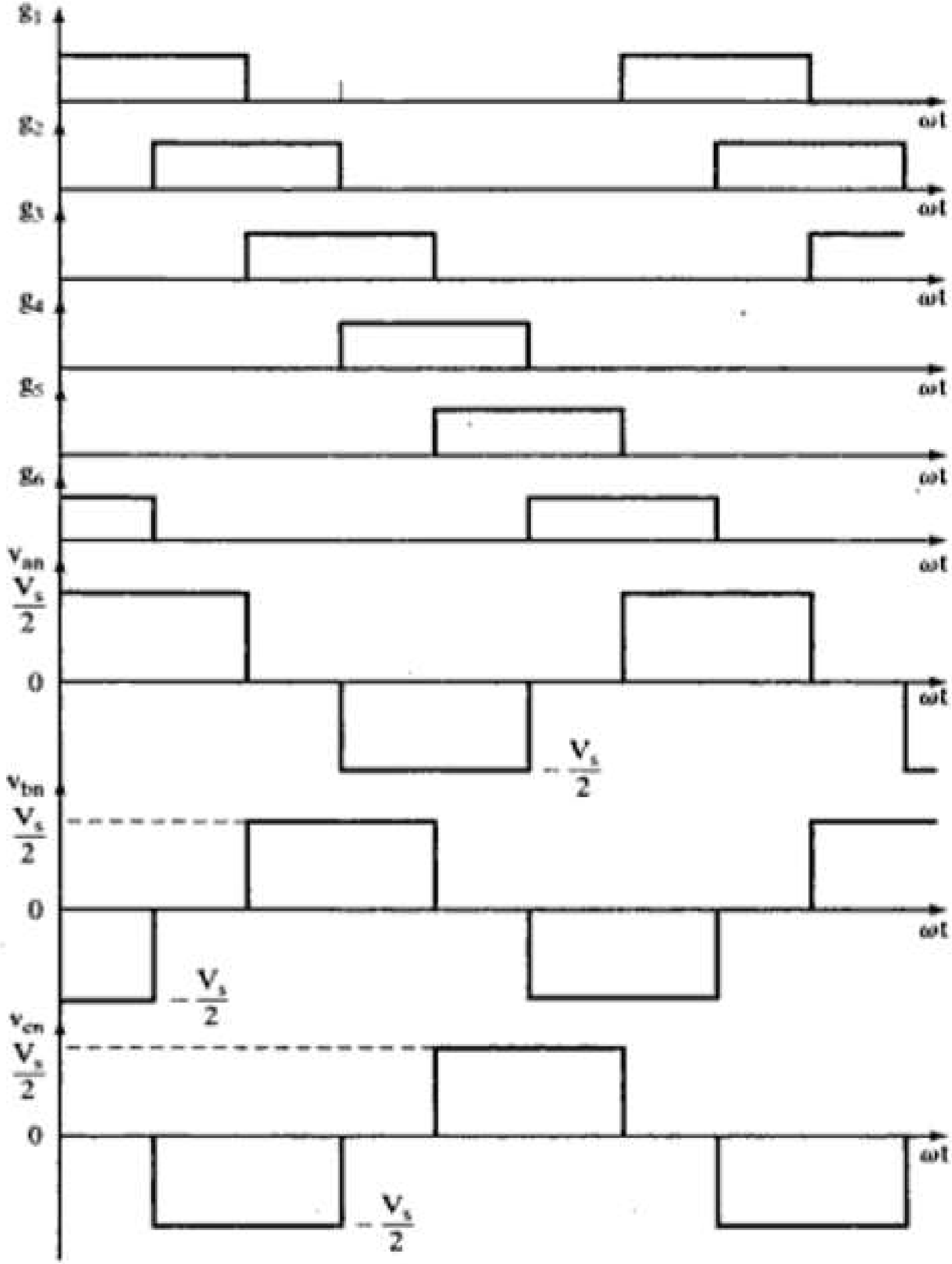

Figure: 4.25 Line and phase voltages of three phase bridge inverter

Voltage control techniques for inverters

Pulse width modulation techniques

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. Therefore, waveform average value is given by,

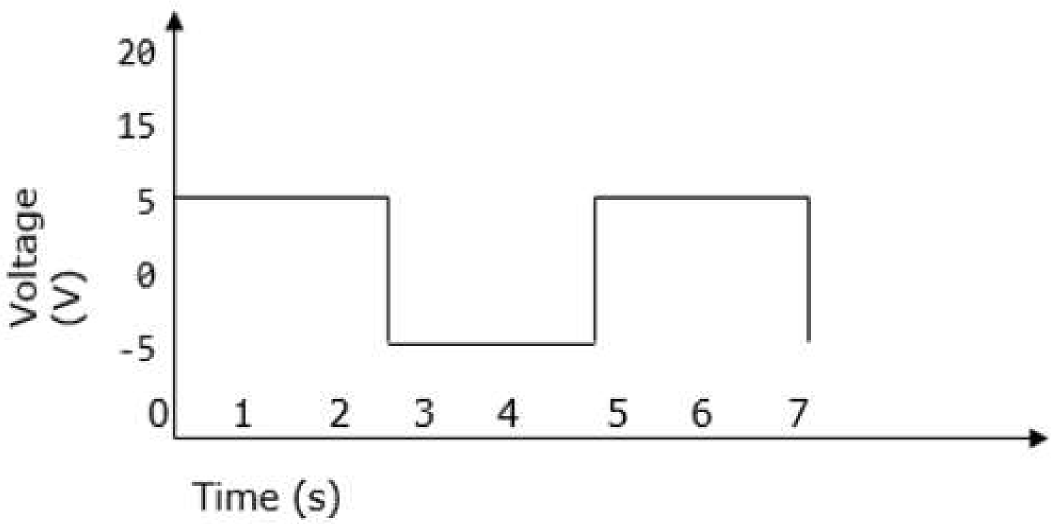

Figure: 4.26 Square waveform used for PWM technique

Sinusoidal Pulse Width Modulation

In a simple source voltage inverter, the switches can be turned ON and OFF as needed. During each cycle, the switch is turned on or off once. This results in a square waveform. However, if the switch is turned on for a number of times, a harmonic profile that is improved waveform is obtained.

The sinusoidal PWM waveform is obtained by comparing the desired modulated waveform with a triangular waveform of high frequency. Regardless of whether the voltage of the signal is smaller or larger than that of the carrier waveform, the resulting output voltage of the DC bus is either negative or positive.

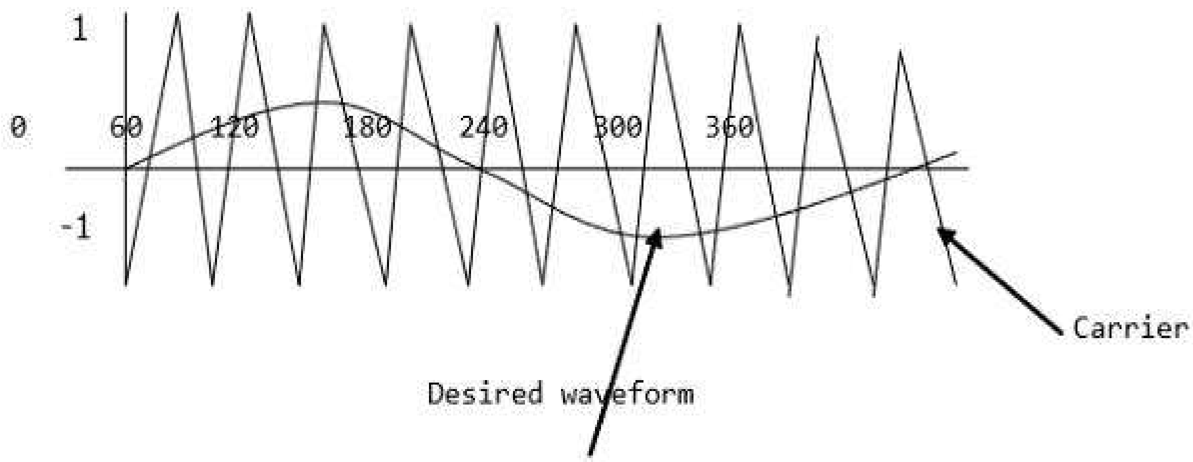

Figure: 4.27 Sinusoidal PWM waveform

The sinusoidal amplitude is given as A_m and that of the carrier triangle is give as A_c. For sinusoidal PWM, the modulating index m is given by A_m/A_c.

Modified Sinusoidal Waveform PWM

A modified sinusoidal PWM waveform is used for power control and optimization of the power factor. The main concept is to shift current delayed on the grid to the voltage grid by modifying the PWM converter. Consequently, there is an improvement in the efficiency of power as well as optimization in power factor.

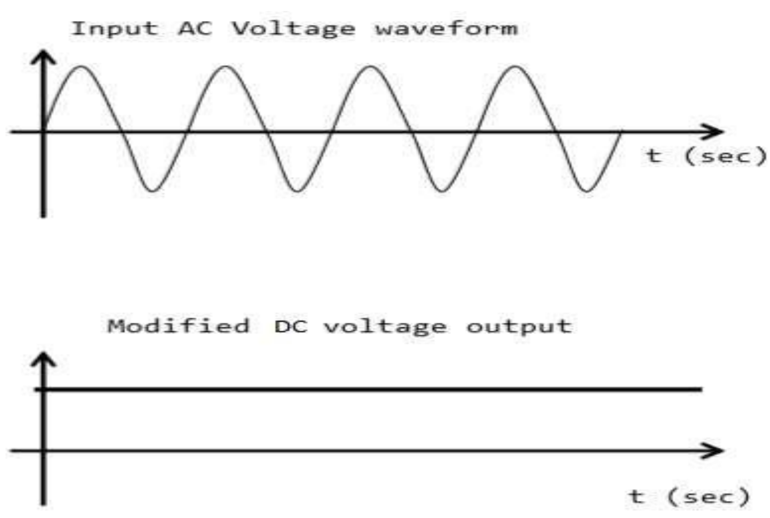

Figure: 4.28 Modified sinusoidal PWM waveform

Multiple PWM

The multiple PWM has numerous outputs that are not the same in value but the time period over which they are produced is constant for all outputs. Inverters with PWM are able to operate at high voltage output.

