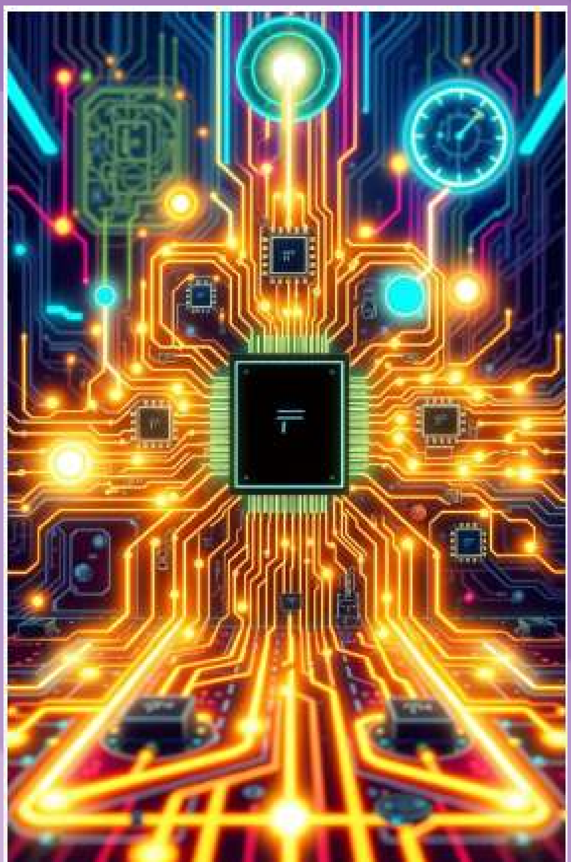
POWER ELECTRONIC BASICS



PREFACE

Ananda Chaitanya Foundation, founded by Shri.Thillai Senthil Prabu, is committed to enhancing the well-being of individuals and communities through a range of transformative initiatives. These projects span education, skill development, spiritual growth, and healthcare, creating a holistic approach to societal upliftment.

"VAIYA THALAMAI KOL" - Ananda Chaitanya Training Academy (ACTA) is a Skill Development and Soft Skills Training initiative of Ananda Chaitanya Foundation that focuses on providing technical training and soft skills development.

Under the guidance of Shri. Thillai Senthil Prabu this book is compiled by Ananda Chaitanya Foundation's ACTA team members Shri. Devendra Kumar.M and Shri.Rajamurugan.K .

This handbook on Power Electronic basics is useful for the Students and working professionals to advance their careers and strengthen their foundational understanding of power electronics.

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UNIT – I
POWER SEMICONDUCTOR DEVICES

1.1 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 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.

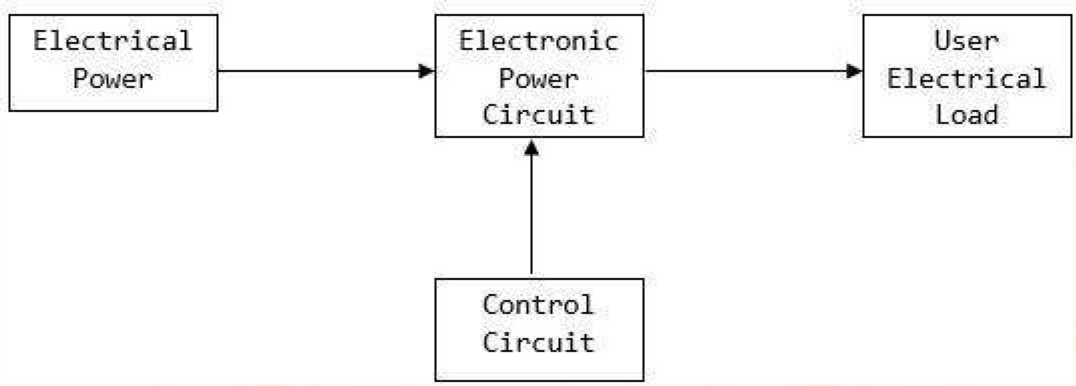


Figure: 1.1. Block diagram of DC power supply

1.2 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.

1.3 POWER SEMICONDUCTOR DEVICES

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

Thyristors are a family of p-n-p-n structured power semiconductor switching devices

1.4 POWER DIODES

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.

1.5 POWER TRANSISTORS

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

- Bipolar junction transistors (BJTs)
- Metal-oxide semiconductor filed-effect transistors (MOSFETs)
- Static Induction transistors (SITs)
- Insulated-gate bipolar transistors(IGBTs)

ADVANTAGES OF BJT'S

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

DEMERITS OF BJT

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

1.6 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 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.

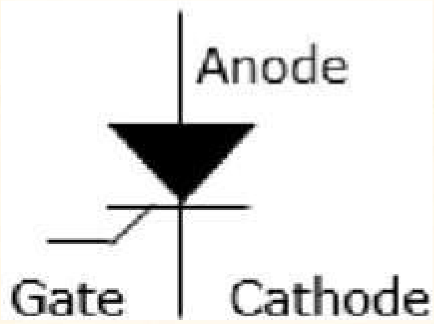


Figure: 1.4. Symbol of thyristor

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

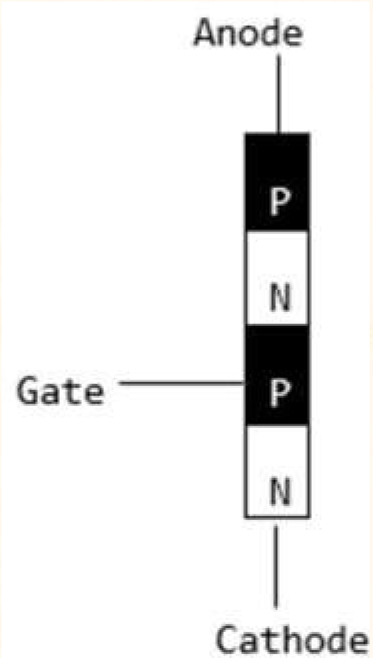


Figure: 1.5. Structure of thyristor

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.

1.7 MODES OF OPERATION IN SCR

1. 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.
2. 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.

1. 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.

1.8 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,

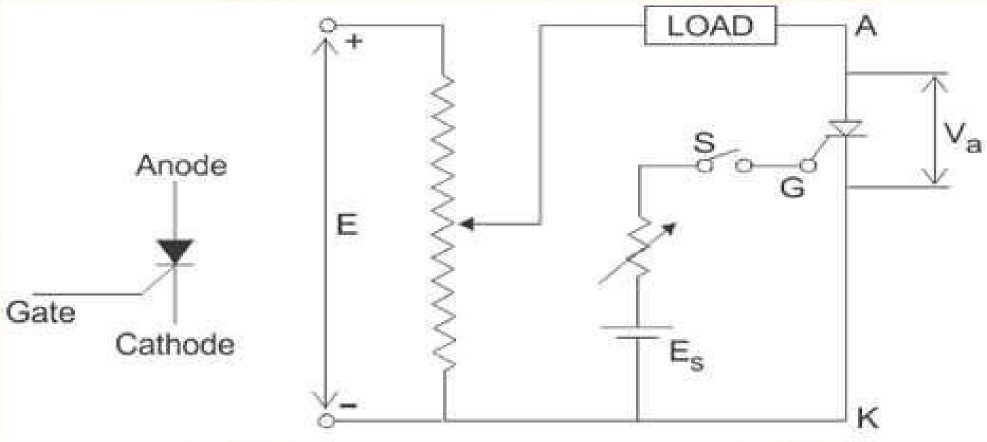


Figure: 1.6. Circuit diagram for characteristics of SCR

From the circuit diagram above we can see the anode and cathode are connected to the supply voltage through the load. Another secondary supply Es 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 Va and anode current Ia 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

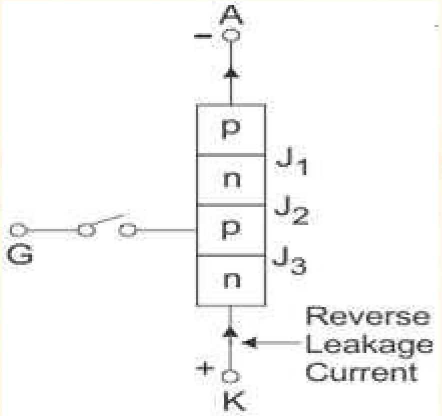


Figure: 1.7. Reverse blocking mode of SCR

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 Es 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.

Here Junctions J1 and J3 are reverse biased whereas the junction J2 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 VBR, an avalanche occurs at J1 and J3 and the reverse current increases rapidly. A large current associated with VBR 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 VBR. When reverse voltage applied across a thyristor is less than VBR, the device offers very high impedance in the reverse direction. The SCR in the reverse blocking mode may therefore be treated as open circuit.

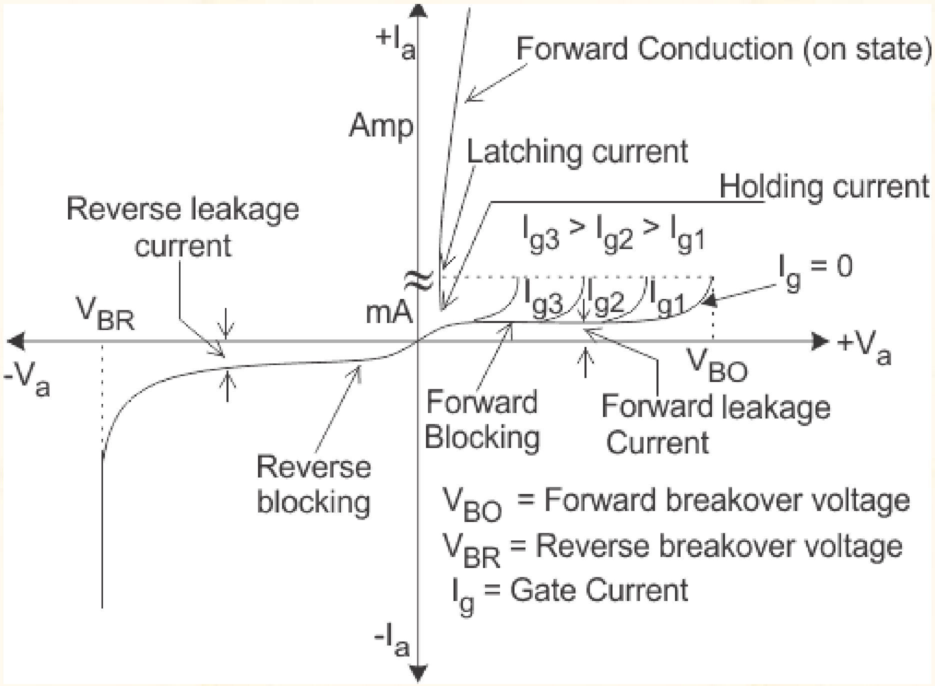


Figure: 1.8. V- I characteristics of SCR

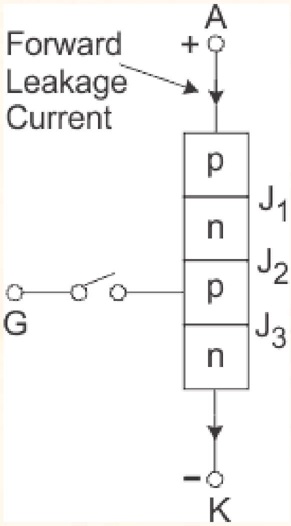


Figure: 1.9. Forward connection of SCR

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.

Forward Blocking Mode

As we can see the junctions J1 and J3 are now forward biased but junction J2 goes 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 J2 will have an avalanche breakdown at a voltage called forward break over voltage VB0 of the thyristor. But, if we keep the forward voltage less than VBO, 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 J2 will have an avalanche breakdown at forward break over voltage VBO 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. In this mode of operation, the thyristor conducts maximum current with minimum voltage drop, this is known as the forward conduction forward conduction or the turn on mode of the thyristor.

1.9 SERIES AND PARALLEL CONNECTIONS OF SCRS

In many power control applications the required voltage and current ratings exceed the voltage and current that can be provided by a single SCR. Under such situations the SCRs are required to be connected in series or in parallel to meet the requirements. Sometimes even if the required rating is available, multiple connections are employed for reasons of economy and easy availability of SCRs of lower ratings. Like any other electrical equipment, characteristics/properties of two SCRs of same make and ratings are never same and this leads to certain problems in the circuit. The mismatching of SCRs is due to differences in

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

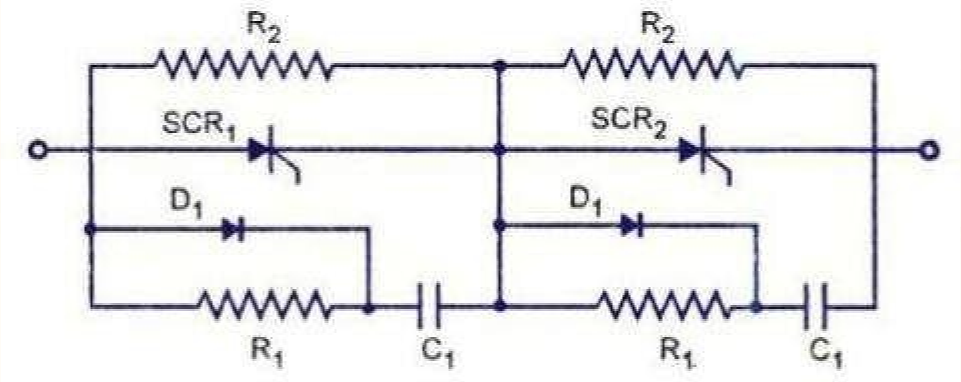


Figure: 1. 27. Series connection of SCRs

(i) Series Connection of an SCR

1. Unequal distribution of voltage across SCRs
2. Difference in recovery characteristics.

Care must be taken to share the voltage equally. For steady-state conditions, voltage sharing is achieved by using a resistance or a Zener diode in parallel with each SCR. For transient voltage sharing a low non-inductive resistor and capacitor in series are placed across each SCR, as shown in figure. Diodes D1 connected in parallel with resistor Rl, helps in dynamic stabilization. This circuit reduces differences between blocking voltages of the two devices within permissible limits. Additionally the R-C circuit can also serve the function of 'snubber circuit'. Values of R1 and C1 can primarily be calculated for snubber circuit and a check can be made for equalization. If ΔQ is the difference in recovery charge of two devices arising out of different recovery current for different time and ΔV is the permissible difference in blocking voltage then

$$C1 = \Delta Q / \Delta V$$

The value of resistance Rx should be sufficient to over damp the circuit. Since the capacitor C1 can discharge through the SCR during turn-on, there can be excessive power dissipation, but the switching current from C1 is limited by the resistor R1 This resistance also serves the purpose of damping out 'ringing' which is oscillation of C1 with the circuit inductance during commutation. All the SCRs connected in series should be turned-on at the same time when signals are applied to their gates simultaneously.

String efficiency = Voi or actual current rating of the whole string

No of SCRs in string ×Voi or current rating of individual SCR

This phenomenon increases the reliability of the string, but reduces the utilization of each SCR. Thus string efficiency decreases. Reliability of string is measured by derating factor (DRF) which is given by the expression

DRF = 1- string efficiency

(ii) Parallel Connection of an SCR

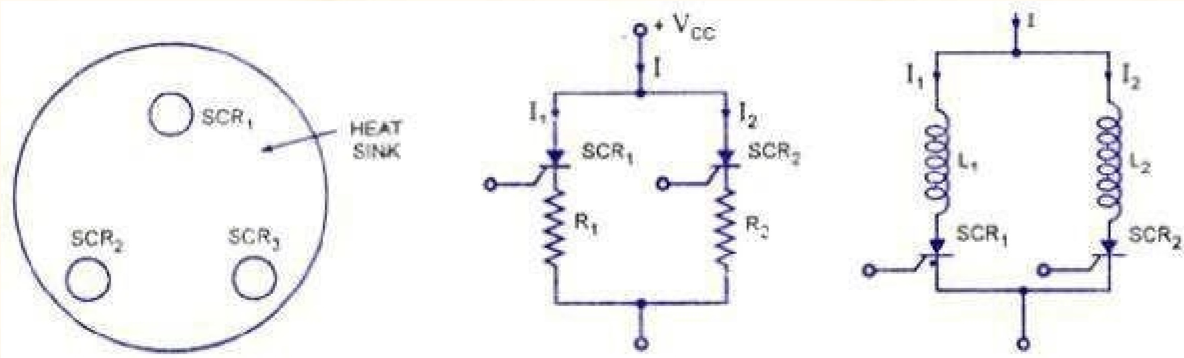


Figure: 1. 28. Parallel connection of SCRs

When the load current exceeds the SCR current rating, SCRs are connected in parallel to share the load current. But when SCRs are operated in parallel, the current sharing between them may not be proper. The device having lower dynamic resistance will tend to share more current. This will raise the temperature of that particular device in comparison to other, thereby reducing further its dynamic resistance and increasing current through it. This process is cumulative and continues till the device gets punctured. Some other factors which directly or indirectly add to this problem are difference in turn-on time, delay time, finger voltage and loop inductance.

Arrangement of SCRs in the cubicle also plays vital role. When the SCRs are connected in parallel, it must be ensured that the latching current level of the all the SCRs is such that when gate pulse is applied, all of them turn-on and remain on when the gate pulse is removed. Further the holding currents of the devices should not be so much different that at reduced load current one of the device gets turned-off because of fall of current through it blow its holding current value. This is particularly important because on increase in load current, the device which has stopped conducting cannot start in the absence of gate pulse.

Another point to be considered is the on-state voltage across the device. For equal sharing of currents by the devices voltage drop across the parallel paths must be equal. For operation of all the SCRs connected in parallel at the same temperature, it becomes necessary to use a common heat sink for their mounting, as illustrated in figure. Resistance compensation used for dc circuits is shown in figure. In this circuit the resistors Rx and R2 are chosen so as to cause equal voltage drop in both arms. Inductive compensation used for ac circuits is shown in figure The difference in characteristics due to different turn-on time, delay time, finger voltage, latching current, holding current can be minimized by using inductive compensation. Firing circuits giving high rate of rise can be used to reduce mismatch of gate characteristics and delay time. Current sharing circuits must be designed so as to distribute current equally at maximum temperature and maximum anode current. This is done to ensure that the devices share current equally under worst operating conditions. Mechanical arrangement of SCRs also plays an important role in reducing mismatching. Cylindrical construction is perhaps the best from this point of view.