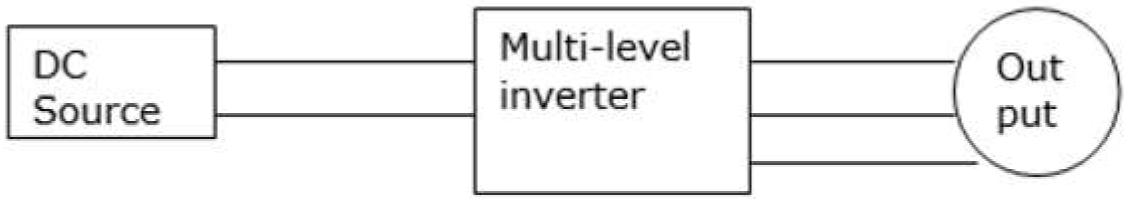

Figure: 4.29 Block diagram of multiple PWM technique

The waveform below is a sinusoidal wave produced by a multiple PWM

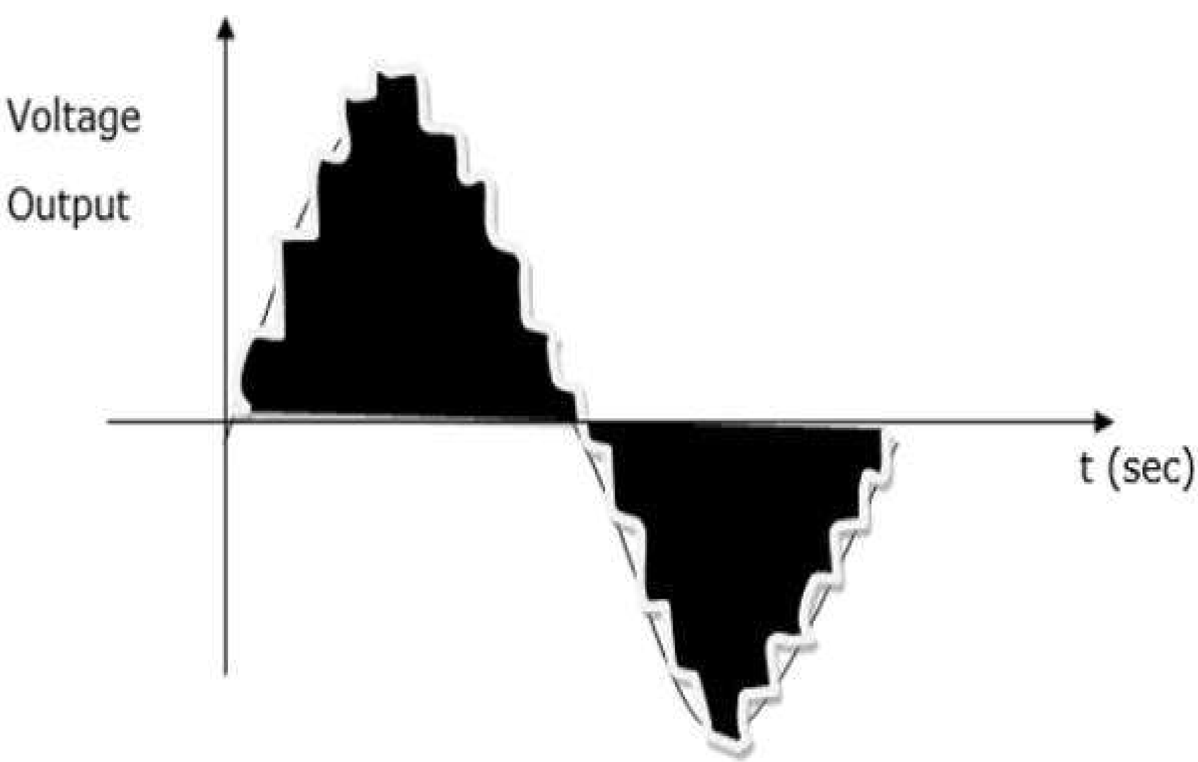

Figure: 4.30 Waveform of multiple PWM technique

Operation of sinusoidal pulse width modulation

The sinusoidal PWM (SPWM) method also known as the triangulation, sub harmonic, or sub oscillation method, is very popular in industrial applications. The SPWM is explained with reference to Figure, which is the half-bridge circuit topology for a single-phase inverter.

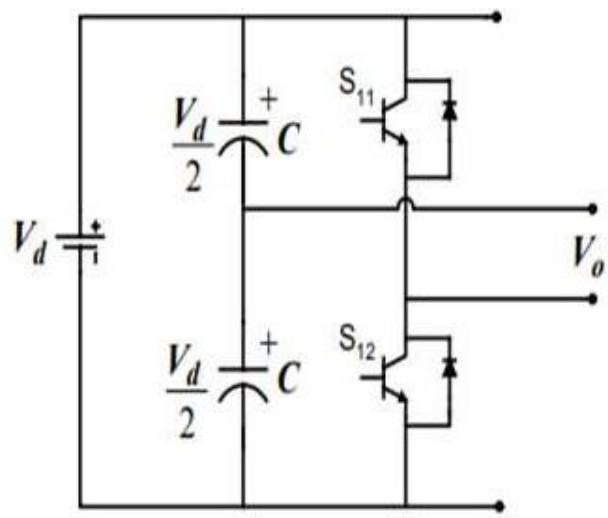

Figure: 4.31 schematic diagram of Half bridge PWM inverter

For realizing SPWM, a high-frequency triangular carrier wave is compared with a sinusoidal reference of the desired frequency. The intersection of and waves determines the switching instants and commutation of the modulated pulse. The PWM scheme is illustrated in Figure, in which v_c the peak value of triangular carrier wave and v_r is that of the reference, or modulating signal. The figure 4.32 shows the triangle and modulation signal with some arbitrary frequency and magnitude. In the inverter of figure 4.33 the switches and are controlled based on the comparison of control signal and the triangular wave which are mixed in a comparator. When sinusoidal wave has magnitude higher than the triangular wave the comparator output is high, otherwise it is low.

$$v_r > v_c \qquad S_{11} \text{ is on }, \; V_{out} = \frac{V_d}{2}$$

and

$$v_r < v_c \qquad S_{12} \text{ is on }, \; V_{out} = -\frac{V_d}{2}$$

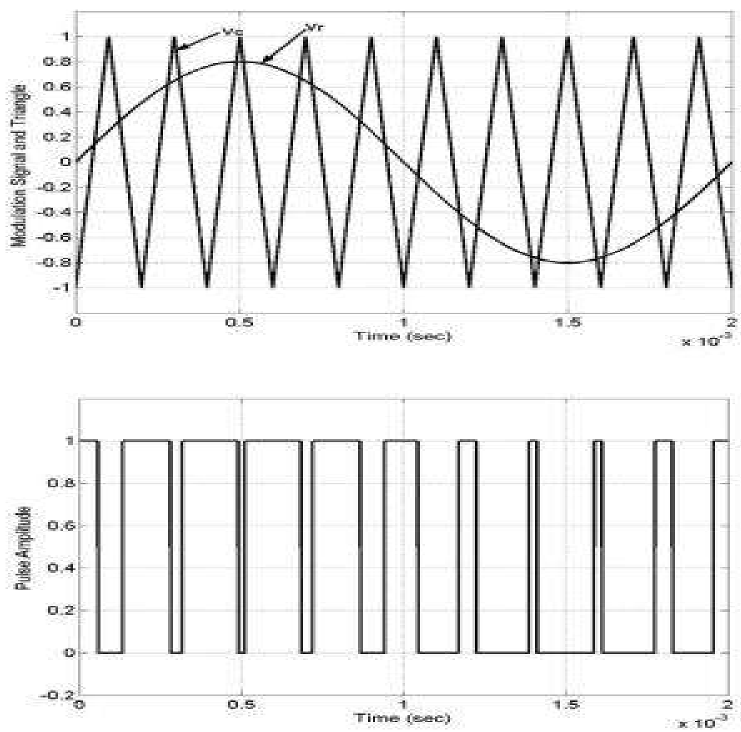

Figure: 4.32 Sine-Triangle Comparison and switching pulses of half bridge PWM inverter

The comparator output is processes in a trigger pulse generator in such a manner that the output voltage wave of the inverter has a pulse width in agreement with the comparator output pulse width. The magnitude ratio of V_r/V_C is called the modulation index (MI) and it controls the harmonic content of the output voltage waveform. The magnitude of fundamental component of output voltage is proportional to MI. The amplitude of the triangular wave is generally kept constant. The frequency modulation ratio is defined as,

$$M_F = \frac{fr}{fm}$$

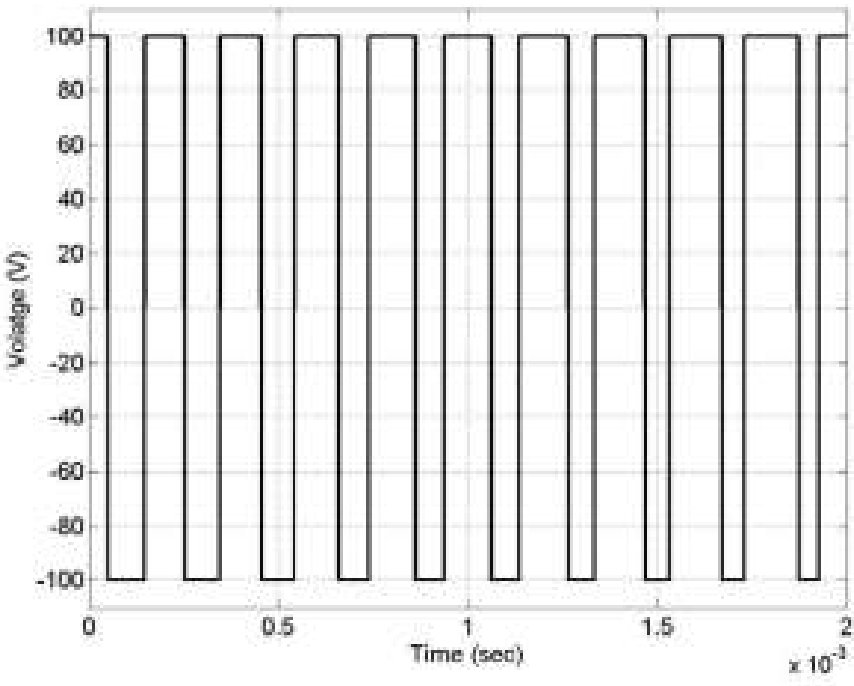

Figure: 4.33 Output voltage of the Half-Bridge inverter

Current source inverter

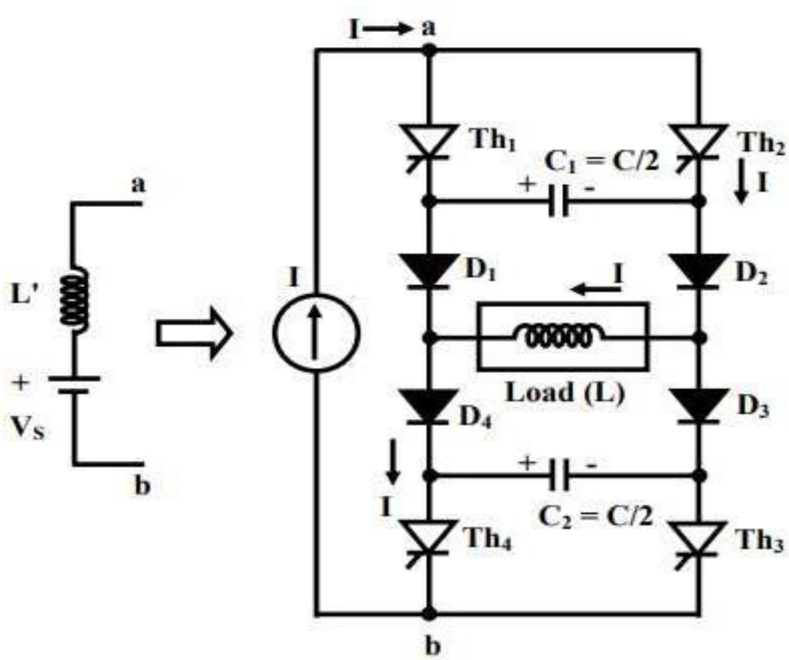

Figure: 4.34 Single phase current source inverter (CSI) of ASCI type

The circuit of a Single-phase Current Source Inverter (CSI) is shown in Fig. 4.34. The type of operation is termed as Auto-Sequential Commutated Inverter (ASCI). A constant current source is assumed here, which may be realized by using an inductance of suitable value, which must be high, in series with the current limited dc voltage source. The thyristor pairs, Th1 & Th3, and Th2 & Th4, are alternatively turned ON to obtain a nearly square wave current waveform. Two commutating capacitors − C1 in the upper half, and C2 in the lower half, are used. Four diodes, D1–D4 are connected in series with each thyristor to prevent the commutating capacitors from discharging into the load. The output frequency of the inverter is controlled in the usual way, i.e., by varying the half time period, (T/2), at which the thyristors in pair are triggered by pulses being fed to the respective gates by the control circuit, to turn them ON, as can be observed from the waveforms (Fig. 5.35). The inductance (L) is taken as the load in this case, the reason(s) for which need not be stated, being well known. The operation is explained by two modes.

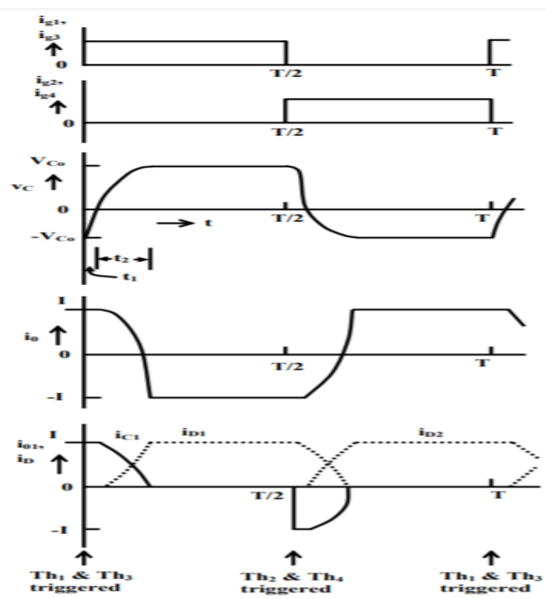

Figure: 4.35 output waveforms of Single phase current source inverter

Mode I: The circuit for this mode is shown in Fig. 4.36. The following are the assumptions. Starting from the instant, , the thyristor pair, Th − t = 0 2 & Th4, is conducting (ON), and the current (I) flows through the path, Th2, D2, load (L), D4, Th4, and source, I. The commutating capacitors are initially charged equally with the polarity as given, i.e., This means that both capacitors have right hand plate positive and left-hand plate negative. If two capacitors are not charged initially, they have to pre-charge.

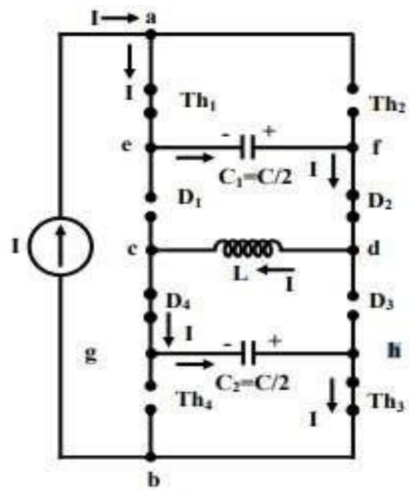

Figure: 4.36 Mode I operation of CSI

Mode II: The circuit for this mode is shown in Fig. 4.37. Diodes, D2 & D4, are already conducting, but at t=t1 , diodes, D1 & D3, get forward biased, and start conducting. Thus, at the end of time t1, all four diodes, D1–D4 conduct. As a result, the commutating capacitors now get connected in parallel with the load (L).

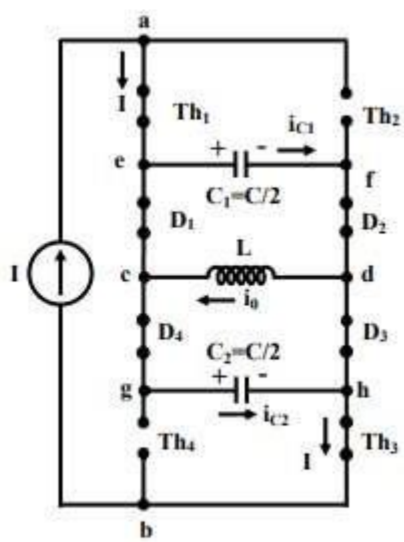

Figure: 4.37 Mode II operation of CSI

Load Commutated CSI

Two commutating capacitors, along with four diodes, are used in the circuit for commutation from one pair of thyristors to the second pair. Earlier, also in VSI, if the load is capacitive, it was shown that forced commutation may not be needed. The operation of a single-phase CSI with capacitive load (Fig. 4.38) is discussed here. It may be noted that the capacitor, C is assumed to be in parallel with resistive load (R). The capacitor, C is used for storing the charge, or voltage, to be used to force-commutate the conducting thyristor pair as will be shown. As was the case in the last lesson, a constant current source, or a voltage source with large inductance, is used as the input to the circuit.

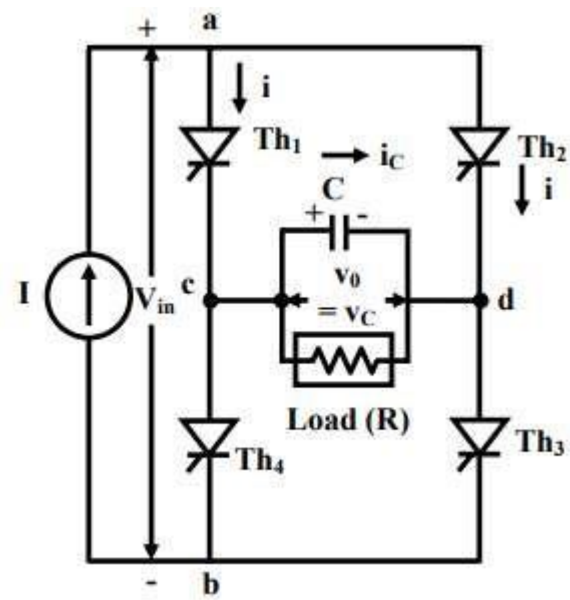

Figure: 4.38 Circuit diagram of load commutated CSI

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. 4.39 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 = −Vv1 , 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.

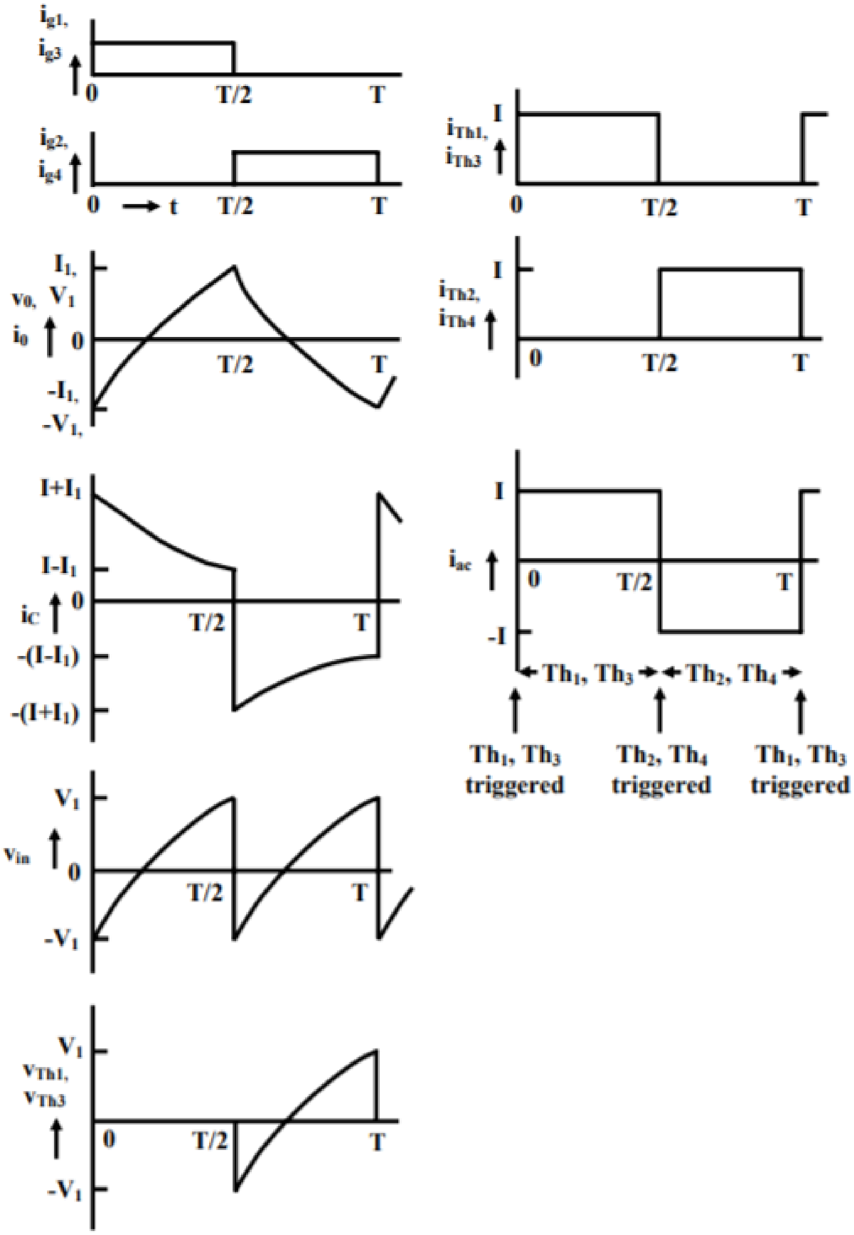

Figure: 4.39 Voltage and current waveforms of load commutated CSI

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9. Rashid M.H , Power electronics hank book, Academics press publications., 2nd Edition, 2007.