Derating:

Even with all the measures taken, it is preferable to derate the device for series/parallel operation. Another reason for derating is poor cooling and heat dissipation as number of devices operates in the same branch of the circuit. Normal derating factors are 10 to 15% for parallel connection of SCRs depending upon the number of devices connected in parallel. Higher voltage safety factor is taken when SCRs are connected in series.

1.10 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. 40 to Fig. 41. It has three terminals called collector, emitter and gate.

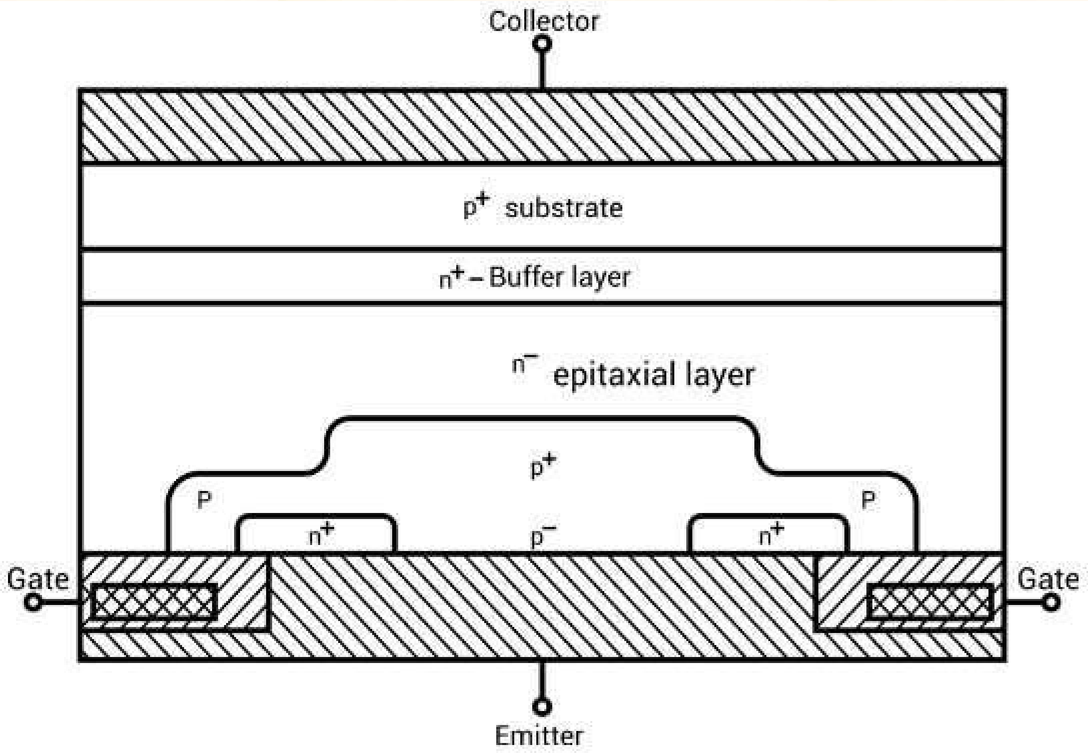


Figure: 1. 40. Cross -sectional structural diagram of IGBT

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:

1. Punch-through IGBT: Heavily doped n buffer layer ➔less switching time
2. 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)

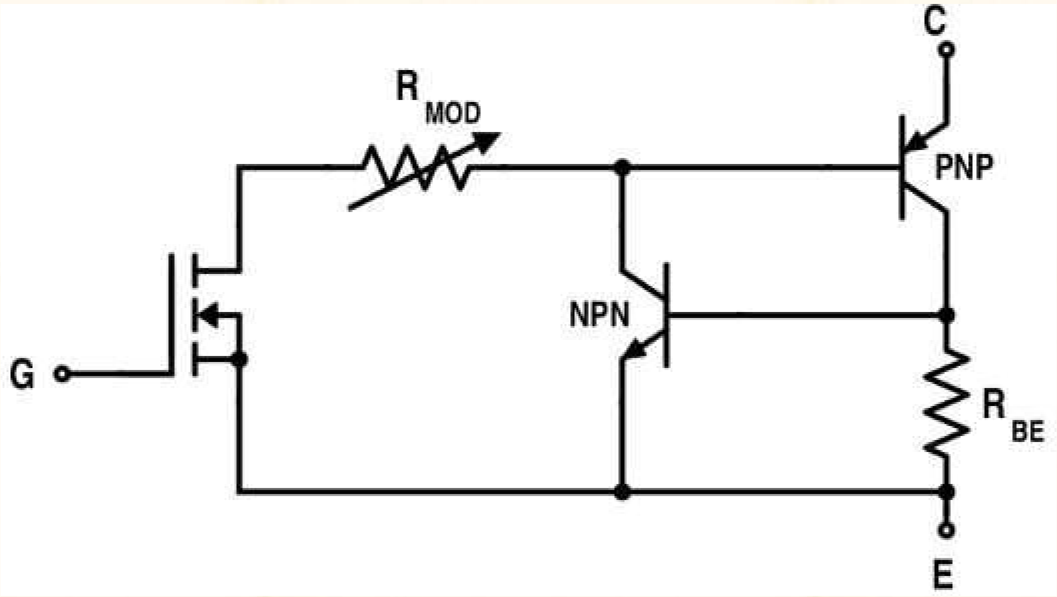


Figure: 1. 41. Equivalent diagram of IGBT

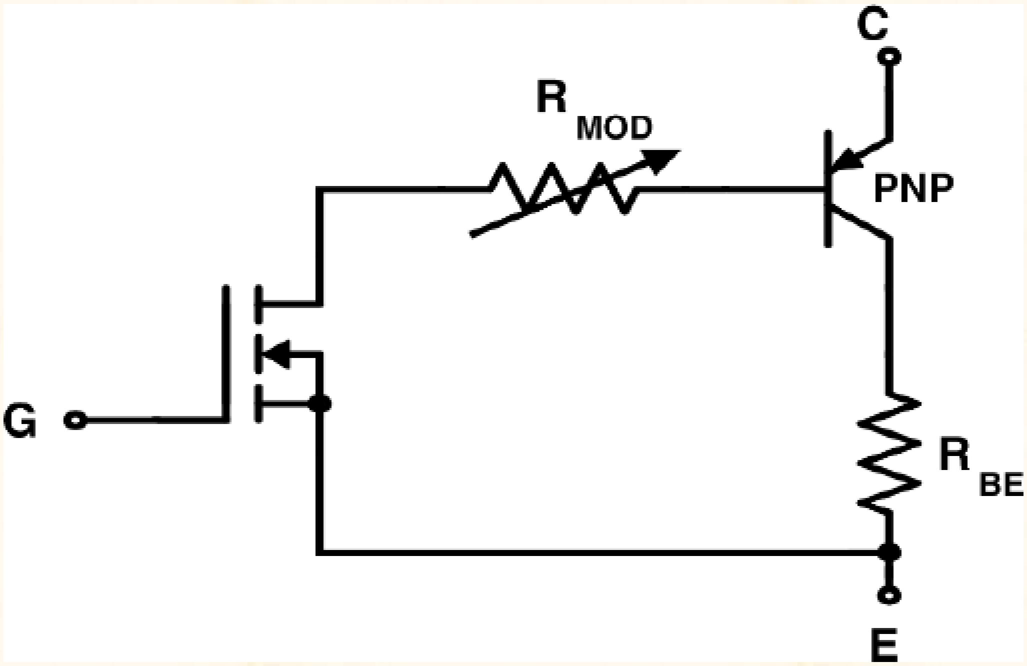


Figure: 1. 42. Simplified Equivalent diagram of IGBT

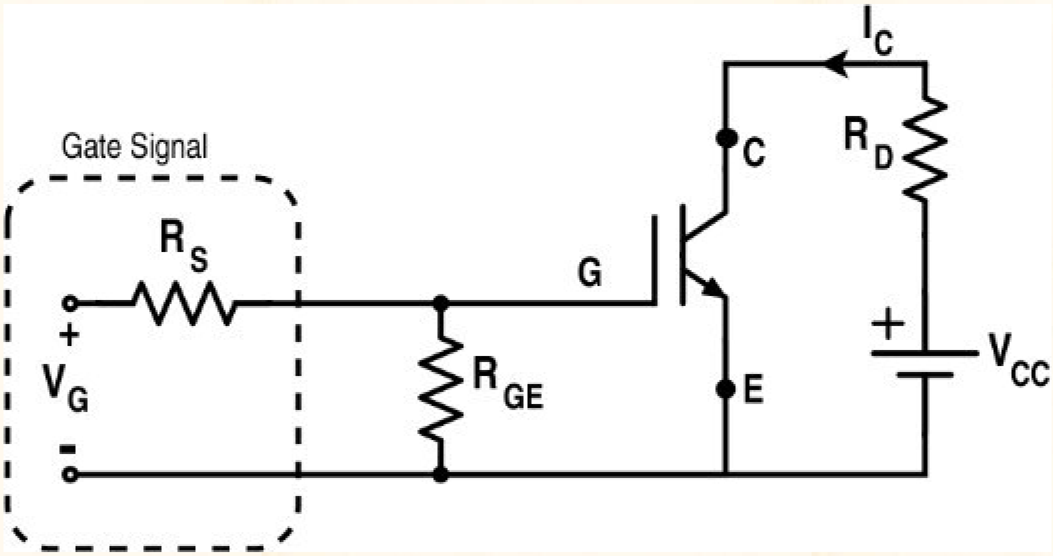


Figure: 43. Equivalent diagram of IGBT

Based on this circuit diagram given in Fig. 43, forward characteristics and transfer characteristics are obtained which are given in Fig. 44 and Fig. 45. Its switching characteristic is also shown in Fig. 45.

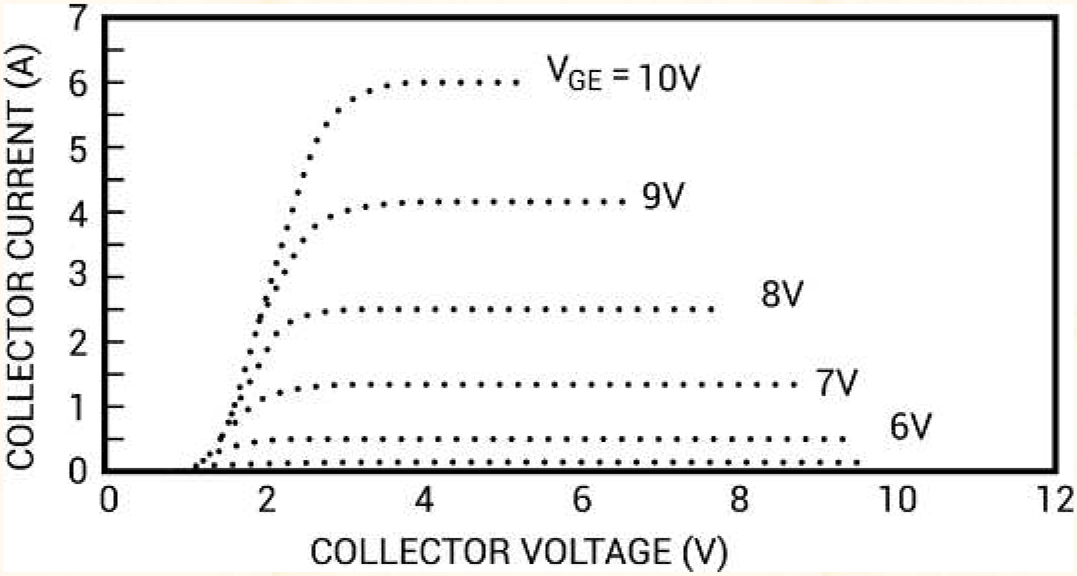


Figure: 1. 44. Forward characteristics of IGBT

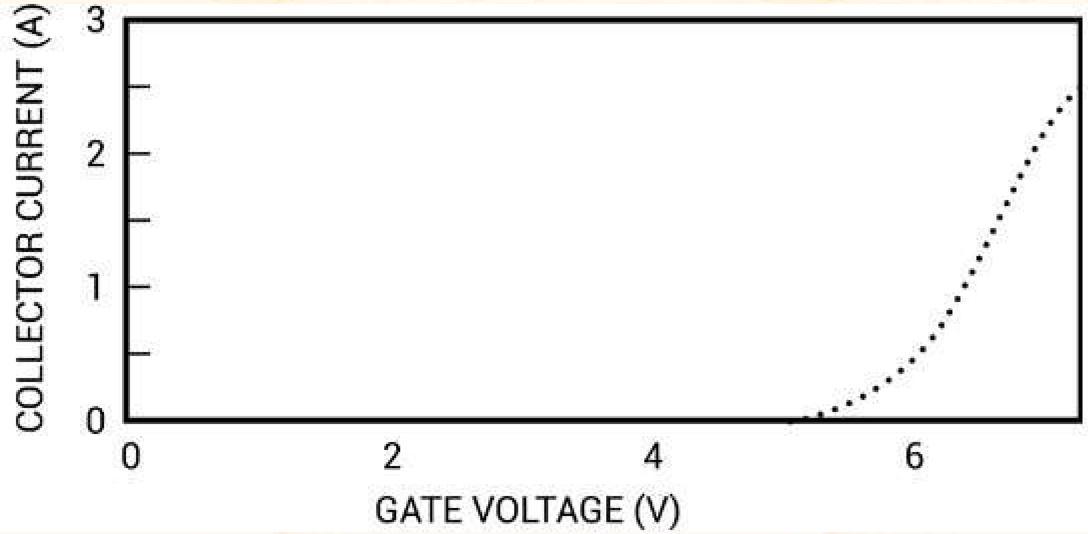


Figure: 1.45. Transfer characteristics of IGBT

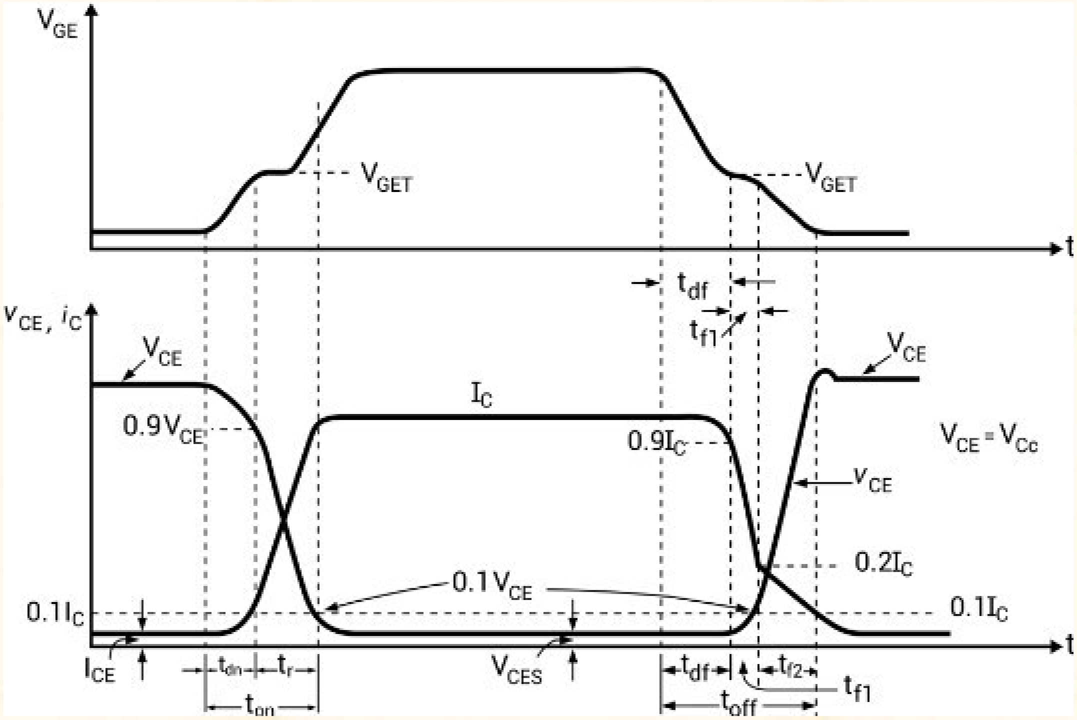


Figure: 1. 46. Dynamic characteristics of IGBT

(Note: Tdn : delay time ; Tr: rise time ; Tdf : delay time ; Tf1: initial fall time ; Tf2: final fall time)

1.11 GTO (Gate Turn-off Thyristor)

GTO can be turned on with the positive gate current pulse and turned off with the negative gate current pulse. Its capability to turn off is due to the diversion of PNP collector current by the gate and thus breaking the regenerative feedback effect.

Actually the design of GTO is made in such a way that the pnp current gain of GTO is reduced. A highly doped n spot in the anode p layer form a shorted emitter effect and ultimately decreases the current gain of GTO for lower current regeneration and also the reverse voltage blocking capability. This reduction in reverse blocking capability can be improved by diffusing gold but this reduces the carrier lifetime. Moreover, it requires a special protection.

The symbol for GTO is shown in Fig. 1.46.

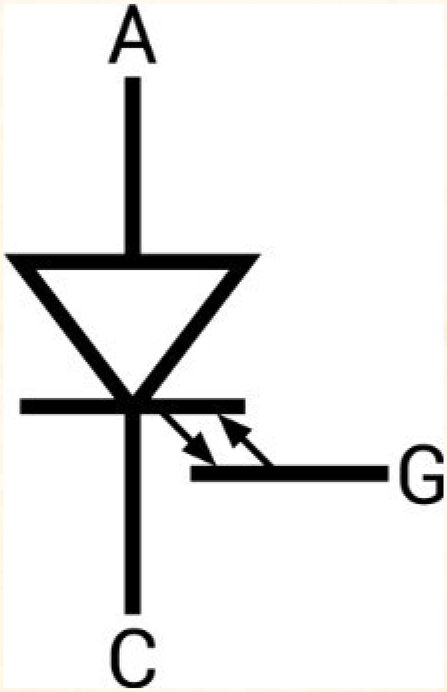


Figure: 1. 47. Symbol of GTO

Overall switching speed of GTO is faster than thyristor (SCR) but voltage drop of GTO is larger. The power range of GTO is better than BJT, IGBT or SCR.