<u>**Question Bank**</u>

UNIT- 4 Inverters			
	Part A	**CO**	**L**
1.	Classify the various advantages of using PWM control of inverters	CO4	L2
2.	Justify why diodes should be connected in antiparallel inverter	CO4	L5
3.	Illustrate the function of feedback diodes in bridge inverter?	CO4	L2
4.	Distinguish voltage-source and current source inverters?	CO4	L4
5.	Classify the different types of PWM inverter?	CO4	L2
6.	Distinguish Single pulse PWM and multiple PWM	CO4	L4
7.	Classify the advantages of Multiple PWM.	CO4	L2
8.	Justify Why thyristors are not preferred for Inverter?	CO4	L5
9.	Interpret the necessity of return current diodes in inverter	CO4	L2
	Part B	**CO**	**L**
1.	Examine the operation of operation of full bridge voltage source inverter with RL load.	CO4	L4
2.	Examine the operation of single phase capacitor commutated CSI with R load.	CO4	L4
4.	Justify why PWM technique is required in inverters? Explain the various types PWM technique.	CO4	L5
5.	Examine the operation of operation of half bridge voltage source inverter with RL load.	CO4	L4
6.	Explain the operation of 3 phase bridge inverter for 120^o mode of operation with aid of relevant phase and line voltage waveforms.	CO4	L5
7.	Explain the operation of 3 phase bridge inverter for 180^o mode of operation with aid of relevant phase and line voltage waveforms.	CO4	L5
8.	Examine the operation of single phase auto sequential commutated CSI with RL load.	CO4	L4

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DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

UNIT – V
POWER ELECTRONICS – SEE1305

Applications

SMPS: Flyback and Push Pull SMPS - UPS: Redundant and Non-Redundant - HVDC Transmission systems – DC – DC converters for Electric Vehicles - Inverters for standalone photovoltaic systems.

UNIT – V

Applications

SMPS (Switched Mode Power Supplies)

Switched Mode Power Supplies, (often abbreviated to SMPS) are considerably more complex than the linear regulated power supplies described in Power Supplies Module 2. The main advantage of this added complexity is that switched mode operation gives regulated DC supplies that can deliver more power for a given size, cost and weight of power unit. A number of different design types are used. Where the input is the AC mains (line) supply the AC is rectified and smoothed by a reservoir capacitor before being processed by what is in effect a DC to DC converter, to produce a regulated DC output at the required level. Hence a SMPS can be used as an AC to DC converter, for use in many mains powered circuits, or DC to DC, either stepping the DC voltage up or down as required, in battery powered systems.

Fig. 5.1 shows a block diagram example of a typical SMPS with an AC Mains (line) input and a regulated DC output. The output rectification and filter are isolated from the High Frequency switching section by a high frequency transformer, and voltage control feedback is via an opto isolator. The control circuit block is typical of specialist ICs containing the high frequency oscillator, pulse width modulation, voltage and current control and output shut down sections.

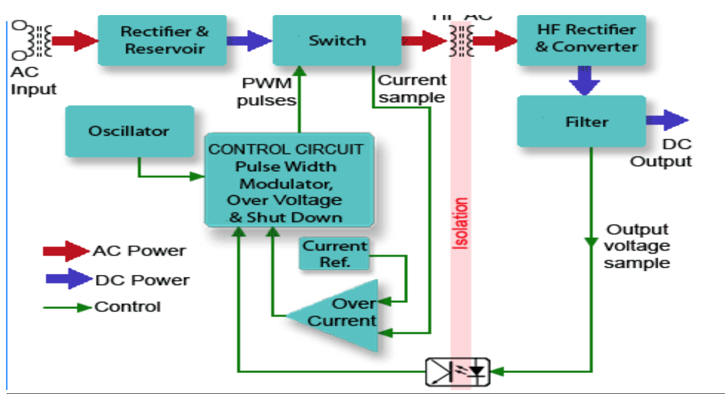


Figure. 5.1 SMPS Block Diagram

The purpose of a SMPS, a common feature (after conversion of AC to DC if required) is the use of a high frequency square wave to drive an electronic power switching circuit. This circuit is used to convert the DC supply into high frequency, high current AC, which by various means, depending on the design of the circuit, is reconverted into a regulated DC output. The reason for this double conversion process is that, by changing the DC or mains frequency AC to a high frequency AC, the components, such as transformers, inductors and capacitors, needed for conversion back to a regulated DC supply, can be much smaller and cheaper than those needed to do the same job at mains (line) frequency. The high frequency AC produced during the conversion process is a square wave, which provides a means of controlling the output voltage by means of pulse width modulation. This allows the regulation of the output to be much more efficient than is possible in linear regulated supplies.

The combination of a square wave oscillator and switch used in switched mode supplies can also be used to convert DC to AC. In this way the switched mode technique also be used as an 'inverter' to create an AC supply at mains potential from DC supplies such as batteries, solar panels etc.

Flyback Converter

Flyback Converter is a type of Switch Mode Power Supply typically used in low power applications. Flyback Converter is an Isolated Type SMPS where the input and output are isolated with a transformer. The following is the circuit of a simple Flyback Converter.

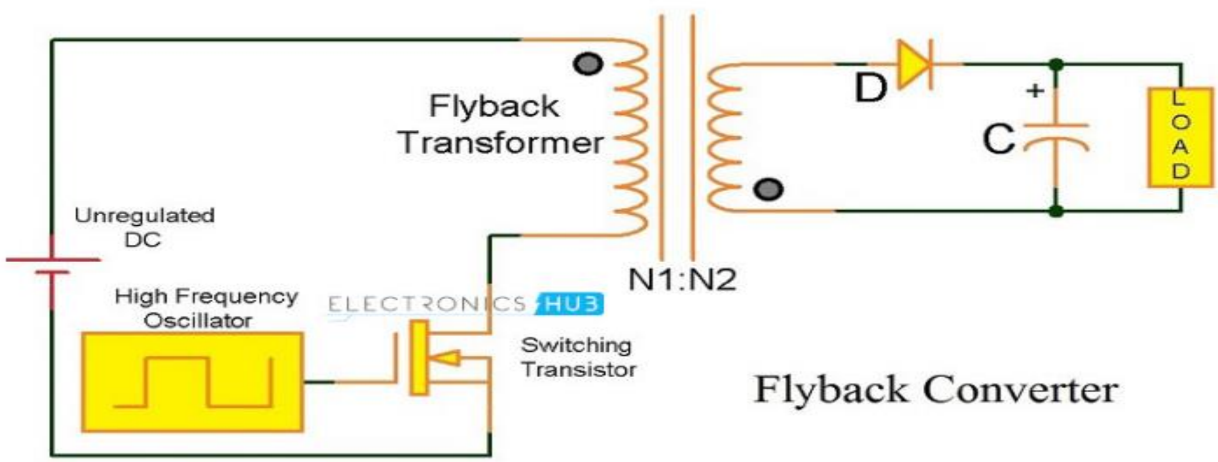


Figure 5.2 Flyback Converter

The main components of a Flyback Converter are a Switching Transistor, Oscillator Circuit, Transformer, switch (like a Diode) and a Capacitor. The Transformer is different from a normal transformer and is called a Flyback Transformer. In this transformer, the Primary and Secondary do not conduct simultaneously.

When the Transistor is turned ON, the current flows through the primary of the transformer with the dot being higher potential. As a result, the polarity of the voltage induced in the secondary will be reverse to that of primary. Hence, the diode D gets reverse biased.If the capacitor got charged in the previous cycle, it will discharge through the load. The following image shows this period of operation in the flyback converter.

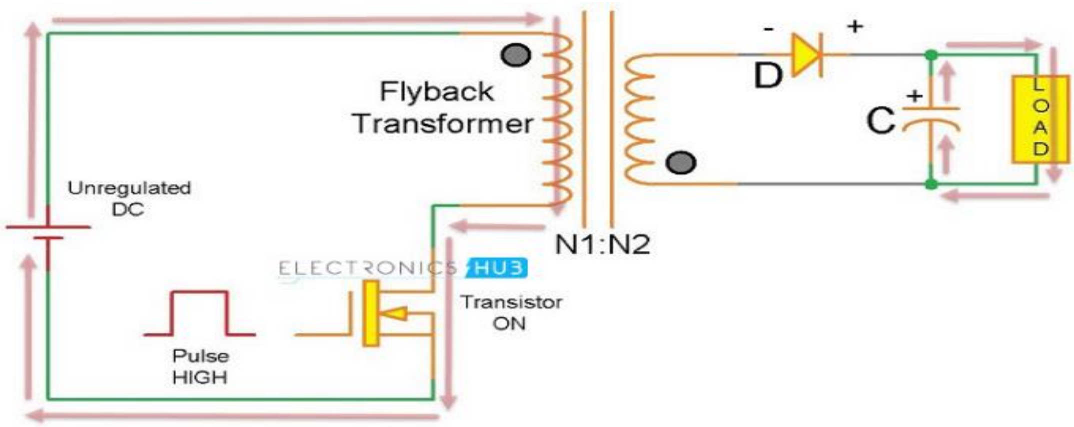


Figure 5.3 When Transistor ON

The operation of the Flyback converter in the other period i.e. Transistor OFF period is illustrated in the following image. When the pulse becomes LOW, the transistor is turned OFF and the primary of the transformer do not conduct.

The energy in the secondary of the transformer will be released into the circuit and also the polarity in the secondary is reversed i.e. it becomes positive. Hence, the diode is forward biased allowing the energy stored in the secondary coil acting as the source. It recharges the capacitor and also supplies the current to load.

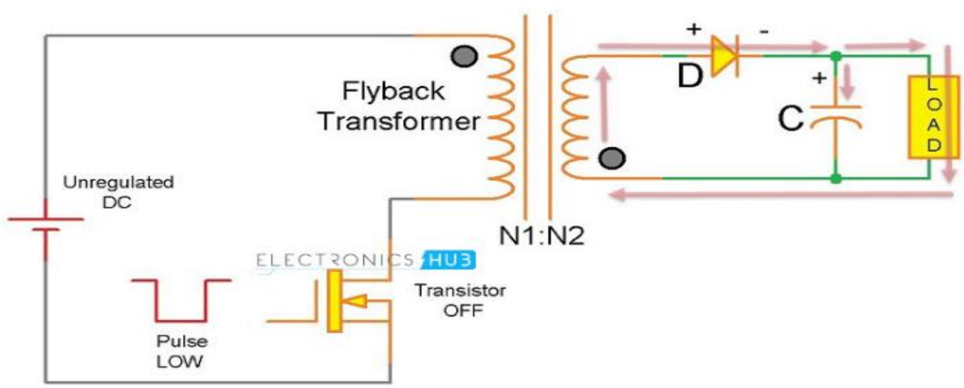


Figure 5.4 When Transistor OFF

The output voltage in Flyback Converter can be higher or lower than the input voltage and is dependent on the turns ratio of the primary and secondary of the transformer.