The static voltage current characteristics of GTO are similar to SCR except that the latching current of GTO is larger (about 2 A) as compared to SCR (around 100-500 mA).

The gate drive circuitry with switching characteristics is given in Fig. 1.48 and Fig. 1.49.

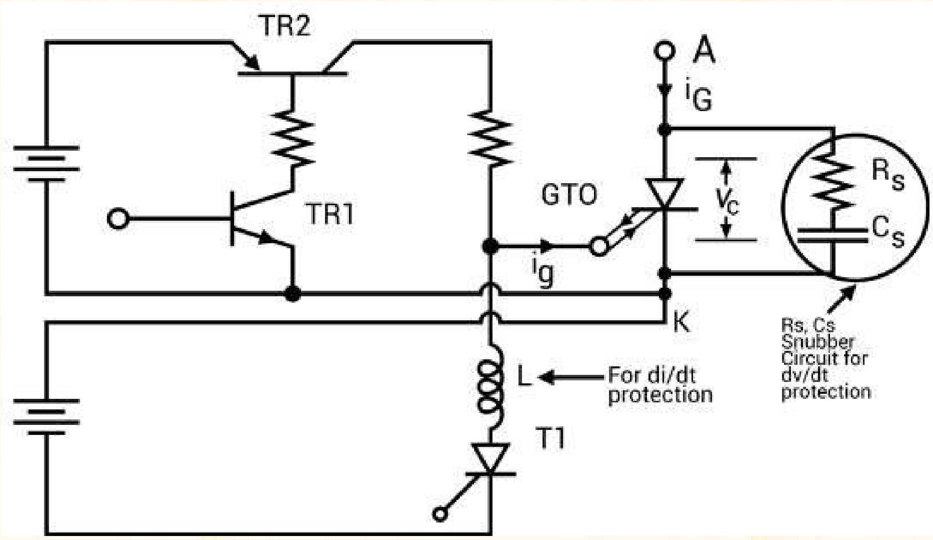


Figure: 1. 48. Gate Drive Circuit for GTO

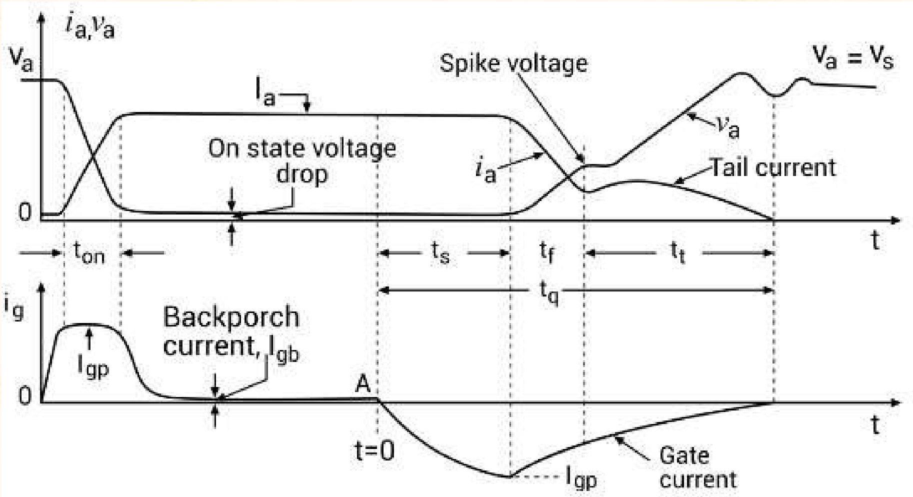


Figure: 1. 49. Switching characteristics for GTO

1.12 COMPARISON BETWEEN BJT AND 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.

UNIT – II
AC TO DC CONVERTER

2.1 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.

2.2 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.

2.3 TYPES OF PHASE CONTROLLED RECTIFIER

This type of rectifier uses a single Thyristor device to provide o/p control only in one half cycle of input AC supply, and it offers low DC output.

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.

(iii) Full wave Controlled Rectifier:

- This type of rectifier provides higher DC output
- Full wave bridge controlled rectifiers do not need a center tapped transformer
- Full wave controlled rectifier with a center tapped transformer requires two Thyristors.

(iv) Three-phase Controlled Rectifier

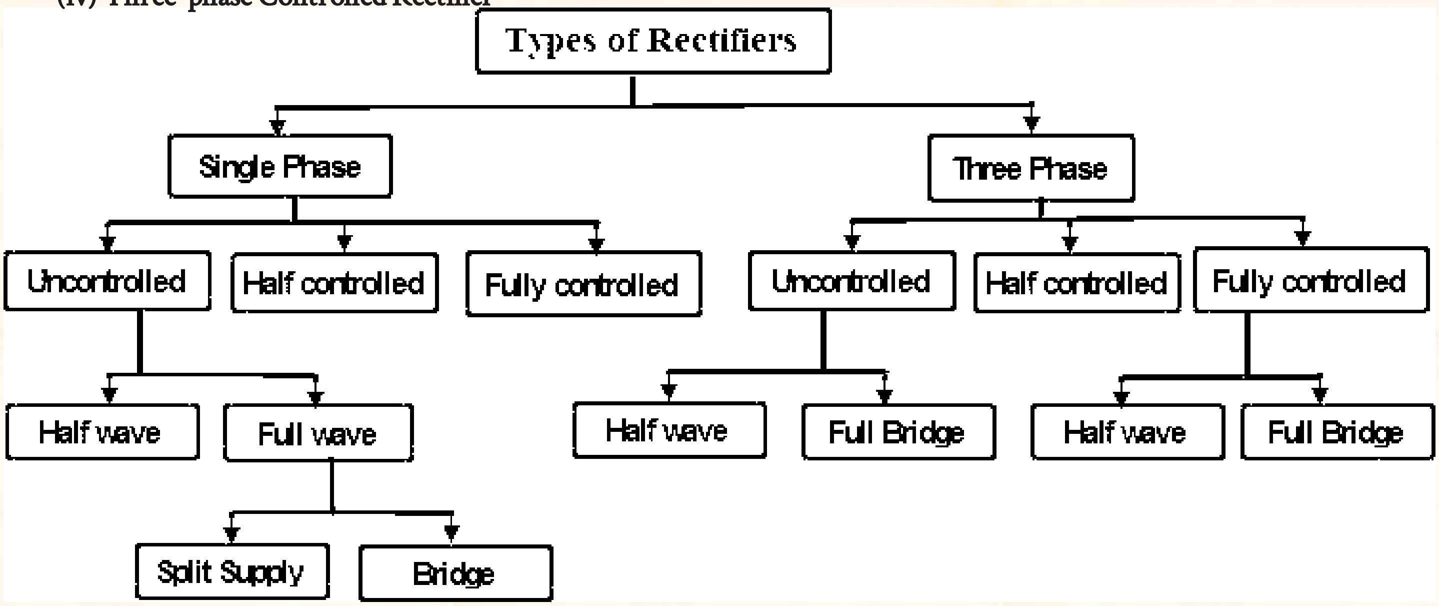


Figure: 2.1. Classification of rectifiers

(i) Single-phase Controlled Rectifier

- This type of rectifier which works from single phase AC i/p power supply.
- Single Phase Controlled Rectifiers are classified into different types.

(ii) Half wave Controlled Rectifier:

- This type of rectifier which works from three phase AC i/p power supply
- A semi converter is a one quadrant converter that has one polarity of o/p voltage and current.

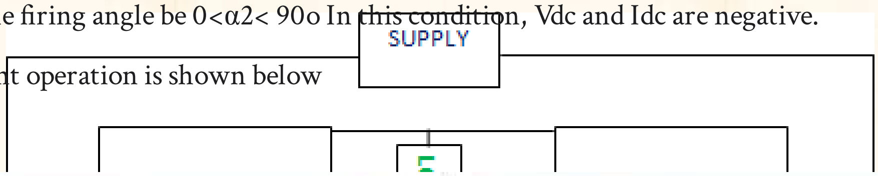
(i) Non Circulating Current Mode

- A full converter is 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.
- One converter will perform at a time. So there is no circulating current between the converters.
- Dual converter works in four quadrants – both o/p voltage and o/p current can have both the polarities.
- During the converter 1 operation, firing angle (α1) will be 0<α1< 90o; Vdc and Idc are positive.
- During the converter 2 operation, firing angle (α2) will be 0<α2< 90o; Vdc and Idc are negative.

2.4 INTRODUCTION TO DUAL CONVERTERS

- Two converters will be in the ON condition at the same time. So circulating current is present.
- The firing angles are adjusted such that firing angle of converter 1 (α1) + firing angle of converter 2 (α2) = 180o.
- Converter 1 performs as a controlled rectifier when firing angle be 0<α1< 90o and Converter 2 performs as an inverter when the firing angle be 90o<α2< 180o. In this condition, Vdc and Idc are positive.
- Converter 1 performs as an inverter when firing angle be 90o<α1< 180o and Converter 2 performs as a controlled rectifier when the firing angle be 0<α2< 90o In this condition, Vdc and Idc are negative.
- The four quadrant operation is shown below

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



2.5 MODE

There ar

(ii) Circulatin

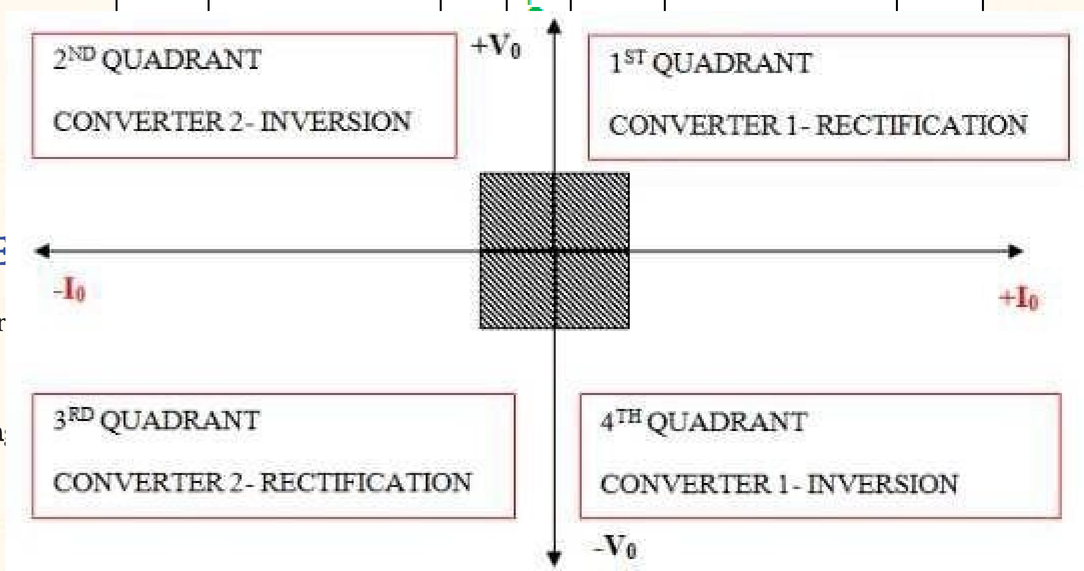


Figure: 2.29 Four quadrant operations of dual converter

2.6 IDEAL DUAL CONVERTER

The term 'ideal' refers to the ripple free output voltage. For the purpose of unidirectional flow of DC current, two diodes (D1 and D2) are incorporated between the converters. However, the direction of current can be in any way. The average output voltage of the converter 1 is V01 and converter 2 is V02. To make the output voltage of the two converters in same polarity and magnitude, the firing angles of the Thyristors have to be controlled.

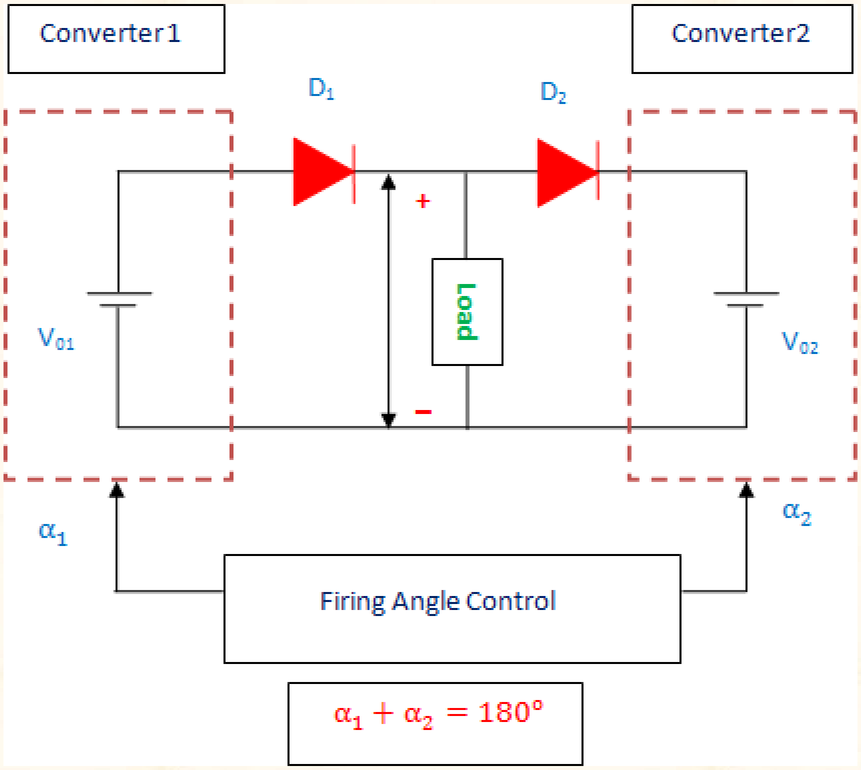


Figure: 2.30 Ideal dual converter

2.7 SINGLE PHASE DUAL CONVERTER

The source of this type of converter will be single-phase supply. Consider, the converter is in non- circulating mode of operation. The input is given to the converter 1 which converts the AC to DC by the method of rectification. It is then given to the load after filtering. Then, this DC is provided to the converter 2 as input. This converter performs as inverter and converts this DC to AC. Thus, we get AC as output. The circuit diagram is shown below.

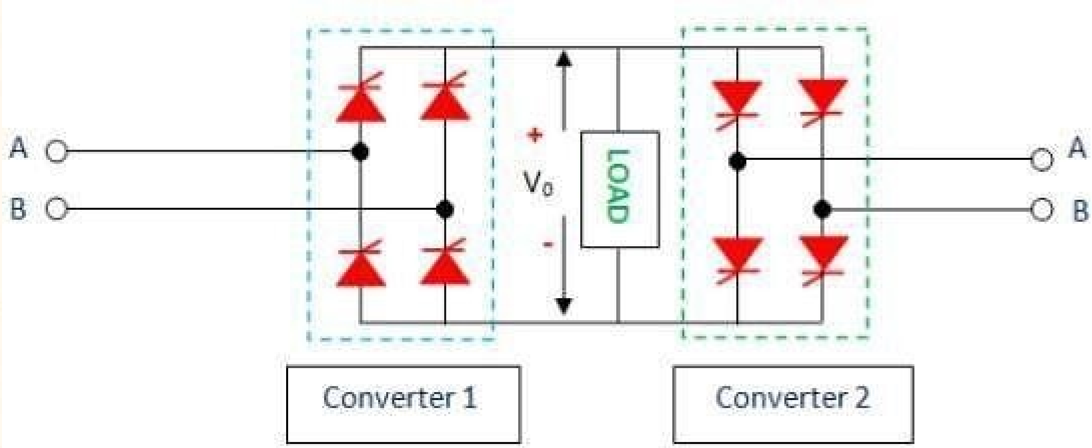


Figure: 2.31 Single phase Dual converter

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

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

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

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

Output voltage,

$$V_0 = V_{01} = -V_{02}$$
$$V_{max} Cos\alpha_1 = -V_{max} Cos\alpha_2$$
$$Cos\alpha_1 = Cos(180^o - \alpha_2) \; or \; Cos\alpha_2 = Cos(180^o + \alpha_2)$$
$$\alpha_1 + \alpha_2 = 180^o \; And \; \alpha_1 - \alpha_2 = 180^o$$
$$\alpha_1 + \alpha_2 = 180^o$$

The firing angle can never be greater than 180o. So,

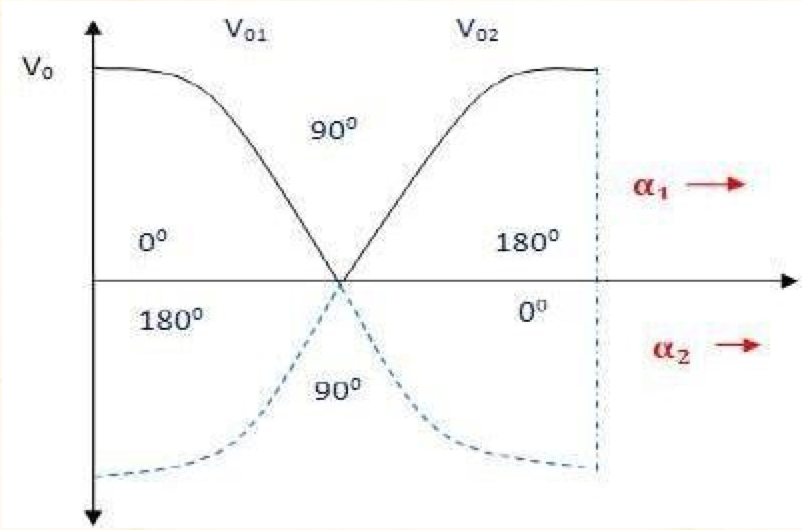


Figure: 2.32 output voltage variation with firing angle

2.8 THREE PHASE DUAL CONVERTER

In this, three-phase rectifier and three-phase inverter are used. The processes are similar to single-phase dual converter. The three-phase rectifier will do the conversion of the three-phase AC supply to the DC. This DC is filtered and given to the input of the second converter. It will do the DC to AC conversion and the output that we get is the three-phase AC. Applications where the output is up to 2 megawatts. The circuit is shown below.