Push Pull SMPS

A push–pull converter is a type of DC-to-DC converter, a switching converter that uses a transformer to change the voltage of a DC power supply. The distinguishing feature of a push-pull converter is that the transformer primary is supplied with current from the input line by pairs of transistors in a symmetrical push-pull circuit. The transistors are alternately switched on and off, periodically reversing the current in the transformer. Therefore, current is drawn from the line during both halves of the switching cycle. This contrasts with buck-boost converters, in which the input current is supplied by a single transistor which is switched on and off, so current is only drawn from the line during half the switching cycle. During the other half the output power is supplied by energy stored in inductors or capacitors in the power supply. Push–pull converters have steadier input current, create less noise on the input line, and are more efficient in higher power applications.

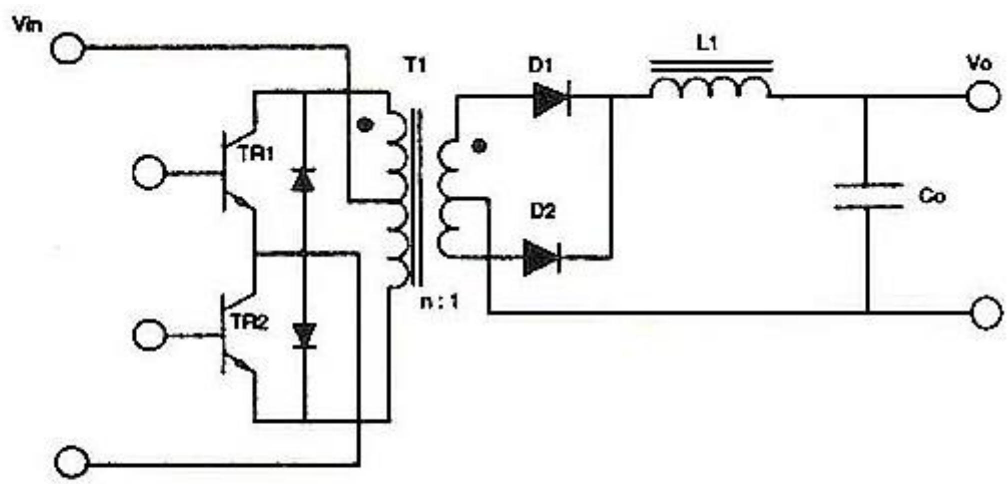


Figure 5.5 Push Pull SMPS

The term push–pull is sometimes used to generally refer to any converter with bidirectional excitation of the transformer. For example, in a full-bridge converter, the switches (connected as an H-bridge) alternate the voltage across the supply side of the transformer, causing the transformer to function as it would for AC power and produce a voltage on its output side. However, push–pull more commonly refers to a two-switch topology with a split primary winding. In any case, the output is then rectified and sent to the load. Capacitors are often included at the output to filter the switching noise. In practice, it is necessary to allow a small interval between powering the transformer one way and powering it the other: the “switches” are usually pairs of transistors (or similar devices), and were the two transistors in the pair to switch simultaneously there would be a risk of shorting out the power supply. Hence, a small wait is needed to avoid this problem. This wait time is called "Dead Time" and is necessary to avoid transistor shoot-through.

Uninterruptable Power Supply (UPS)

An uninterruptible power supply or uninterruptible power source (UPS) is an electrical apparatus that provides emergency power to a load when the input power source or mains power fails. A UPS differs from an auxiliary or emergency power system or standby generator in that it will provide near-instantaneous protection from input power interruptions, by supplying energy stored in batteries, supercapacitors, or flywheels. The on-battery run-time of most uninterruptible power sources is relatively short (only a few minutes) but sufficient to start a standby power source or properly shut down the protected equipment. It is a type of continual power system.

A UPS is typically used to protect hardware such as computers, data centers, telecommunication equipment or other electrical equipment where an unexpected power disruption could cause injuries, fatalities, serious business disruption or data loss. UPS units range in size from units designed to protect a single computer without a video monitor (around 200 volt-ampere rating) to large units powering entire data centers or buildings. The world's largest UPS, the 46-megawatt Battery Electric Storage System (BESS), in Fairbanks, Alaska, powers the entire city and nearby rural communities during outages.

The offline/standby UPS offers only the most basic features, providing surge protection and battery backup. The protected equipment is normally connected directly to incoming utility power. When the incoming voltage falls below or rises above a predetermined level the SPS turns on its internal DC-AC inverter circuitry, which is powered from an internal storage battery. The UPS then mechanically switches the connected equipment on to its DC-AC inverter output.

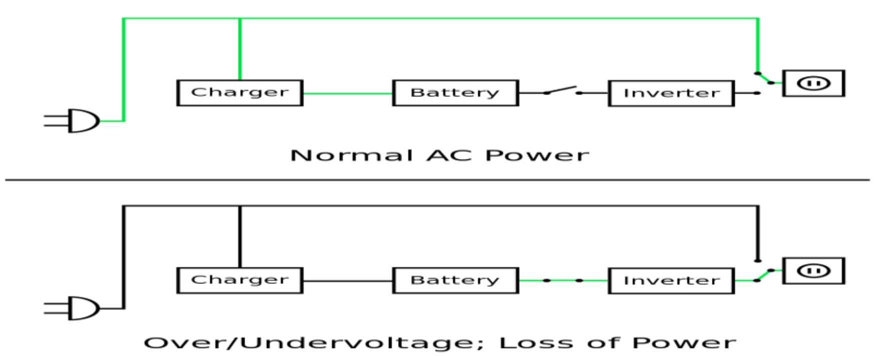


Figure 5.6 Redundant UPS and Non – Redundant ups

The switch-over time can be as long as 25 milliseconds depending on the amount of time it takes the standby UPS to detect the lost utility voltage. The UPS will be designed to power certain equipment, such as a personal computer, without any objectionable dip or brownout to that device.

In an online UPS, the batteries are always connected to the inverter, so that no power transfer switches are necessary. When power loss occurs, the rectifier simply drops out of the circuit and the batteries keep the power steady and unchanged. When power is restored, the rectifier resumes carrying most of the load and begins charging the batteries, though the charging current may be limited to prevent the high-power rectifier from overheating the batteries and boiling off the electrolyte. The main advantage of an on-line UPS is its ability to provide an "electrical firewall" between the incoming utility power and sensitive electronic equipment.

The online UPS is ideal for environments where electrical isolation is necessary or for equipment that is very sensitive to power fluctuations. Although it was at one time reserved for very large installations of 10 kW or more, advances in technology have now permitted it to be available as a common consumer device, supplying 500 W or less. The online UPS may be necessary when the power environment is "noisy", when utility power sags, outages and other anomalies are frequent, when protection of sensitive IT equipment loads is required, or when operation from an extended-run backup generator is necessary.

The basic technology of the online UPS is the same as in a standby or line-interactive UPS. However it typically costs much more, due to it having a much greater current AC-to-DC battery-charger/rectifier, and with the rectifier and inverter designed to run continuously with improved cooling systems. It is called a double-conversion UPS due to the rectifier directly driving the inverter, even when powered from normal AC current.

Applications

UPS systems are used when it is desirable that a loss of commercial (or primary) power will have minimal effect on the priority loads. The usual applications include communication systems, machine control systems, medical equipment systems, computer systems, emergency lighting and egress equipment, fire alarms.

High Voltage Direct Current (HVVDC) Transmission systems

AC power is generated in the generating station. This should first be converted into DC. The conversion is done with the help of rectifier. The DC power will flow through the overhead lines. At the user end, this DC has to be converted into AC. For that purpose, an inverter is placed at the receiving end. Thus, there will be a rectifier terminal in one end of HVDC substation and an inverter terminal in the other end. The power of the sending end and user end will be always equal (Input Power = Output Power).

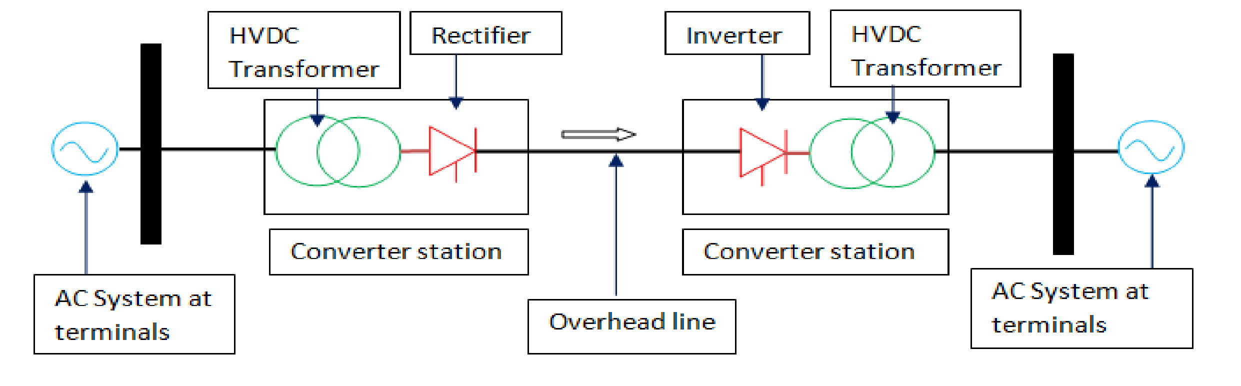


Figure 5.7 HVDC Layout

When there are two converter stations at both ends and a single transmission line is termed as two terminal DC systems. When there are two or more converter stations and DC transmission lines is termed as multi-terminal DC substation.

The components of the **HVDC Transmission** system and its function are explained below. Converters: The AC to DC and DC to AC conversion are done by the converters. It includes transformers and valve bridges.

Smoothing Reactors: Each pole consist of smoothing reactors which are of inductors connected in series with the pole. It is used to avoid commutation failures occurring in inverters, reduces harmonics and avoids discontinuation of current for loads.

Electrodes: They are actually conductors which are used to connect the system to the earth.

Harmonic Filters: It is used to minimize the harmonics in voltage and current of the converters used.

DC Lines: It can be cables or overhead lines.

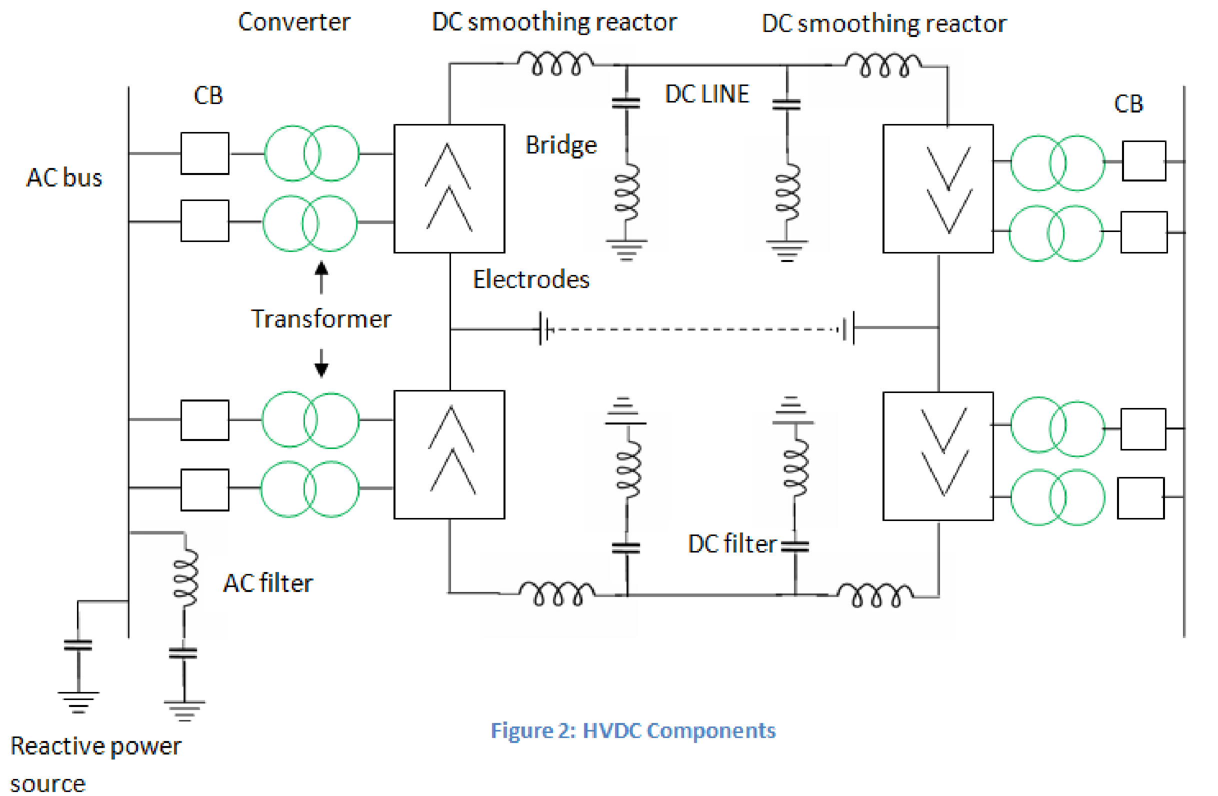


Figure. 5.8. HVDC COMPONENTS

Reactive Power Supplies: The reactive power used by the converters could be more than 50% of the total transferred active power. So the shunt capacitors provide this reactive power.

AC Circuit Breakers: The fault in the transformer is cleared by the circuit breakers. It also used to disconnect the DC link.

HVDC System Configurations

The classification of HVDC links are as follows:

Mono Polar Links

Single conductor is required and water or ground act as the return path. If the earth resistivity is high, metallic return is used.

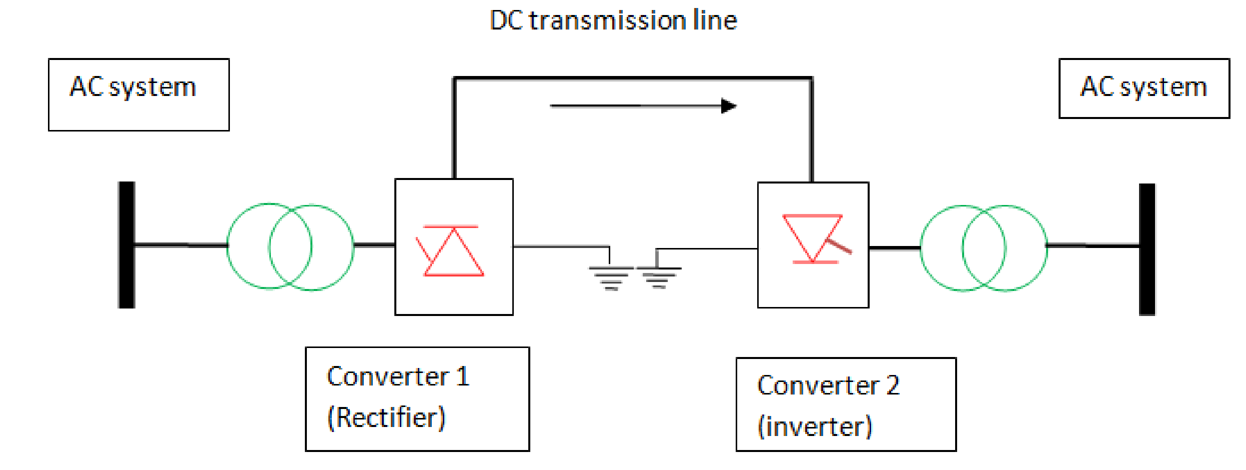


Figure 5.9. Mono polar link

Bipolar Links

Double converters of same voltage rating are used in each terminal. The converter junctions are grounded.

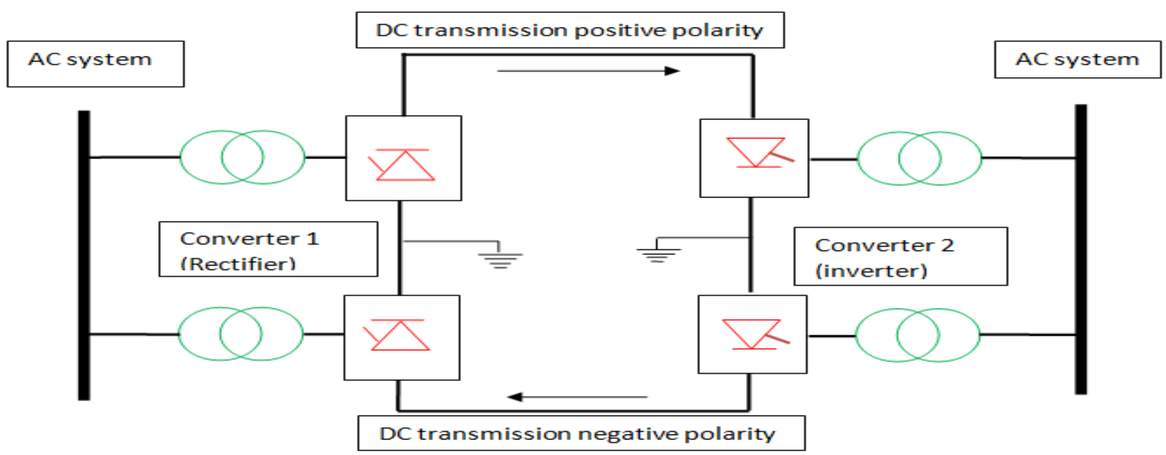


Figure 5.10. Bipolar link

Homo Polar Links

It consists of more than two conductors which is having equal polarity generally negative. Ground is the return path.

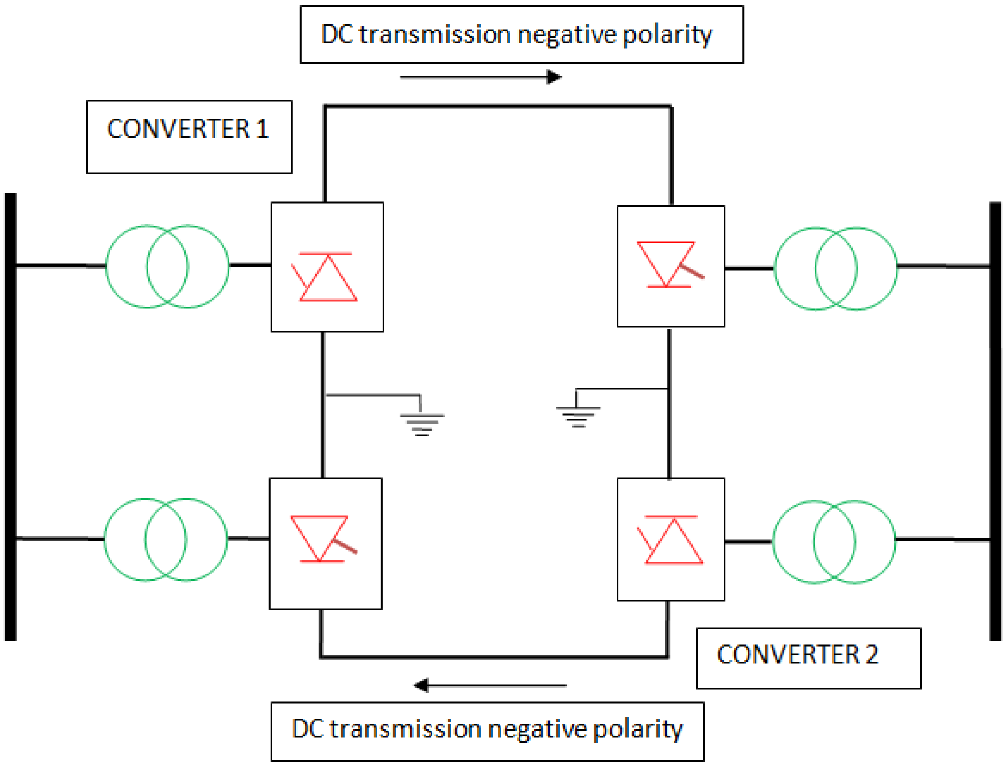


Figure 5.11. Homo ploar link

Comparison of both HVAC and HVDC Transmission System

HVDC Transmission System	HVAC Transmission System
Low losses.	Losses are high due to the skin effect and corona discharge
Better Voltage regulation and Control ability.	Voltage regulation and Control ability is low.
Transmit more power over a longer distance.	Transmit less power compared to a HVDC system.
Less insulation is needed.	More insulation is required.
Reliability is high.	Low Reliability.
Asynchronous interconnection is possible.	Asynchronous interconnection is not possible.
Reduced line cost due to fewer conductors.	Line cost is high.
Towers are cheaper, simple and narrow.	Towers are bigger compared to HVDC.