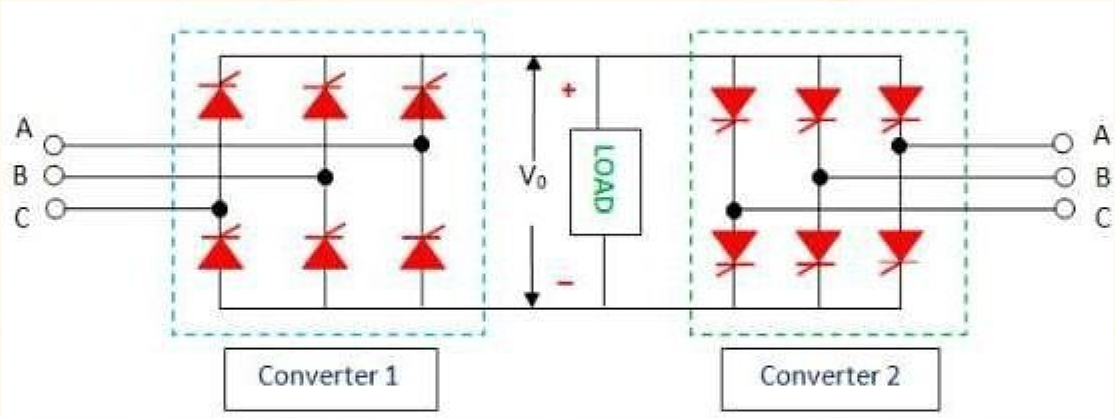


Figure: 2.33 Three phase dual converter

APPLICATION OF DUAL CONVERTER

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

UNIT III - AC VOLTAGE CONTROLLERS AND CYCLO CONVERTERS

3.1 INTRODUCTION TO AC VOLTAGE CONTROLLERS

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

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'

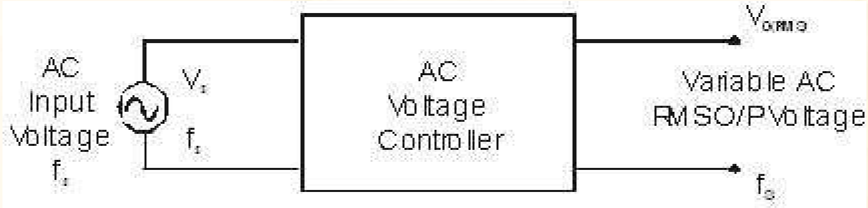


Figure: 3.1 Block diagram of AC voltage controller

These are the two ac output voltage control techniques.

3.2 CONTROL STRATEGIES

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

1. Phase control

- On-Off control

On-Off control

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 upto 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.

3.3 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 Controllers
- Three Phase AC 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.

3.4 APPLICATIONS OF AC VOLTAGE CONTROLLERS

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.

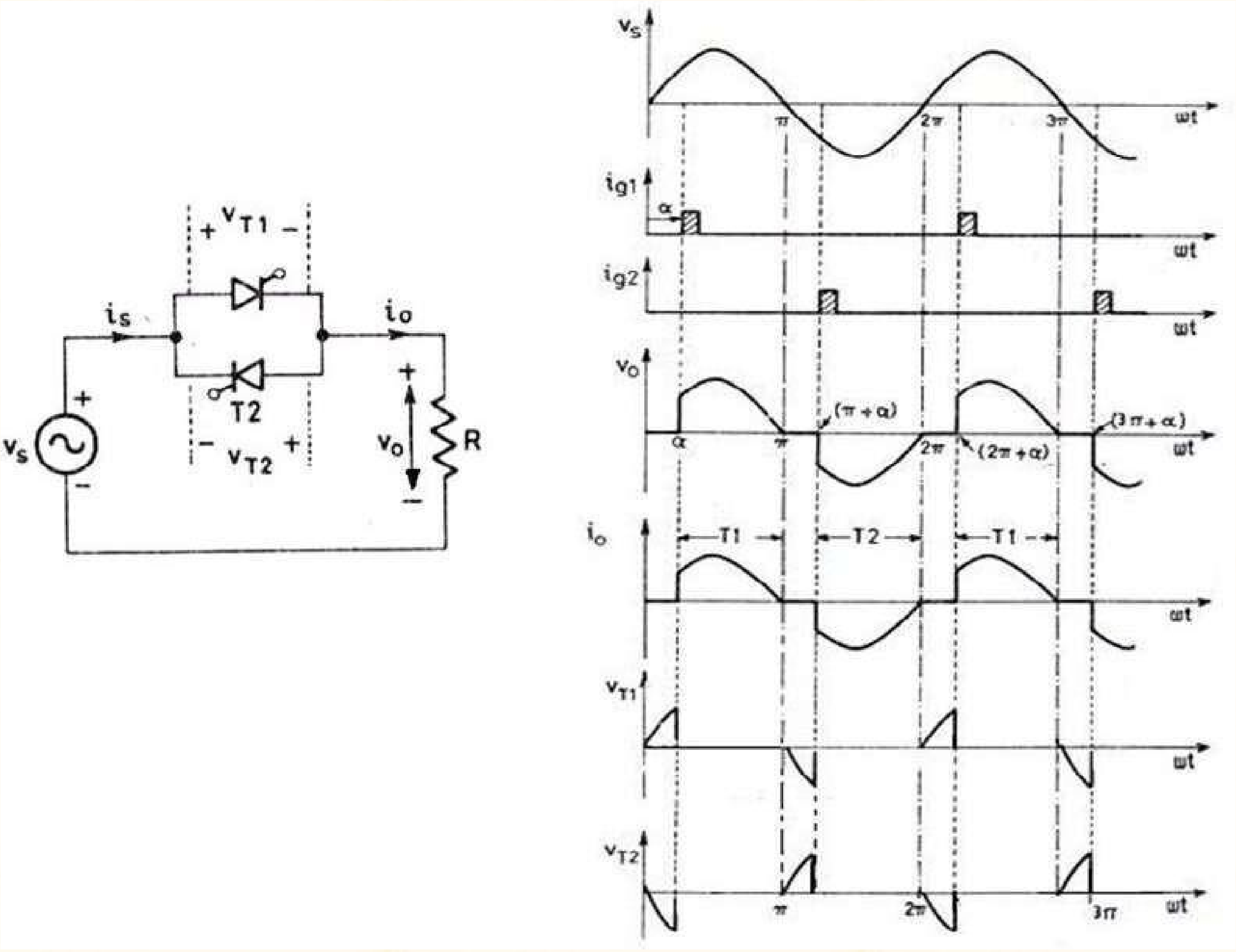


Figure: 3.2 Circuit diagram and output waveforms of AC voltage controller with R load

The Fig. 2.35 illustrates the operation of the PAC converter with a resistive load. The device(s) 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 Vrms decides the power supplied to the load. It can be computed as

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

3.5 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 inspite 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

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

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

3.6 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 α > φ, 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 180o. 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, is and the second, it is the transient component.

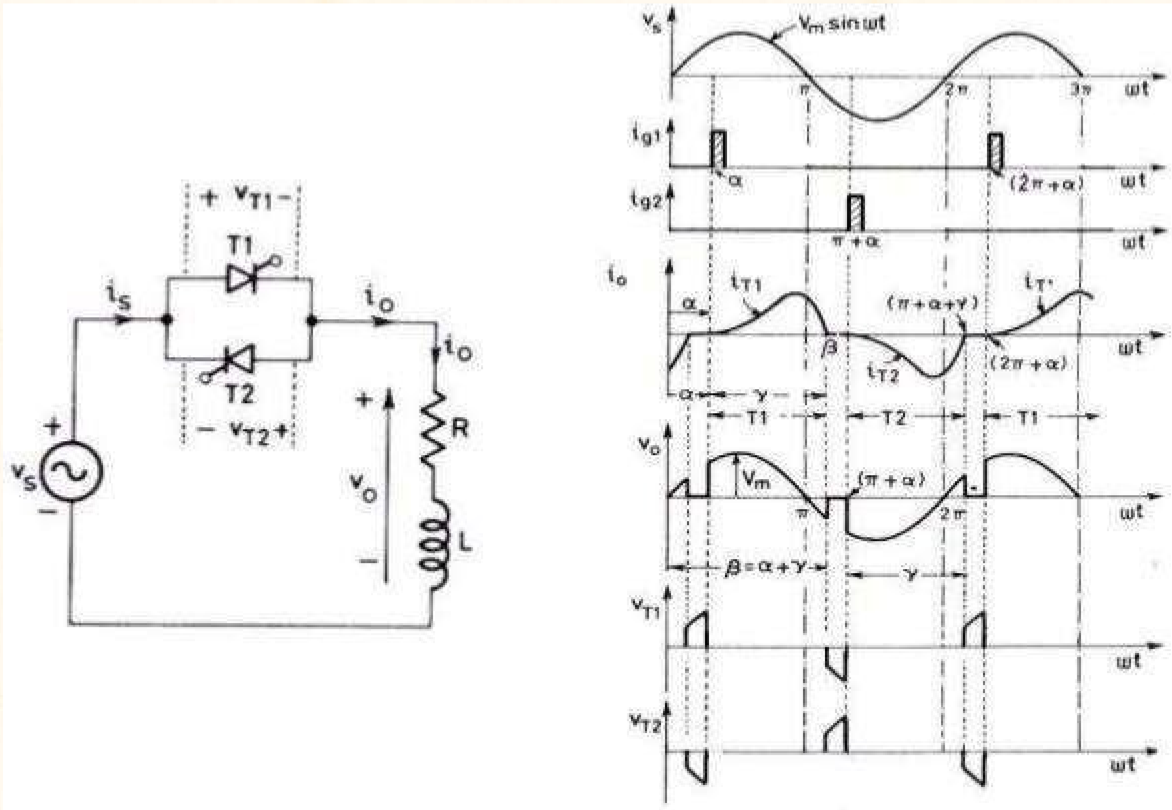


Figure: 3.3 Circuit diagram and output waveforms of AC voltage controller with RL load

$$L\frac{di}{dt} + Ri = v_s$$

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

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 is. The 'transient component' of load current it, again in each half cycle, must add up to zero with this is 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. Fig. 2. 36 illustrates these relations. When a device is in conduction, the load current is governed by the equation

Since at t = 0, i load = 0 and supply voltage vs = $\sqrt{2}V\sin\omega t$ 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.

3.7 MODES OF OPERATION OF TRIAC

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

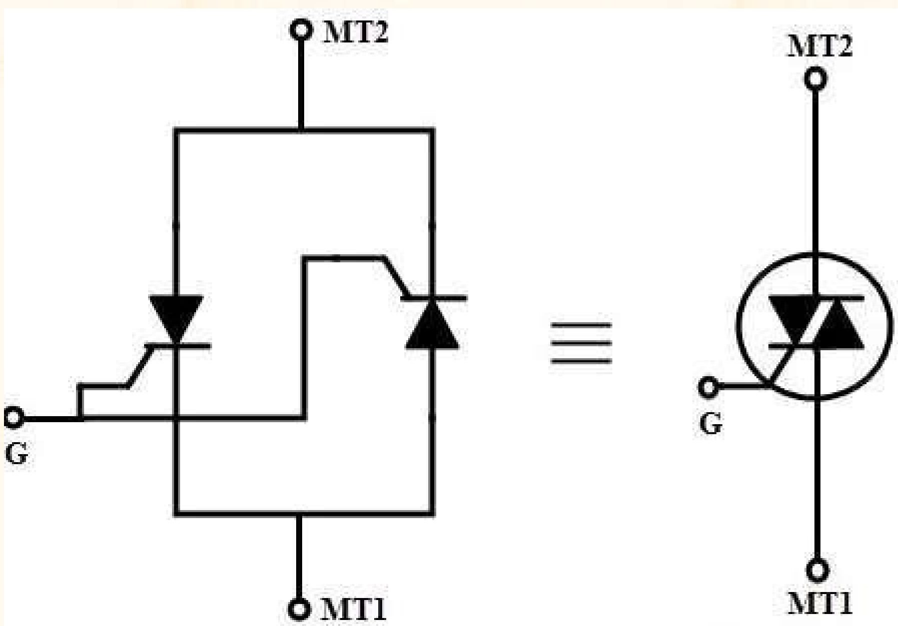


Figure: 3.4 Two thyristor analogy and circuit symbol of TRIAC

The TRIAC has three terminals namely Main Terminal 1(MT1), Main Terminal 2 (MT2) and Gate (G) as shown in figure. If MT1 is forward biased with respect to MT2, then the current flows from MT1 to MT2. Similarly, if the MT2 is forward biased with respect to MT1, then the current flows from MT2 to MT1. The above two conditions are achieved whenever the gate is triggered with an appropriate gate pulse. Similar to the SCR, TRIAC is also turned by injecting appropriate current pulses into the gate terminal. Once it is turned ON, it loses its gate control over its conduction. So TRIAC can be turned OFF by reducing the current to zero through the main terminals.

3.8 CONSTRUCTION OF TRIAC

A TRIAC is a five layer, three terminal semiconductor device. The terminals are marked as MT1, MT2 as anode and cathode terminals in case of SCR. And the gate is represented as G similar to the thyristor. The gate terminal is connected to both N4 and P2 regions by a metallic contact and it is near to the MT1 terminal. The terminal MT1 is connected to both N2 and P2 regions, while MT2 is connected to both N3 and P1 regions. Hence, the terminals MT1 and MT2 connected to both P and N regions of the device and thus the polarity of applied voltage between these two terminals decides the current flow through the layers of the device.

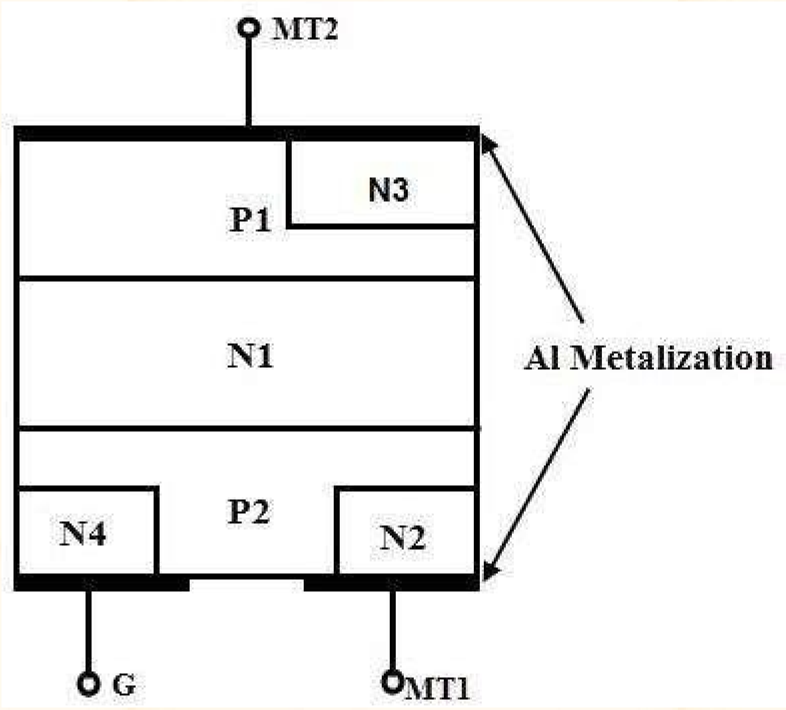


Figure: 3.5 construction of TRIAC

With the gate open, MT2 is made positive with respect to MT1 for a forward biased TRIAC. Hence TRIAC operates in forward blocking mode until the voltage across the TRIAC is less than the forward break over voltage. Similarly for a reverse biased TRIAC , MT2 is made negative with respect to MT1 with gate open. Until the voltage across the TRIAC is less than the reverse break over voltage, device operates in a reverse blocking mode. A TRIAC can be made conductive by either positive or negative voltage at the gate terminal.

3.9 WORKING AND OPERATION OF TRIAC

It is possible to connect various combinations of negative and positive voltages to the triac terminals because it is a bidirectional device. The four possible electrode potential combinations which make the triac to operate four different operating quadrants or modes are given as.

1. MT2 is positive with respect to MT1 with a gate polarity positive with respect to MT1.
2. MT2 is positive with respect to MT1 with a gate polarity negative with respect to MT1.
3. MT2 is negative with respect to MT1 with a gate polarity negative with respect to MT1.
4. MT2 is negative with respect to MT1 with a gate polarity positive with respect to MT1.

In general, latching current is higher in second quadrant or mode whilst gate trigger current is higher in the fourth mode compared with other modes for any TRIAC . Most of the applications, negative triggering current circuit is used that means 2 and 3 quadrants are used for a reliable triggering in bidirectional control and also when the gate sensitivity is critical. The gate sensitivity is highest with modes 1 and 4 are generally employed.

Mode 1: MT2 is Positive, Positive Gate Current

When the gate terminal is made positive with respect to MT1, gate current flows through the P2 and N2 junction. When this current flows, the P2 layer is flooded with electrons and further these electrons are diffused to the edge of junction J2 (or P2-N1 junction). These electrons collected by the N1 layer builds a space charge on the N1 layer. Therefore, more holes from the P1 region are diffused into the N1 region to neutralize the negative space charges. These holes arrive at the junction J2 and produce the positive space charge in the P2 region, which causes more electrons to inject into P2 from N2. This results a positive regeneration and finally the main current flows from MT2 to MT1 through the regions P1- N1 – P2 – N2.