Disadvantages of HVDC Transmission

- Converters with small overload capacity are used.
- Circuit Breakers, Converters and AC filters are expensive especially for small distance transmission.
- No transformers for altering the voltage level.
- HVDC link is extremely complicated.
- Uncontrollable power flow.

Application of HVDC Transmission

- Undersea and underground cables
- AC network interconnections
- Interconnecting Asynchronous system

DC – DC converters for Electric Vehicles

The general block diagram of Electric Vehicle (EV)is shown in figure. 5.12. It consists of charger, Battery, Power Converter, Electric motor, Shaft and Wheels.

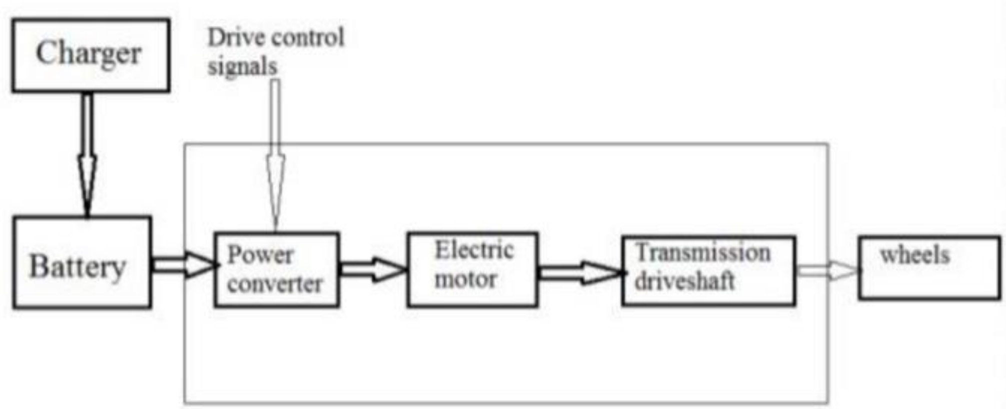


Figure 5.12 General Block diagram of EV

This section presents the advantages and disadvantages of different competitive DC-DC converter topologies suitable for BEV and PHEV powertrains. The converters are switched using power transistors and are categorized based on working principle, operation mode, power level and power flow direction. Generally, in the automotive sector the voltage level of the battery storage system is ~250–360 V and the voltage level of SC is ~150–400 V, which are lower than the required voltage of ~400–750 V for the load (EM) [51]. Therefore, step up HV DC-DC converter topologies are used in BEV and PHEV powertrains and the topologies reviewed in this section are step-up converters.

Boost DC-DC Converter

The fig.5.13. shows that the Boost DC-DC Converter (BC). The boost DC-DC converter is a power converter that steps-up the input voltage while stepping down the input current. It is a class of switched-mode power supply (SMPS) having at least one energy storage element (a capacitor, an inductor, or the two in combination) and at least two semiconductors (a diode and a switch). In BC, a series connected inductor with the input DC source helps to reduce input current ripples and a capacitor-based filter is used at the output side to eliminate the output voltage ripples. Boost DC-DC converters have various advantages. A moderate output voltage gain can be obtained (4%) the switch can be easily driven concerning ground, the input current is continuous and filtering and meeting EMI requirements are simple for this converter. From the design a moderate efficiency can be achieved (83~85% at full load). The output voltage is single polarity and circuitry is rather simple, thus the cost is lower, which makes it a suitable option for BEV and PHEV powertrain.

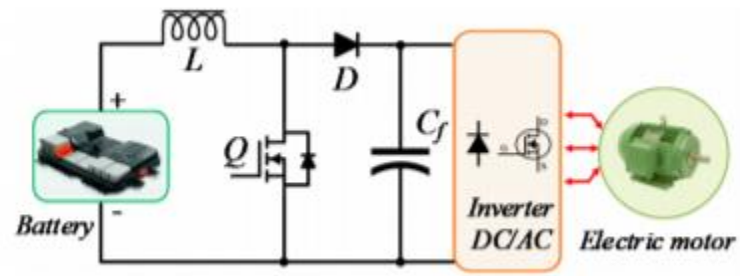


Figure 5.13 DC-DC Boost converter

The boost DC-DC converter also has some drawbacks. As the requirement of a large capacitor to reduce the ripple at the output voltage, which makes the volume quite large and weight moderately heavy, high voltage gain (>4%) is not suitable for this converter, parallel arrangement of the power-switching devices are required to handle high-power and it requires extra stages to make it short-circuit proof

Interleaved 4-Phase boost DC-DC converter

The Interleaved 4-Phase boost DC-DC converter (IBC) topology allows minimizing the input current ripples and output voltage ripples; it steps up voltage ratio approximately above four times. In this converter, four identical levels are introduced with four inductances (L1, L2, L3, and L4); all these inductors have a separate magnetic core as shown in Figure 5.14. Successive phase shifting of the power switching devices is fixed by the ratio of switching period (T) and the number of Phases (N). Each of the step-up converter levels shares the equal amount of current which is delivered by the electric source, and T/N ratio is present as the period ripple content. Thus, the interleaving technique allows the input inductor size and output capacitor size to be reduced. The frequency of the input current ripples is N times higher than the switching frequency

f_{sw} because the control signals are interleaved and have a phase angle of 360◦/N. As a result, input current ripple and output voltage ripples lessen which is the best reason to choose this converter topology for BEV and PHEV powertrains. In IBC has an efficiency of 92% at 30 kW load. Around an 8% drop in the efficiency is caused by alternating from discontinuous current mode (DCM) to continuous current mode (CCM). This converter is sensitive to duty cycle ratio change. Moreover, magnetic core influence due to load change is notable and the component count is also high.

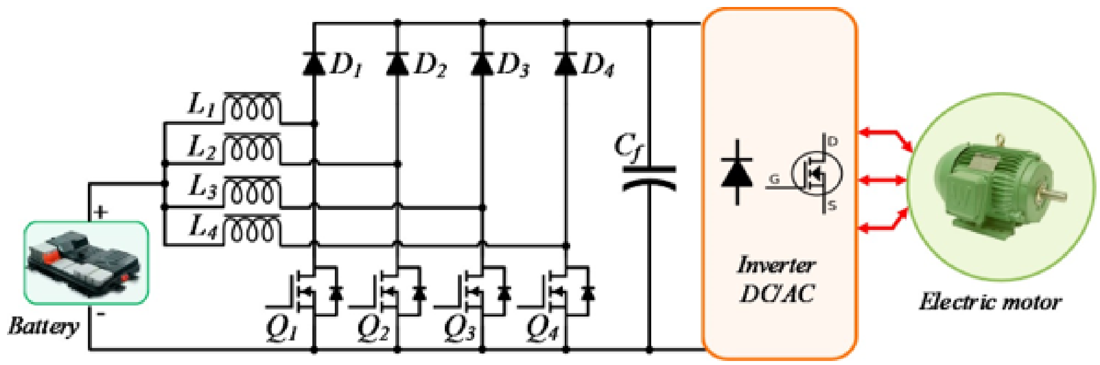


Figure 5.14 Interleaved 4-Phase boost DC-DC converter

<u>Full Bridge Boost DC-DC Converter (FBC)</u>

This converter has three functional stages, namely the inverter (conversion from DC to AC), followed by a high-frequency transformer (HFT) (step up the AC voltage), and followed by a rectifier (conversion the AC back to DC). Utilization of the negative portion of the hysteresis loop reduces the core saturation as the current flows in the opposite direction during alternate half cycles, thus making the flux in the core swing from negative to positive. The duty cycle of the PWM signal can be increased or decreased promptly so that the output voltage is held constant even with a varying input source voltage. However, the duty ratio needs to be kept above 50% to protect semiconductor switches. Hence, identical control signals are used in two legs, which alternate with half period duration. As an HFT is used, a high step-up voltage is possible. Moreover, it provides galvanic isolation between the input side and the load side. At 30 kW load, the efficiency of the converter is approximately 91.5% [49]. A current fed FBC is shown in Figure 5.15.

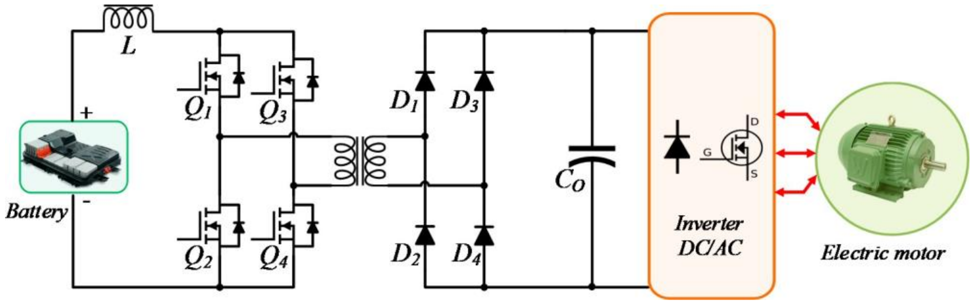


Figure 5.15. Full-bridge Boost DC-DC Converter.

By using the ZVS technique and phase shifted pulse width modulation (PWM) control, the efficiency can be increased even further. As this is a current fed topology, EMI filter suppression is needed to meet the IEEE regulations standard-519. Although this converter has moderately high efficiency, the effect of the HFT leakage inductance is crucial because of the high electrical stress in the switching circuit. Thus, a clamping circuit (passive/active) is required to resolve the peak voltage issue in the switching circuit.

Inverters for standalone photovoltaic systems

A stand-alone power system (SAPS or SPS), also known as remote area power supply (RAPS), is an off-the-grid electricity system for locations that are not fitted with an electricity distribution system. Typical SAPS include one or more methods of electricity generation, energy storage, and regulation.

Electricity is typically generated by one or more of the following methods:

- Photovoltaic system using solar panels
- Wind turbine
- Geothermal source
- Micro combined heat and power
- Micro hydro
- Diesel or biofuel generator
- Thermoelectric generator (TEGs)

Storage is typically implemented as a battery bank, but other solutions exist including fuel cells. Power drawn directly from the battery will be direct current extra low voltage (DC ELV), and this is used especially for lighting as well as for DC appliances. An inverter is used to generate AC low voltage, which more typical appliances can be used.