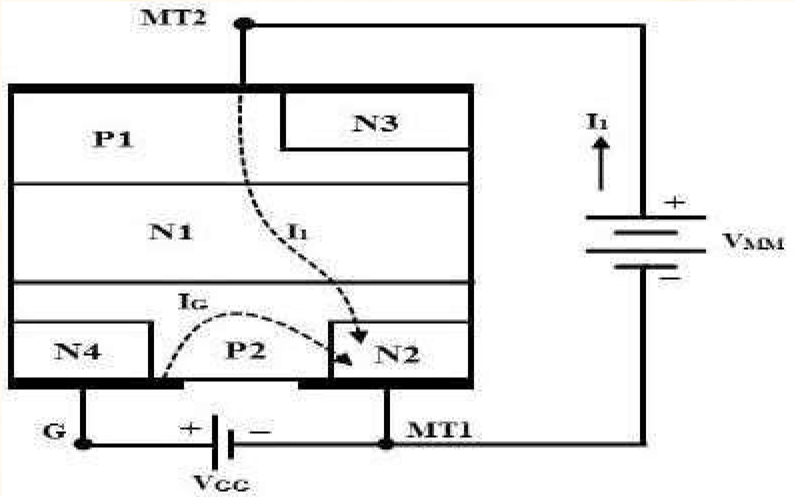


Figure: 3.6 Mode 1 operation of TRIAC

Mode 2: MT2 is Positive, Negative Gate Current

When MT2 is positive and the gate terminal is negative with respect to MT1, gate current flows through the P2-N4 junction. This gate current forward biases the P2-N4 junction for auxiliary P1N1P2N4 structure. This results the TRIAC to conduct initially through the P1N1 P2 N4 layers. This further raises the potential between P2N2 towards the potential of MT2. This causes the current to establish from left to right in the P2 layer which forward biases the junction P2N2. And hence the main structure P1N1P2N2 begins to conduct. Initially conducted auxiliary structure P1N1P2N4 is considered as a pilot SCR while later conducted structure P1N1P2N2 is considered as main SCR. Hence the anode current of pilot SCR serves as gate current to the main SCR. The sensitivity to gate current is less in this mode and hence more gate current is required to turn the TRIAC.

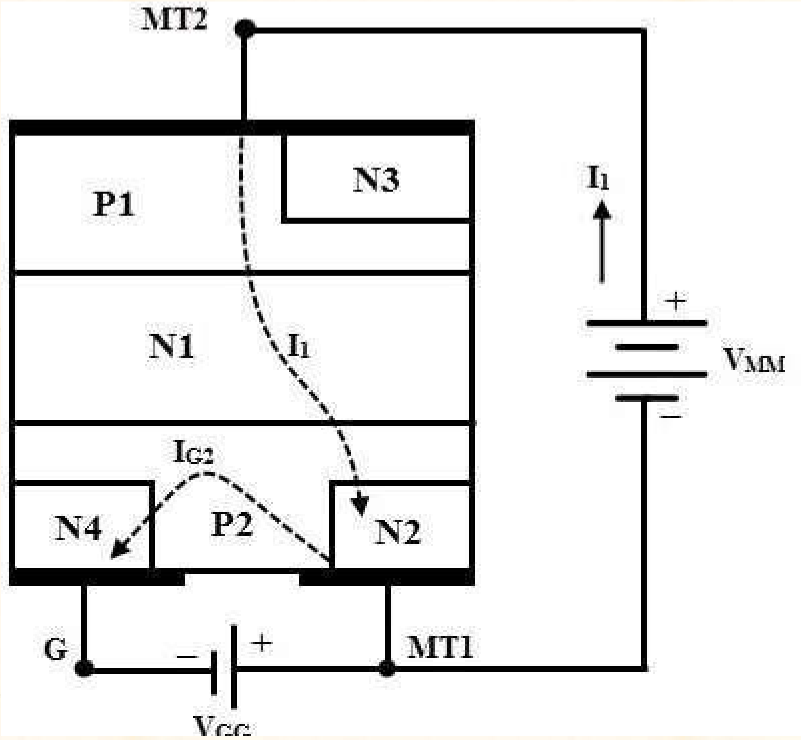


Figure: 3.7 Mode 2 operation of TRIAC

Mode 3: MT2 is Negative, Positive Gate Current

In this mode, MT2 is made negative with respect to MT1 and the device is turned ON by applying a positive voltage between the gate and MT1 terminal. The turn ON is initiated by N2 which acts as a remote gate control and the structure leads to turn ON the TRIAC is P2N1P1N3. The external gate current forward biases the junction P2-N2. N2 layer injects the electrons into the P2 layer which are then collected by junction P2N1. This result to increases the current flow through P2N1 junction.

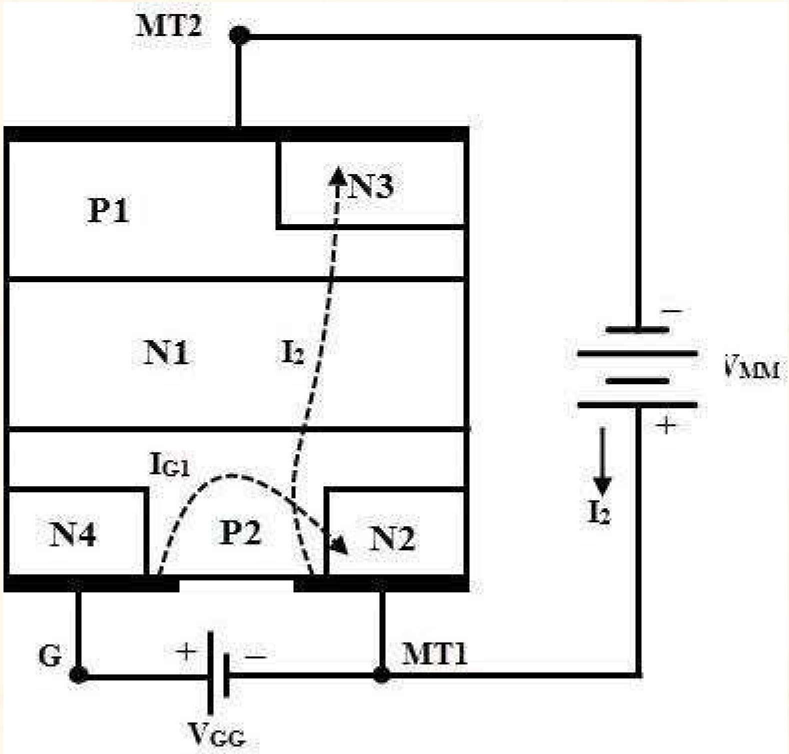


Figure: 3.8 Mode 3 operation of TRIAC

The holes injected from layer P2 diffuse through the N1 region. This builds a positive space charge in the P region. Therefore, more electrons from N3 are diffused into P1 to neutralize the positive space charges. Hence, these electrons arrive at junction J2 and produce a negative space charge in the N1region which results to inject more holes from the P2 into the region N1. This regenerative process continues till the structure P2N1P1N3 turns ON the triac and conducts the external current. As the triac is turned ON by the remote gate N2, the device is less sensitive to the positive gate current in this mode.

Mode 4: MT2 is Negative, Negative Gate Current

In this mode N4 acts as a remote gate and injects the electrons into the P2 region. The external gate current forward biases the junction P2N4. The electrons from the N4 region are collected by the P2N1 junction increase the current across P1N1 junction. Hence the structure P2N1P1N3 turns ON by the regenerative action. The triac is more sensitive in this mode compared with positive gate current in mode 3.

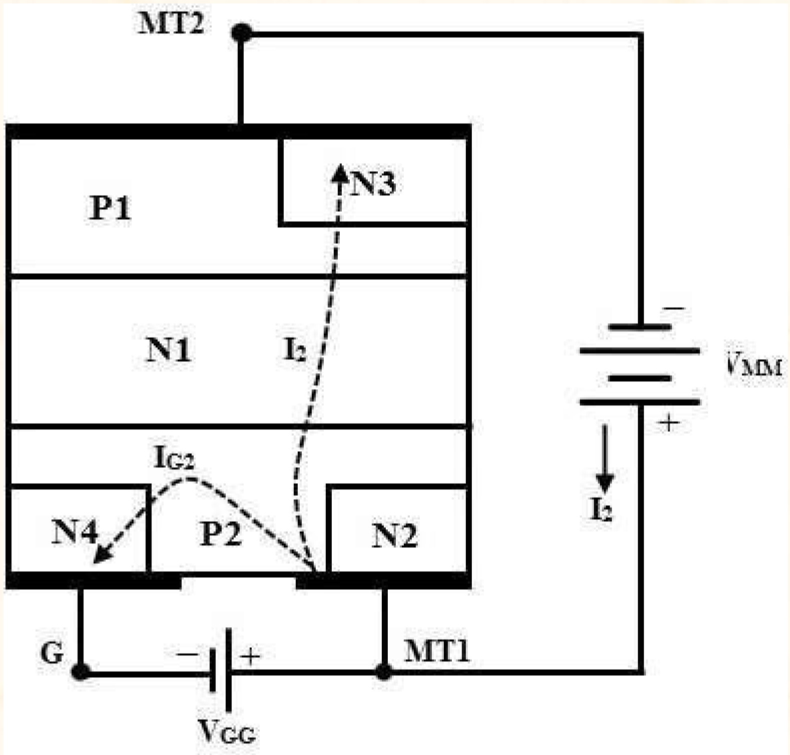


Figure: 3.9 Mode 4 operation of TRIAC

From the above discussion, it is concluded that the modes 2 and 3 are less sensitive configuration which needs more gate current to trigger the TRIAC , whereas more common triggering modes of TRIAC are 1 and 4 which have greater sensitivity. In practice the more sensitive mode of operation is selected such that the polarity of the gate is to match with the polarity of the terminal MT2.

3.10 CHARACTERISTICS OF TRIAC

The TRIAC function like a two thyristors connected in anti-parallel and hence the VI characteristics of TRIAC in the 1st and 3rd quadrants will be similar to the VI characteristics of a thyristors. When the terminal MT2 is positive with respect to MT1 terminal, the TRIAC is said to be in forward blocking mode. A small leakage current flows through the device provided that voltage across the device is lower than the breakover voltage. Once the breakover voltage of the device is reached, then the TRIAC turns ON as shown in below figure. However, it is also possible to turn ON the TRIAC below the VBO by applying a gate pulse in such that the current through the device should be more than the latching current of the TRIAC.

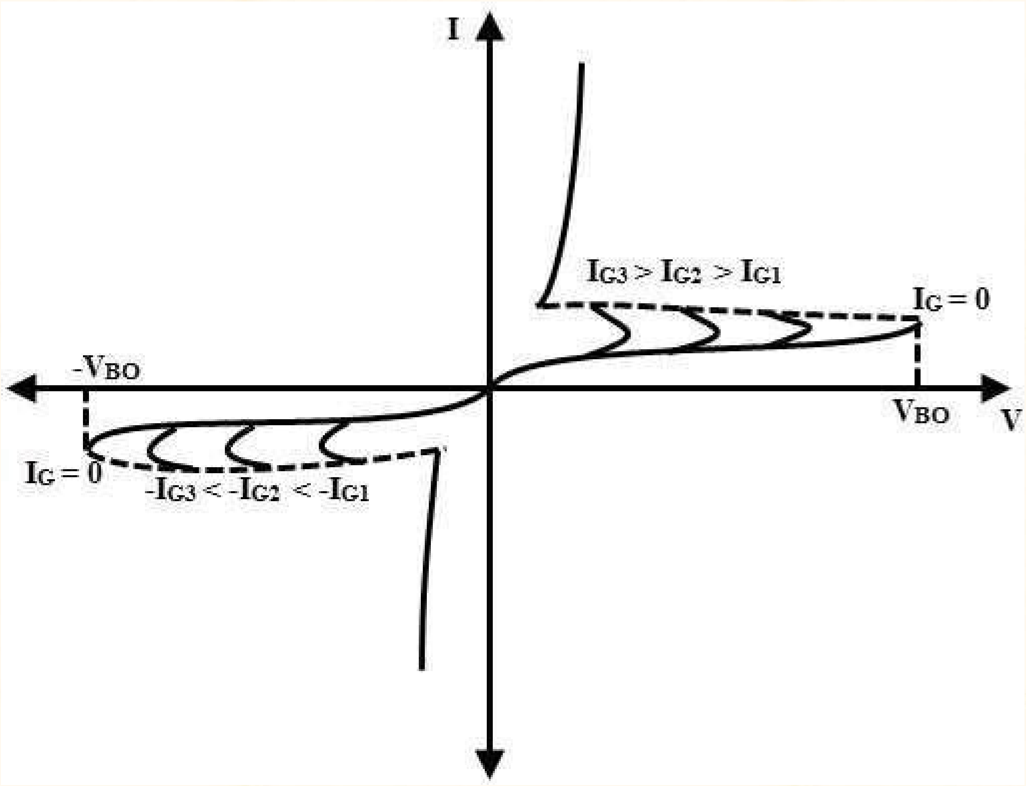


Figure: 3.10 V-I characteristics of TRIAC

Similarly, when the terminal MT2 is made negative with respect to MT1, the TRIAC is in reverse blocking mode. A small leakage current flows through the device until it is triggered by breakover voltage or gate triggering method. Hence the positive or negative pulse to the gate triggers the TRIAC in both directions. The supply voltage at which the TRIAC starts conducting depends on the gate current. If the gate is current is being greater, lesser will be the supply voltage at which the TRIAC is turned ON. Above discussed mode - 1 triggering is used in the first quadrant whereas mode-3 triggering is used in 3rd quadrant. Due to the internal structure of the TRIAC , the actual values of latching current, gate trigger current and holding current may be slightly different in different operating modes. Therefore, the ratings of the TRIAC considerably lower than the thyristors.

3.11 ADVANTAGES OF TRIAC

TRIAC can be triggered by both positive and negative polarity voltages applied at the gate.It can operate and switch both half cycles of an AC waveform.

1. As compared with the anti-parallel thyristor configuration which requires two heat sinks of slightly smaller size, a TRIAC needs a single heat sink of slightly larger size. But the TRIAC may work without a diode, a safe breakdown is possible in either direction.
2. Hence the TRIAC saves both space and cost in AC power applications.
3. In DC applications, SCRs are required to be connected with a parallel diode to protect against reverse voltage.
4. But the TRIAC may work without a diode, a safe breakdown is possible in either direction.

3.12 DISADVANTAGES OF TRIAC

1. A careful consideration is required while selecting a gate trigger circuit since a triac can be triggered in both forward and reverse biased conditions.
2. These have low dv/dt rating as compared with thyristors.
3. These have very small switching frequencies.
4. TRIAC s are less reliable than thyristors.

3.13 INTRODUCTION TO CYCLO CONVERTERS

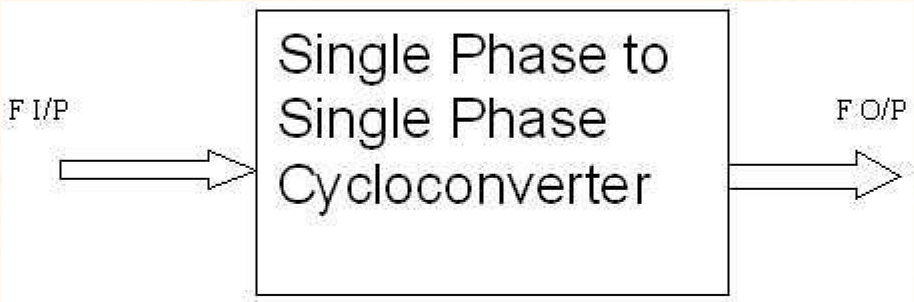


Figure 3.11 Block diagram of cycloconverters

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 .

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 3.11. 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 center 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.

3.14 OPERATION PRINCIPLES

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

(i) SINGLE-PHASE TO SINGLE-PHASE (1 Φ-1 Φ) CYCLOCONVERTER

To understand the operation principles of Cycloconverters, the single-phase to single- phase Cycloconverter (Fig. 3.12) should be studied first. This converter consists of back-to-back connection of two full-wave rectifier circuits. Fig 3.13 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 at a frequency, fi as shown in Fig. 3.13. For easy understanding assume that all the thyristors are fired at $\alpha=0°$.

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.

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.

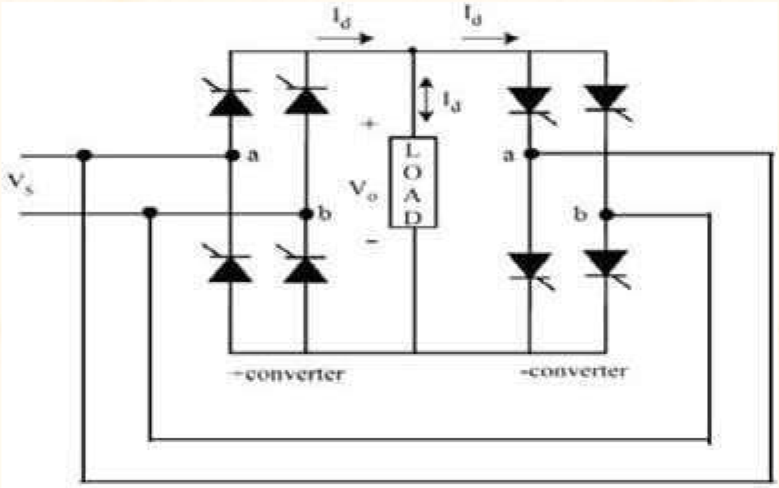


Figure 3.12 circuit diagram of cycloconverter

(ii) SINGLE PHASE MIDPOINT CYCLO CONVERTERS

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

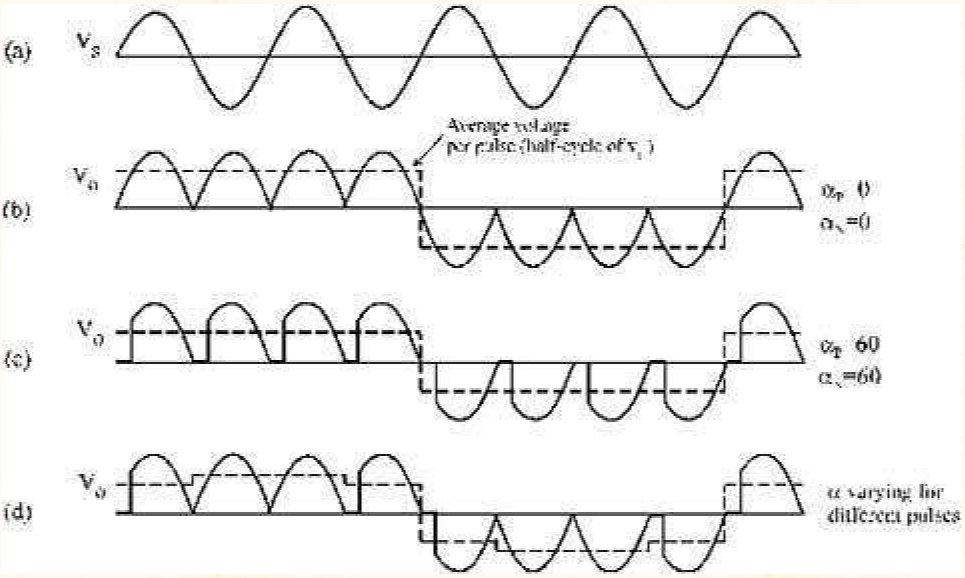


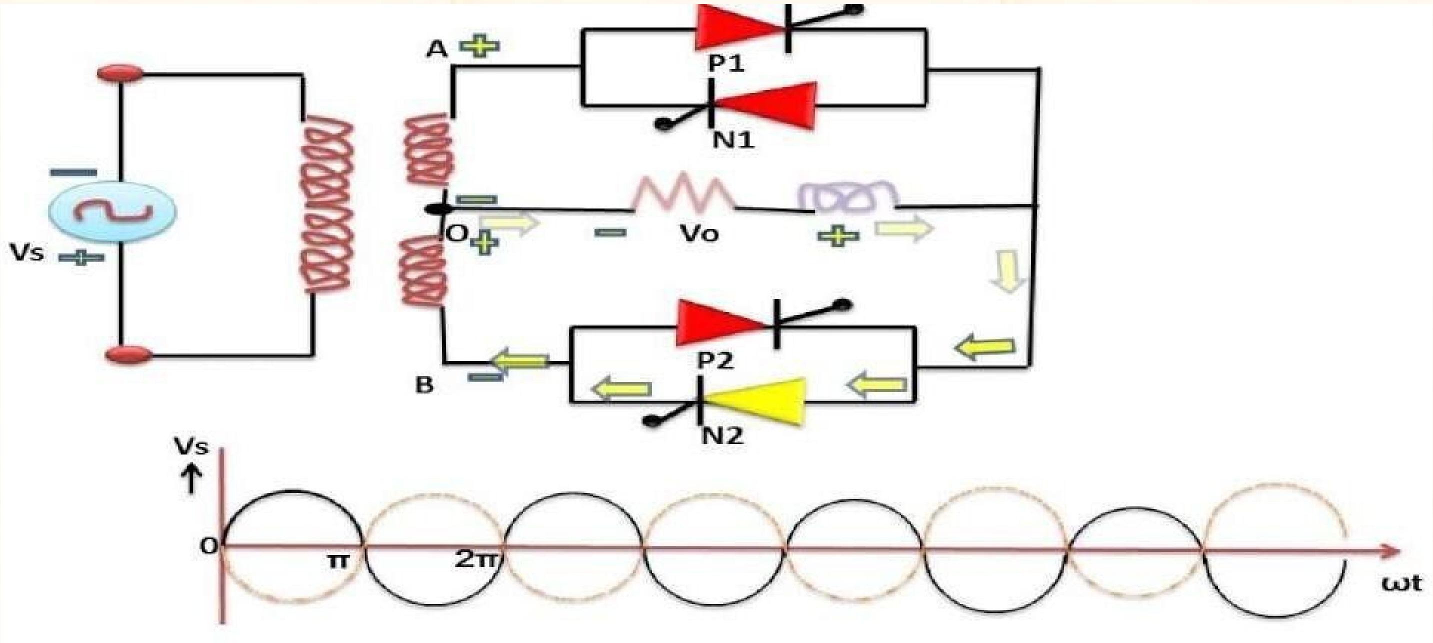
Figure 3.13 Input and output waveforms of cycloconverter

Step-down cyclo-converter

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

Step-up cyclo-converter

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 3.14 circuit diagram of midpoint cycloconverter

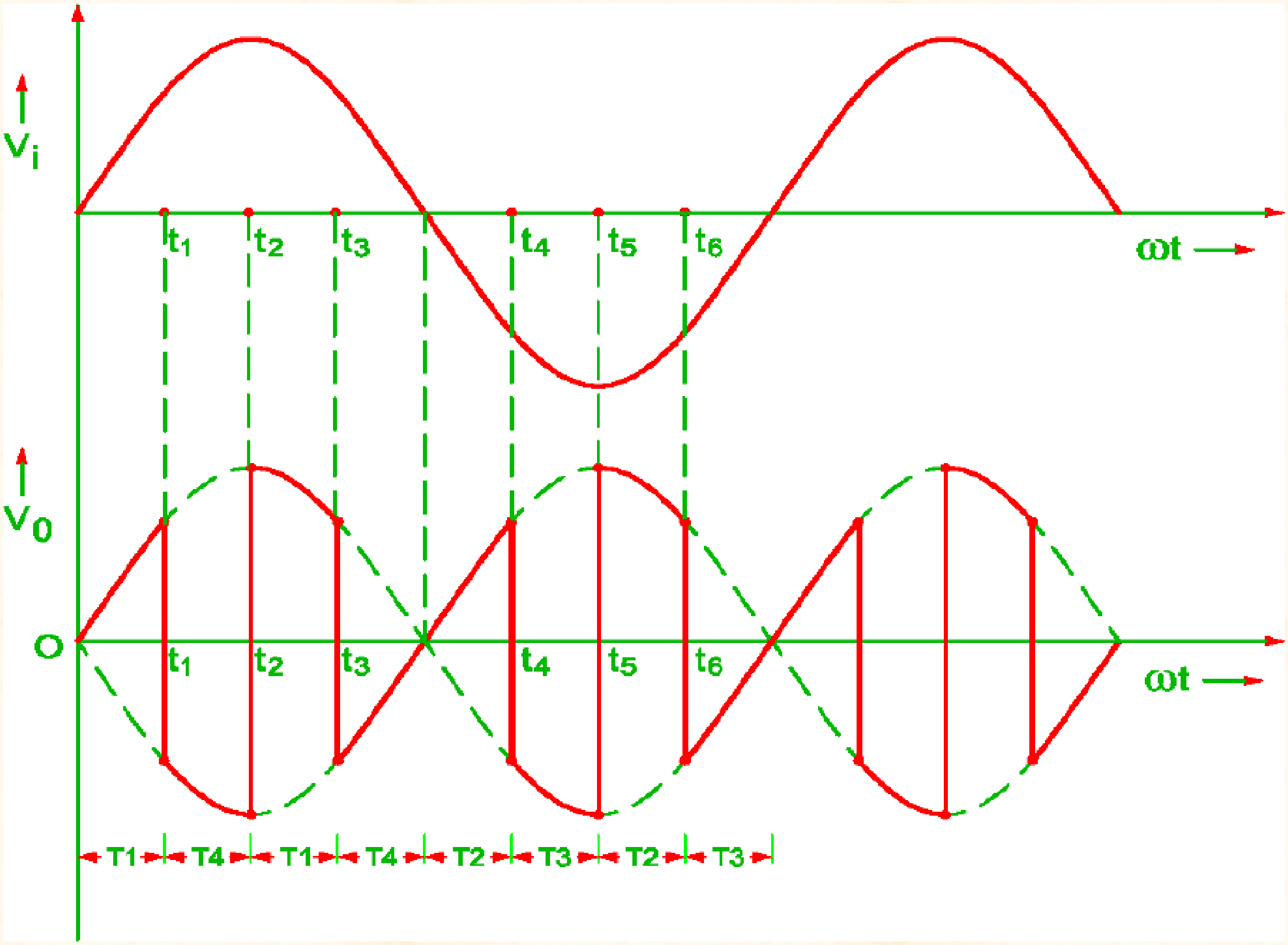


Figure 3.15 Input and output waveforms of midpoint cycloconverter

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 3.14

In figure 3.14 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.

3.15 BRIDGE CONFIGURATION OF SINGLE PHASE CYCLO CONVERTER

The equivalent circuit of a cyclo-converter is shown in figure below. Here each two quadrant phase controlled converter is represented by a voltage source of desired frequency and consider that the output power is generated by the alternating current and voltage at desired frequency.

The diodes connected in series with each voltage source represent the unidirectional conduction of each two quadrant converter. If the output voltage ripples of each converter are neglected, then it becomes ideal and represents the desired output voltage.

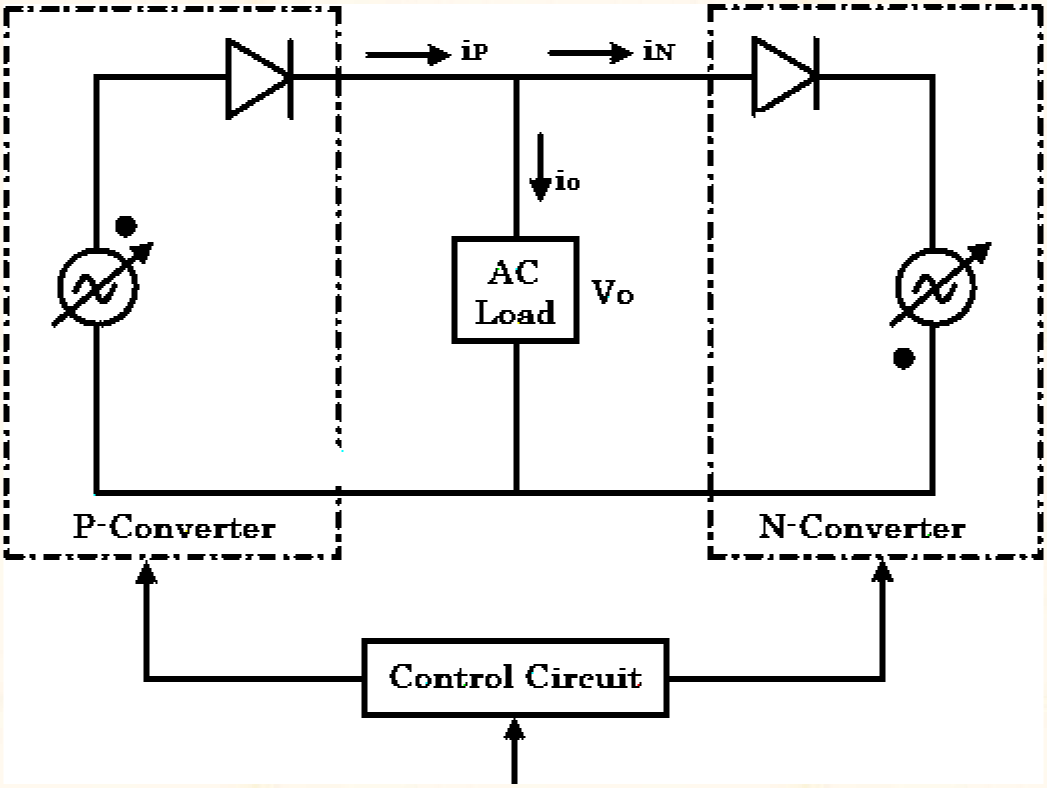


Figure 3.16 Block diagram of bridge type cycloconverter

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.

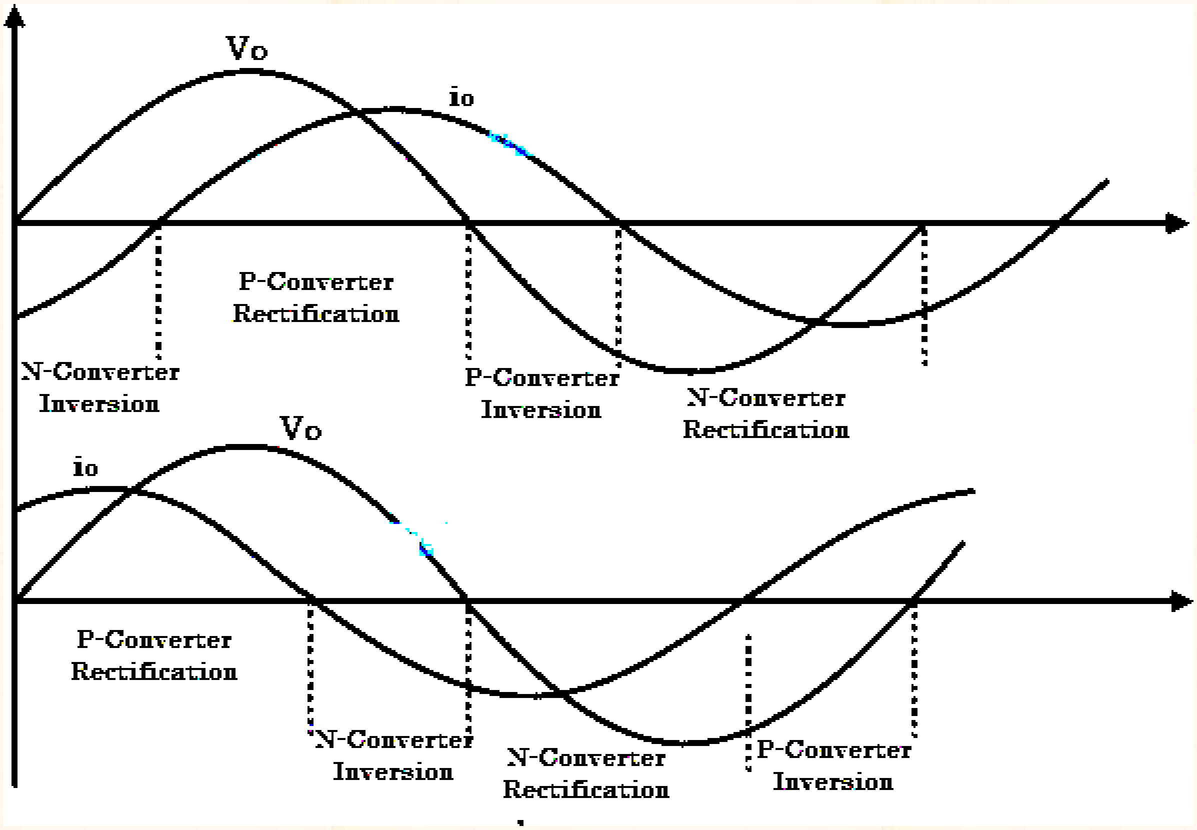


Figure 3.17 Cyclo converter waveforms

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.

3.16 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.

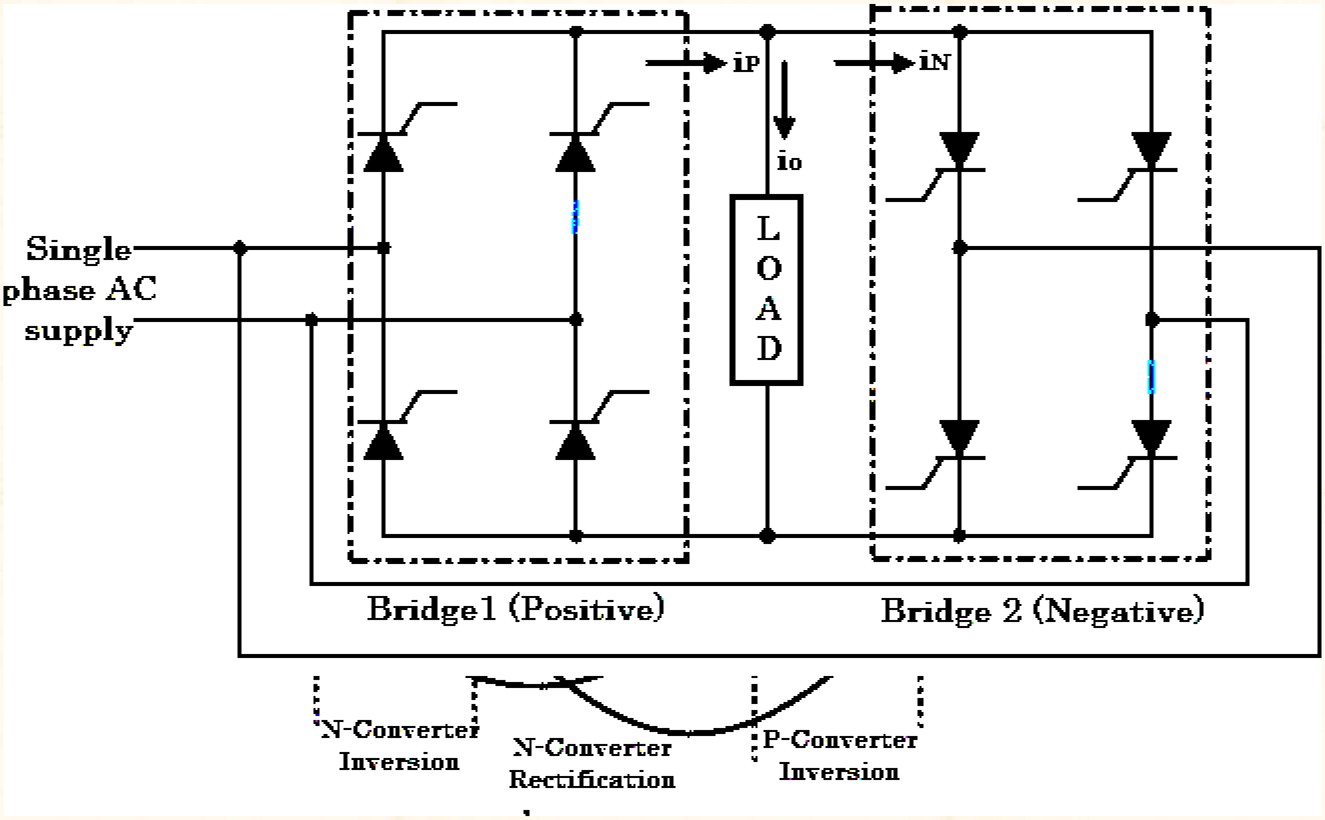


Figure 3.18 Circuit diagram of bridge type cycloconverter

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 so on.