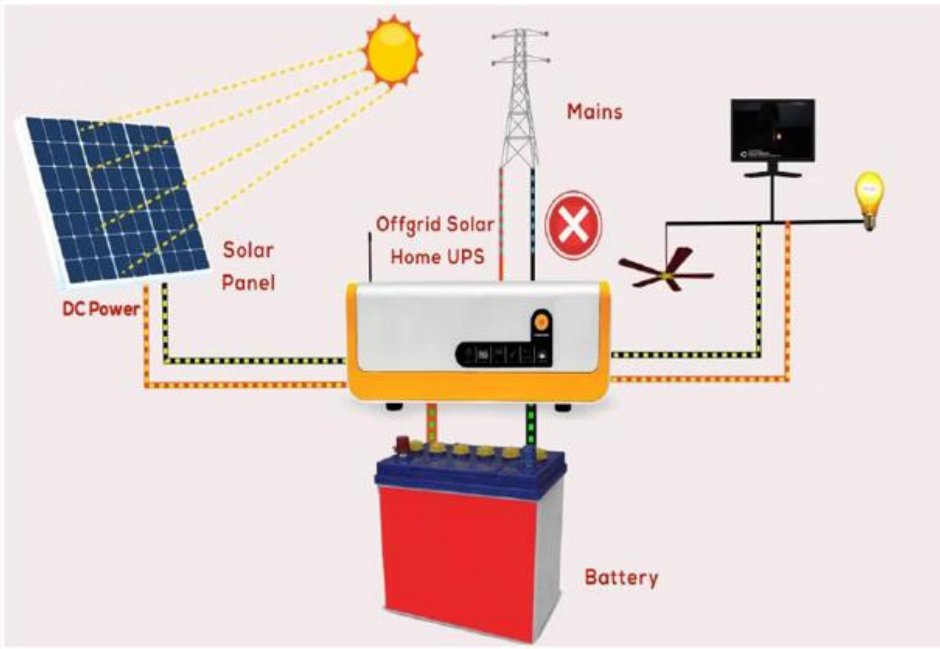


Figure 5.16 Standalone photovoltaic systems

A typical stand-alone solar PV system is shown in figure. 5.16. Stand-alone photovoltaic power systems are independent of the utility grid and may use solar panels only or may be used in conjunction with a diesel generator, a wind turbine or batteries. A photovoltaic system employs solar modules, each comprising a number of solar cells, which generate electrical power. PV installations may be ground-mounted, rooftop mounted, wall mounted or floating. The mount may be fixed or use a solar tracker to follow the sun across the sky.

Inverters convert power from DC to AC while rectifiers con- vert it from AC to DC. Many inverters are bi directional, i.e. they are able to operate in both inverting and rectifying modes. In many stand-alone PV installations, alternating current is needed to operate 230 V (or 110 V), 50 Hz (or 60 Hz) appliances. Generally stand-alone inverters operate at 12, 24, 48, 96, 120, or 240 V DC depending upon the power level. Ideally, an inverter for a stand-alone PV system should have the following features:

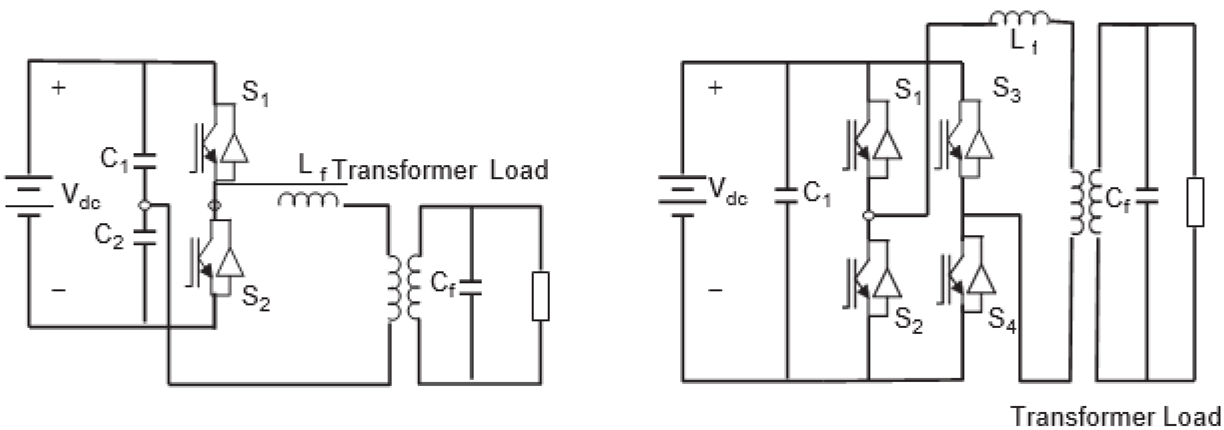
- Sinusoidal output voltage.
- Voltage and frequency within the allowable limits.
- Cable to handle large variation in input voltage.
- Output voltage regulation.

- High efficiency at light loads.
- Less harmonic generation by the inverter to avoid damage to electronic appliances like television, additional losses, and heating of appliances.
- Photovoltaic inverters must be able to withstand over- loading for short term to take care of higher starting currents from pumps, refrigerators, etc.
- Adequate protection arrangement for over/under-voltage and frequency, short circuit etc.
- Surge capacity.
- Low idling and no load losses.
- Low battery voltage disconnect.
- Low audio and radio frequency (RF) noise.

Several different semiconductor devices such as metal oxide semiconductor field effect transistor (MOSFETs) and insulated gate bipolar transistors (IGBTs) are used in the power stage of inverters. Typically MOSFETs are used in units up to 5 kVA and 96 V DC. They have the advantage of low switching losses at higher frequencies. Because the on-state voltage drop is 2 V DC, IGBTs are generally used only above 96 V DC systems. Voltage source inverters are usually used in stand-alone applications. They can be single phase or three phase. There are three switching techniques commonly used: square wave, quasi-square wave, and pulse width modulation. Square-wave or modified square-wave inverters can supply power tools, resistive heaters, or incandescent lights, which do not require a high quality sine wave for reliable and efficient operation. However, many household appliances require low distortion sinusoidal waveforms. The use of true sine-wave inverters is recommended for remote area power systems. Pulse width modulated (PWM) switching is generally used for obtaining sinusoidal output from the inverters.

A general layout of a single-phase system, both half bridge and full bridge, is shown in Fig. 27.18. In Fig. 27.18a, single- phase half bridge is with two switches, S_1 and S_2, the capacitors C_1 and C_2 are connected in series across the DC source. The junction between the capacitors is at the mid-potential.

Voltage across each capacitor is $V_{dc}/2$. Switches S_1 and S_2 can be switched on/off periodically to produce AC voltage. Filter (L_f and C_f) is used to reduce high-switch frequency components and to produce sinusoidal output from the inverter. The output of inverter is connected to load through a transformer. Figure 27.18b shows the similar arrangement for full-bridge configuration with four switches. For the same input source voltage, the full-bridge output is twice and the switches carry less current for the same load power. The power circuit of a three phase four-wire inverter is shown in Fig. 27.19. The output of the inverter is connected to load via three-phase transformer (delta/Y). The star point of the transformer secondary gives the neutral connection. Three phase or single phase can be connected to this system. Alter- natively, a center tap DC source can be used to supply the converter and the mid-point can be used as the neutral.



(a) (b)

Figure 5.17 Single-phase inverter: (a) half bridge and (b) full bridge.

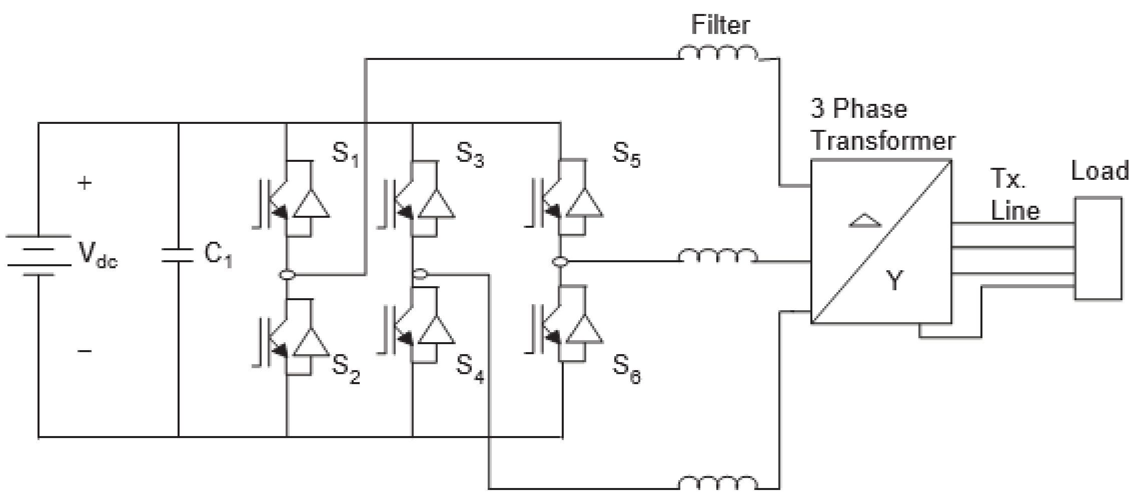


Figure 5.18 A stand-alone three-phase four wire inverter

References

1. Frede Blaabjerg, Tomislav Dragičević and Pooya Davari,”Application of Power Electronics” Special issue published online electronics 2019.
2. Muhammad H Rashid,”Power Electronics Handbook” Academic Press,2007.
3. Sajib Chakraborty,”DC-DC converter topologies for Electric Vehicle” MDPI, 2019.

Question Bank

UNIT-5 Applications			
	Part A	**CO**	**L**
1.	Illustrate the applications of SMPS.	CO5	L2
2.	Classify the types of UPS?	CO5	L2
3.	Outline the applications of UPS?	CO5	L2
4.	Justify why the semiconductor devices are used in UPS.	CO5	L2
5.	Classify out the advantages of HVDC transmission systems.	CO5	L2
6.	Outline applications of Power semiconductor device in HVDC system	CO5	L2
7.	Justify why HVDC systems are preferred for transmitting large power over long distances.	CO5	L4
8.	Outline How the power circuit is differs from control circuit.	CO5	L2
9.	Summarize the advantages of speed control methods for dc motors.	CO5	L2
10.	Justify why PV systems preferred over other renewable sources	CO5	L2
11.	Classify the types of SMPS.		
	PART-B	**CO**	**L**
1.	Explain with suitable circuit diagram the operation of SMPS. What makes it superior to a power supply with regulating transistor.	CO5	L5
2.	List out the specifications of UPS? Construct the detailed block diagram of the two types of UPS and explain their operation	CO5	L5
3.	Analyze with neat circuit diagram the operation of Redundant type UPS.	CO5	L4
4.	Explain with circuit diagram the different types of HVDC systems.	CO5	L5
5.	Analyze the speed control of DC motors using 2 quadrant DC chopper.	CO5	L4
6.	Explain with circuit diagram the operation of 4 quadrant DC drive.	CO5	L5
7.	Analyze in detail about stand alone PV system with nessary diagram.	CO5	L4
8.	Explain in details about Grid connected PV system with nessary diagram.	CO5	L5