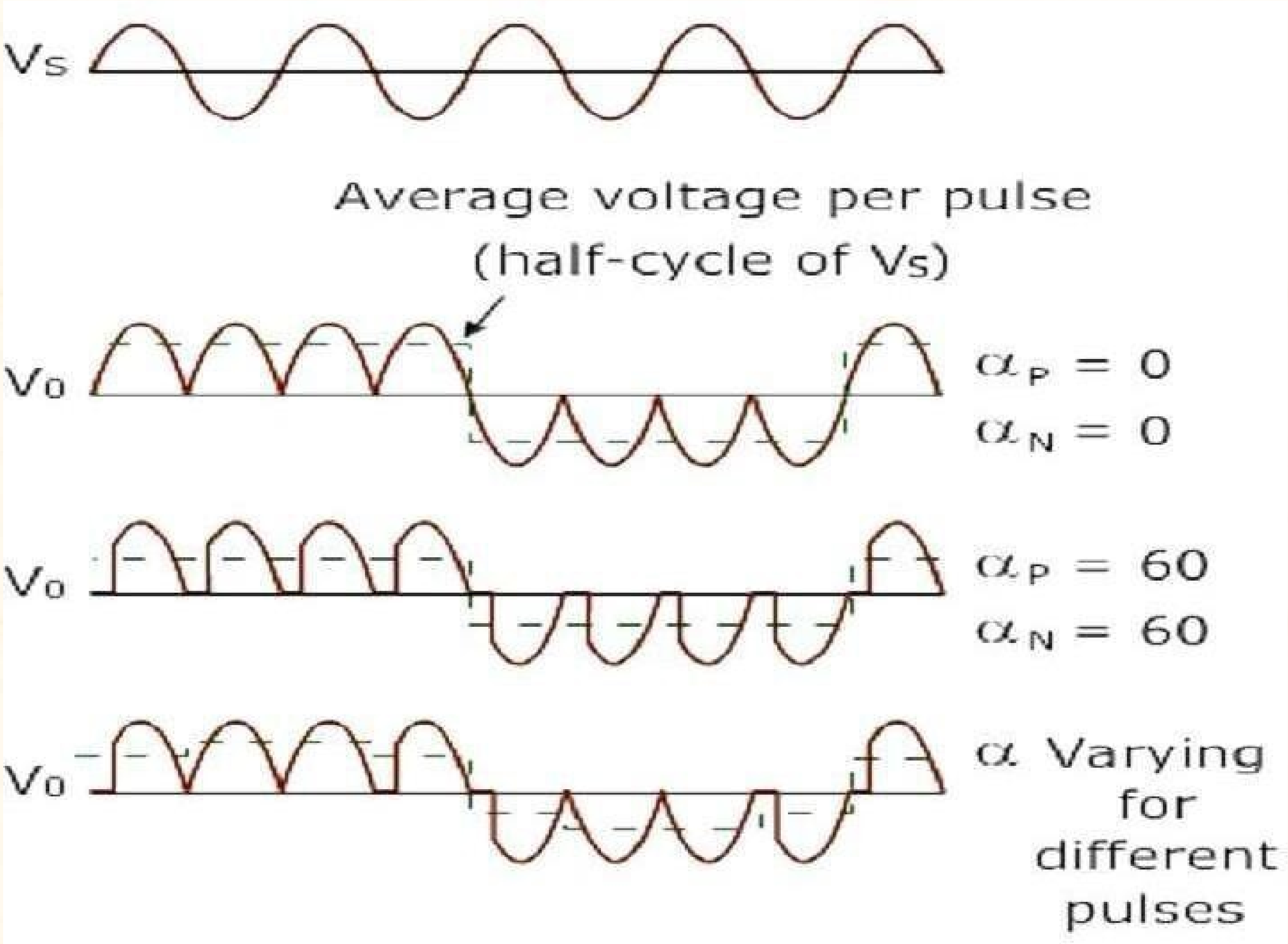


Figure 3.19 Input and output waveforms of bridge type cycloconverter

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.

UNIT IV – DC – DC CONVERTERS

4.1 INTRODUCTION TO CHOPPERS

A chopper uses high speed to connect and disconnect from a source load. A fixed DC voltage is applied intermittently to the source load by continuously triggering the power switch ON/OFF. The period of time for which the power switch stays ON or OFF is referred to as the chopper's ON and OFF state times, respectively.

Choppers are mostly applied in electric cars, conversion of wind and solar energy, and DC motor regulators.

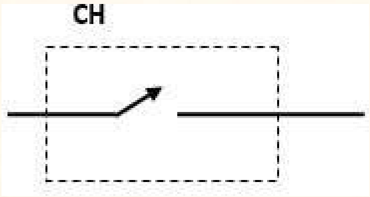


Figure: 3.1 Symbol of chopper

4.2 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:

Time Ratio Control

Current Limit Control

In this, it explains about both the ways of varying the duty cycle. Duty Cycle is the ratio of 'On Time' to 'Time Period of a pulse'.

4.3 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)

4.3.1 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.

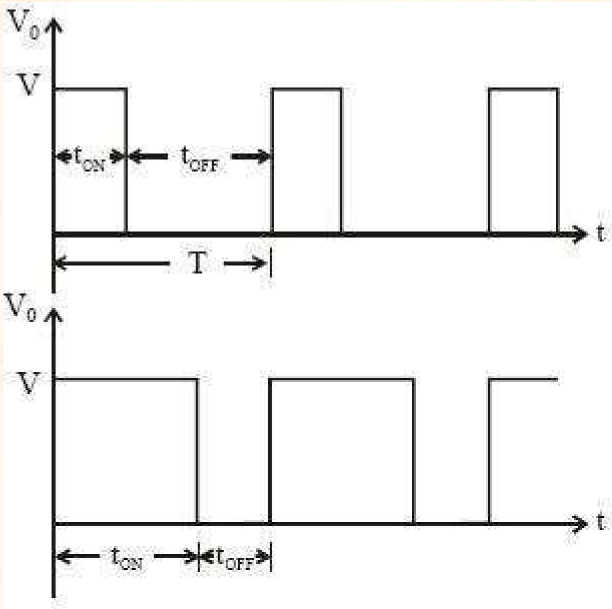


Figure: 3.2 pulse width modulation waveforms

4.3.2 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.

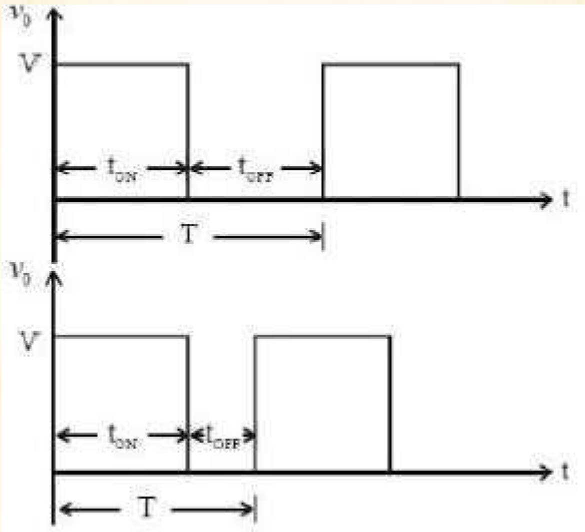


Figure: 3.3 Frequency modulation waveforms

4.4 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.

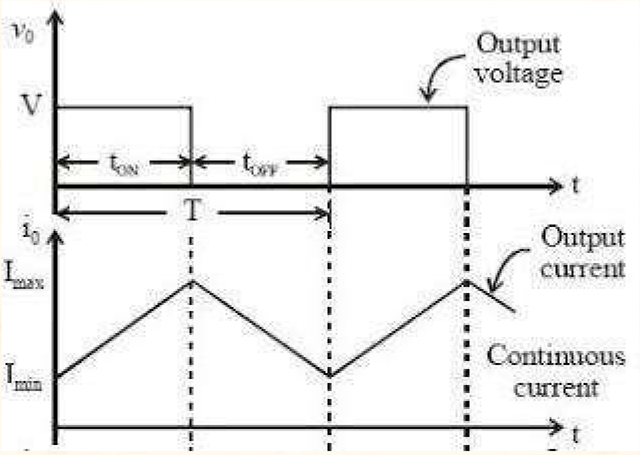


Figure: 3.4 current limit control waveforms

4.5 CLASSIFICATION OF CHOPPERS

Depending on the voltage output, choppers are classified as

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

4.5.1 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 Operation]

4.5.2 STEP DOWN CHOPPER

This is also known as a buck converter. In this chopper, the average voltage output VO is less than the input voltage VS.

When the chopper is ON, VO = VS and when the chopper is off, VO = 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,

$\Delta i=Vs-V0$ TON

L

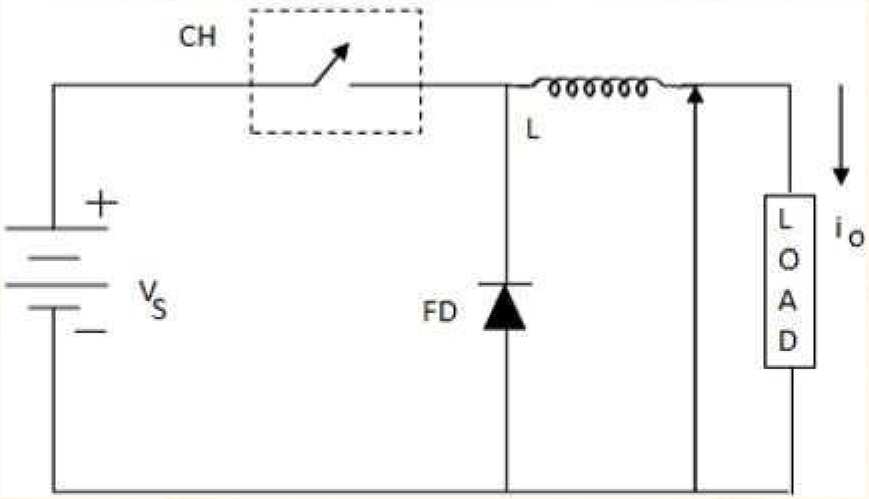


Figure: 3.5 Step down chopper

Where FD is free-wheel diode.

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, Ldi/dt=V0

Rewritten as LΔi/TOFF=V0 LΔi/TOFF=V0 Δi=V0TOFF/L

From the above equations

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

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

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

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

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

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

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

CURRENT AND VOLTAGE WAVEFORMS

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.

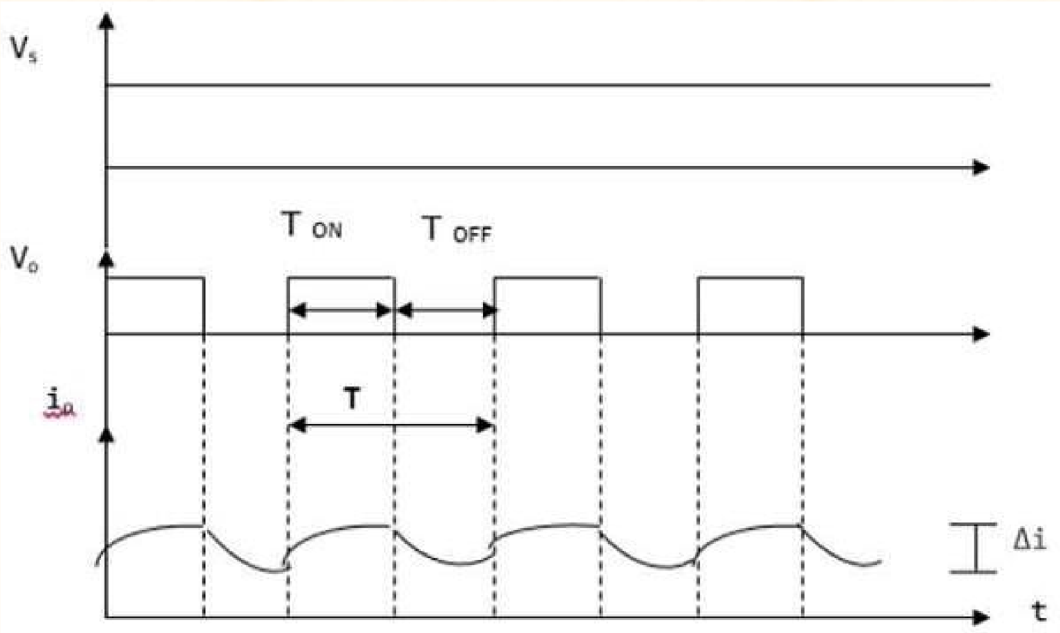


Figure: 3.6 Input and output waveforms

STEP UP CHOPPER

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

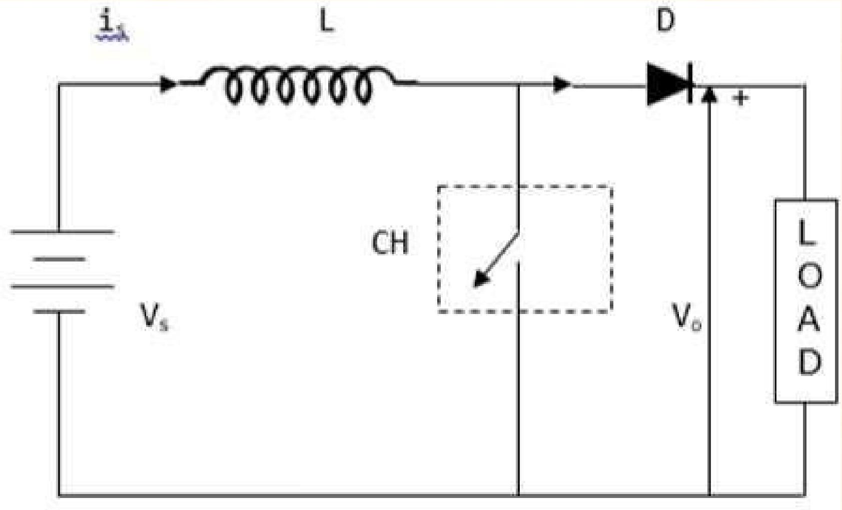


Figure: 3.7 Circuit diagram of step up chopper

CURRENT AND VOLTAGE WAVEFORMS

V0 (average voltage output) is positive when chopper is switched ON and negative when the chopper is OFF as shown in the waveform below.

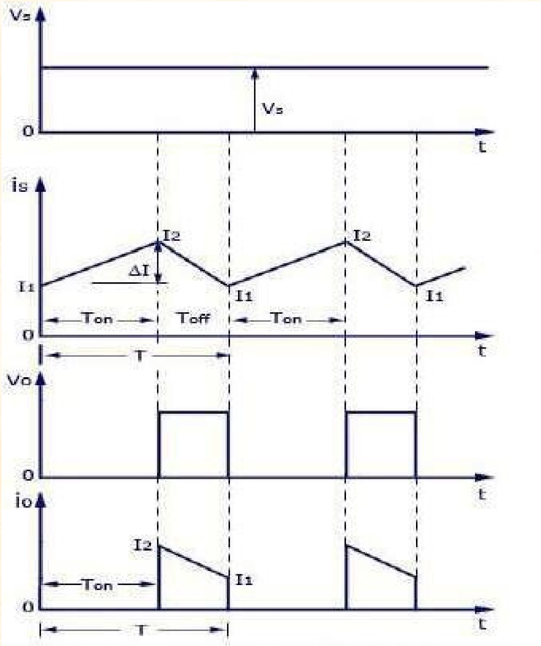


Figure: 3.8 Input and output waveforms of step up chopper

Where

TON – time interval when chopper is ON TOFF – time interval when chopper is OFF VL – Load voltage

Vs – Source voltage

T – Chopping time period = TON + TOFF

Vo is given by –

V0 = 1 ∫*To sdt*

0

When the chopper (CH) is switched ON, the load is short circuited and, therefore, the voltage output for the period TON is zero. In addition, the inductor is charged during this time. This gives VS = VL

Vs = i , Δi = Vs

dt Ton L

Δi = $Vs \times Ton$

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 Vs and VL is given as follows –

V0=VS+VL, VL=V0−VS

di

$L = Vo - Vs$

dt

Δi

$L = Vo - Vs$

$Toff$

Δi = $Vo - Vs$

4.6 PRINCIPLE OF OPERATION

4.6.1 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.

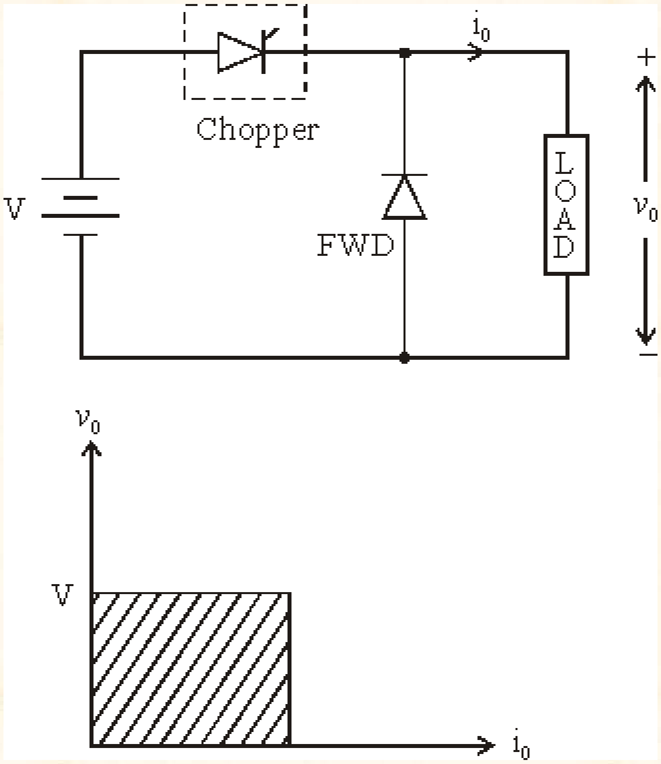


Figure: 3.10 circuit diagram and quadrant operation of Type A chopper

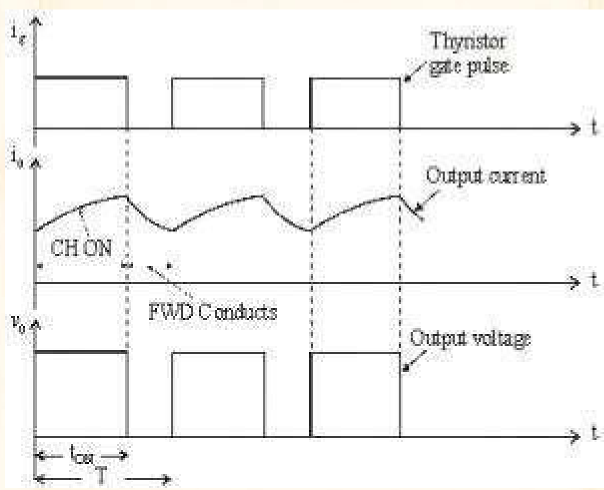


Figure: 3.11 Output voltage and current waveforms of type A chopper

Voltage equation for the circuit shown in figure is

$$V = i_O R + L\frac{di_O}{dt} + E$$

Taking Laplace Transform

$$\frac{V}{S} = RI_O(S) + L\left[S I_O(S) - i_O(0^-)\right] + \frac{E}{S}$$

At $t = 0$, initial current $i_O(0^-) = I_{min}$

$$I_O(S) = \frac{V-E}{LS\left(S+\frac{R}{L}\right)} + \frac{I_{min}}{S+\frac{R}{L}}$$

Taking Inverse Laplace Transform

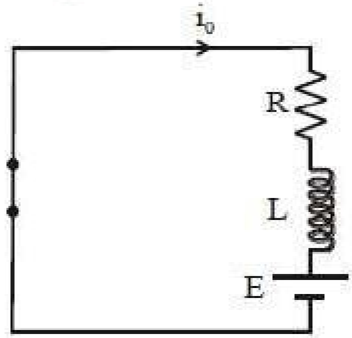
$$i_O(t) = \frac{V-E}{R}\left[1 - e^{-\left(\frac{R}{L}\right)t}\right] + I_{min}e^{-\left(\frac{R}{L}\right)t}$$

This expression is valid for $0 \le t \le t_{ON}$. i.e., during the period chopper is ON.

At the instant the chopper is turned off, load current is

$$i_O(t_{ON}) = I_{max}$$

When Chopper is OFF $\left(0 \le t \le t_{OFF}\right)$



Voltage equation for the circuit shown in figure is

$$0 = Ri_O + L\frac{di_O}{dt} + E$$

Taking Laplace transform

$$0 = RI_O(S) + L\left[SI_O(S) - i_O\left(0^-\right)\right] + \frac{E}{S}$$

Redefining time origin we have at $t = 0$, initial current $i_O\left(0^-\right) = I_{max}$

Therefore $$I_O(S) = \frac{I_{max}}{S + \frac{R}{L}} - \frac{E}{LS\left(S + \frac{R}{L}\right)}$$

TO FIND I_{max} AND I_{min}

At $t = t_{ON} = dT,\ \ i_O(t) = I_{max}$

4.6.2 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.

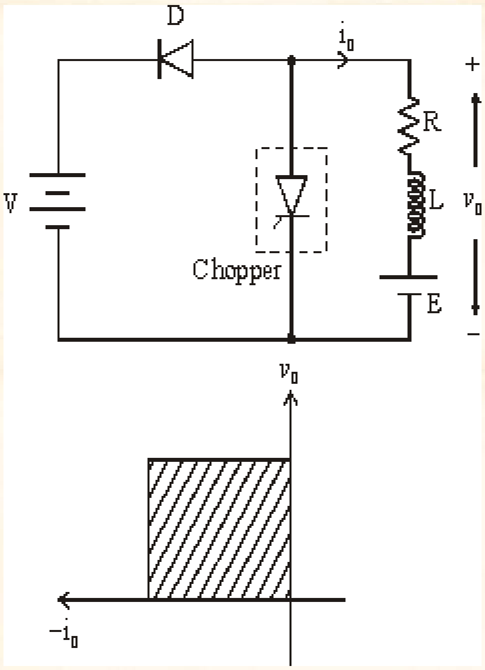


Figure: 3.12 Circuit diagram and quadrant operation of Type B chopper

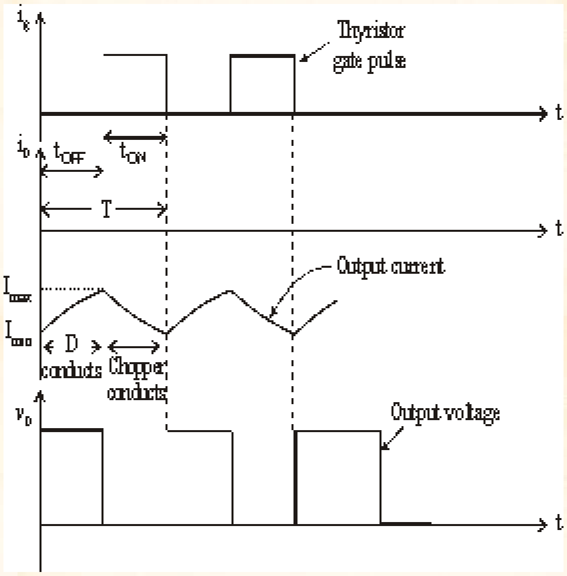


Figure: 3.13 Output voltage and current waveforms of type B chopper

4.6.3 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 D2 conducts.
- For second quadrant operation, CH2 is ON or D1 conducts.
- 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.

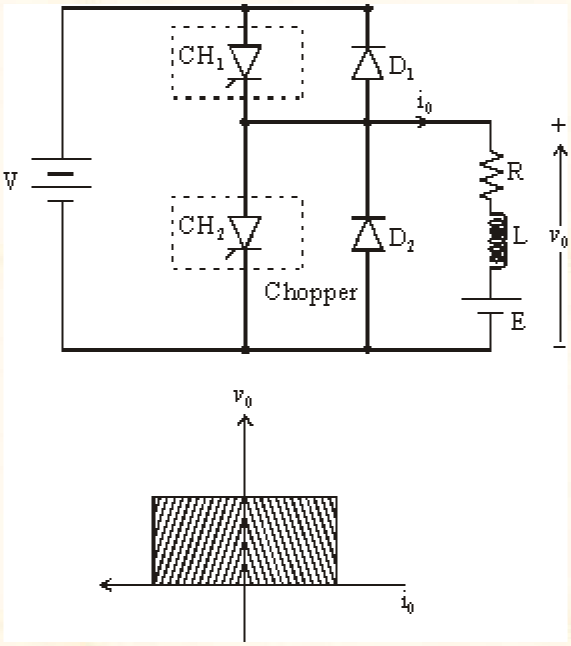


Figure: 3.14 Circuit diagram and quadrant operation of Type C chopper

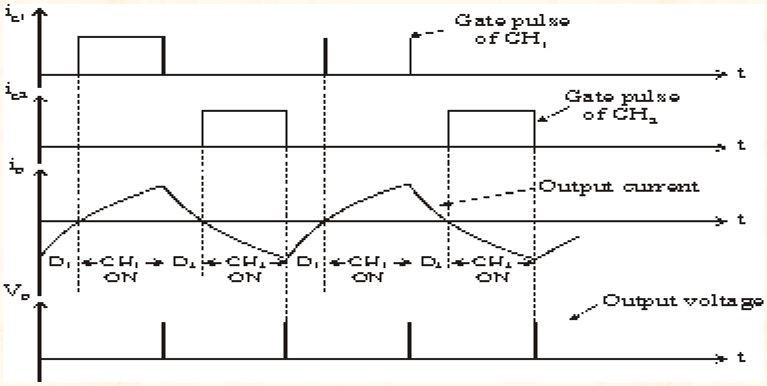


Figure: 3.15 Output voltage and current waveforms of type C chopper

4.6.4 CLASS D CHOPPER

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

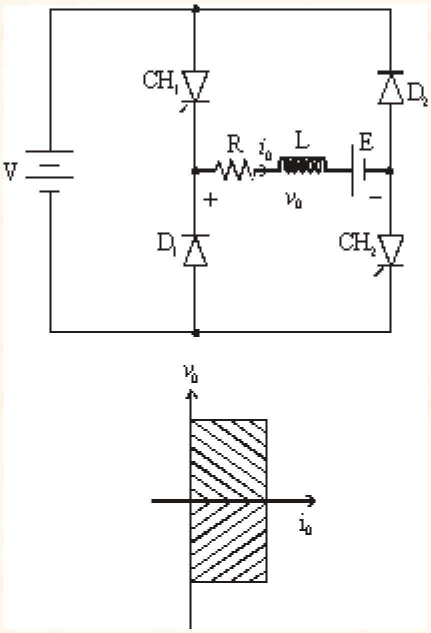


Figure: 3.16 Circuit diagram and quadrant operation of Type D chopper

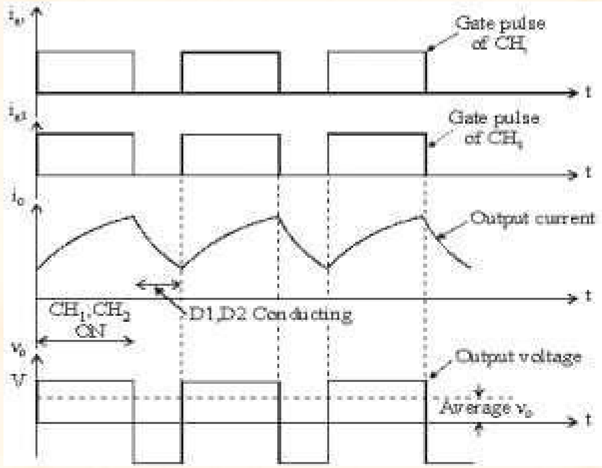


Figure: 3.17 Output voltage and current waveforms of type D chopper

4.6.5 CLASS E CHOPPER

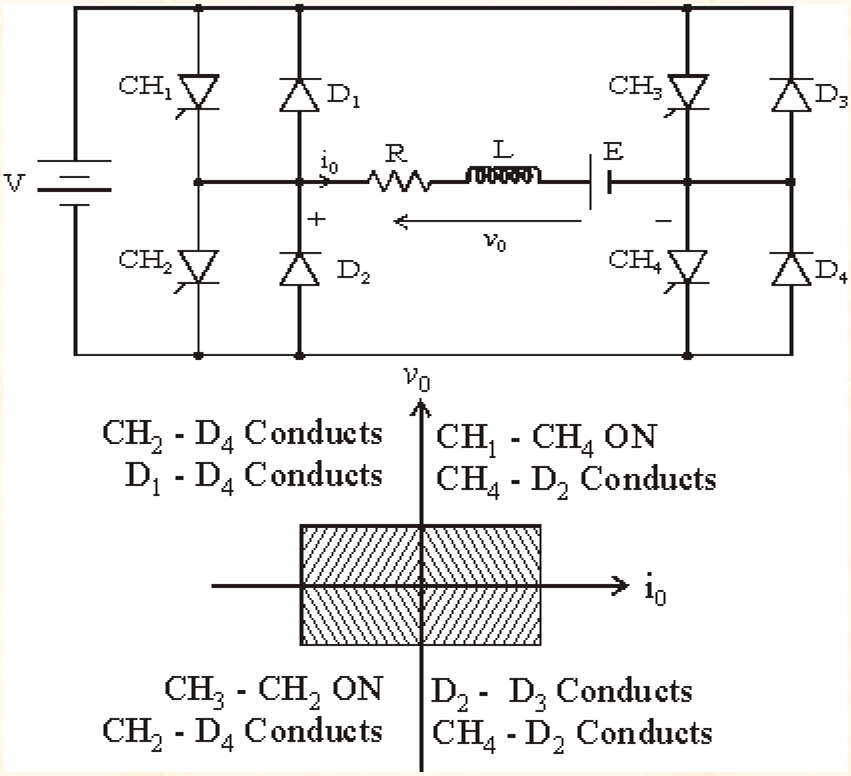


Figure: 3.18 Circuit diagram and quadrant operation of Type E chopper

- Class E is a four quadrant chopper
- When CH1 and CH4 are triggered, output current iO flows in positive direction through CH1 and CH4, and with output voltage vO = V.
- This gives the first quadrant operation.
- When both CH1 and CH4 are OFF, the energy stored in the inductor L drives iO through D2 and D3 in the same direction, but output voltage vO = -V.
- Therefore the chopper operates in the fourth quadrant.
- When CH2 and CH3 are triggered, the load current iO flows in opposite direction & output voltage vO
- = -V.
- Since both iO and vO are negative, the chopper operates in third quadrant.
- When both CH2 and CH3 are OFF, the load current iO continues to flow in the same direction D1 and D4 and the output voltage vO = V.
- Therefore the chopper operates in second quadrant as vO is positive but iO is negative.

4.7 BUCK REGULATOR

With power being a key parameter in many designs, step down or "buck" regulators are widely used.

Although a resistor would enable voltage to be dropped, power is lost, and in applications such as the many battery powered items used today, power consumption is a crucial element.

As a result step down switch mode converters or as they are more commonly termed, buck regulators are widely used.

4.8 LINEAR STEP DOWN

The most basic form of step down transition is to use a resistor as a potential divider or voltage dropper. In some cases a zener diode may also be used to stabilize the voltage.

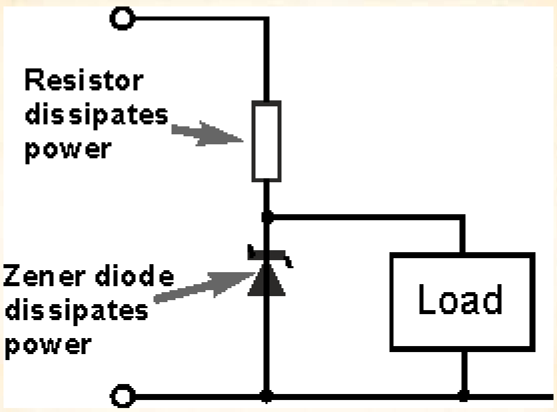


Figure: 3.19 Potential divider circuits

The issue with this form of voltage dropper or step down converter is that it is very wasteful in terms of power. Any voltage dropped across the resistor will be dissipated as heat, and any current flowing through the zener diode will also dissipate heat. Both of these elements result on the loss of valuable energy.

4.9 BASIC BUCK CONVERTER OR REGULATOR

The fundamental circuit for a step down converter or buck converter consists of an inductor, diode, capacitor, switch and error amplifier with switch control circuitry.

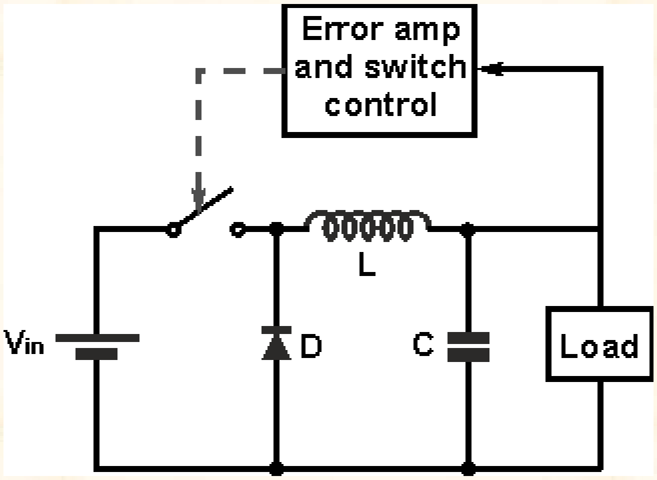


Figure: 3.20 circuit diagram of Buck regulator

The circuit for the buck regulator operates by varying the amount of time in which inductor receives energy from the source.

In the basic block diagram the operation of the buck converter or buck regulator can be seen that the output voltage appearing across the load is sensed by the sense / error amplifier and an error voltage is generated that controls the switch.

Typically the switch is controlled by a pulse width modulator, the switch remaining on of longer as more current is drawn by the load and the voltage tends to drop and often there is a fixed frequency oscillator to drive the switching.

4.10 BUCK CONVERTER OPERATION

When the switch in the buck regulator is on, the voltage that appears across the inductor is Vin - Vout. Using the inductor equations, the current in the inductor will rise at a rate of (Vin-Vout)/L. At this time the diode D is reverse biased and does not conduct.

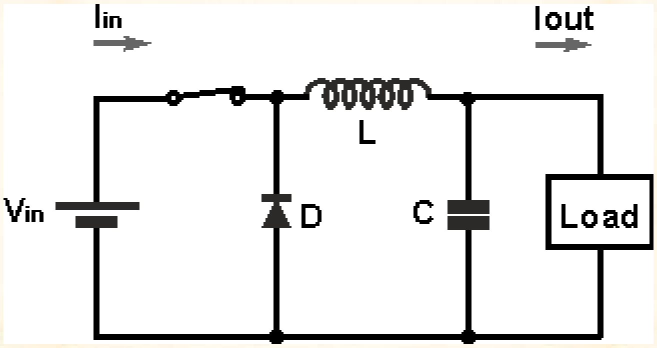


Figure: 3.21 Circuit diagram of Buck regulator during switch on condition

When the switch opens, current must still flow as the inductor works to keep the same current flowing. As a result current still flows through the inductor and into the load. The diode, D then forms the return path with a current I,diode equal to I out flowing through it.

With the switch open, the polarity of the voltage across the inductor has reversed and therefore the current through the inductor decreases with a slope equal to -Vout/L.

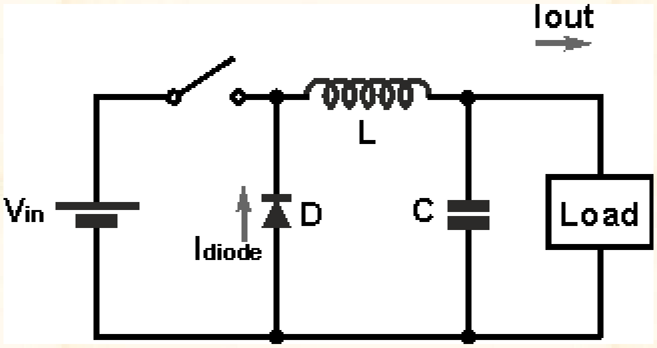


Figure: 3.22 circuit diagram of Buck regulator during switch off condition

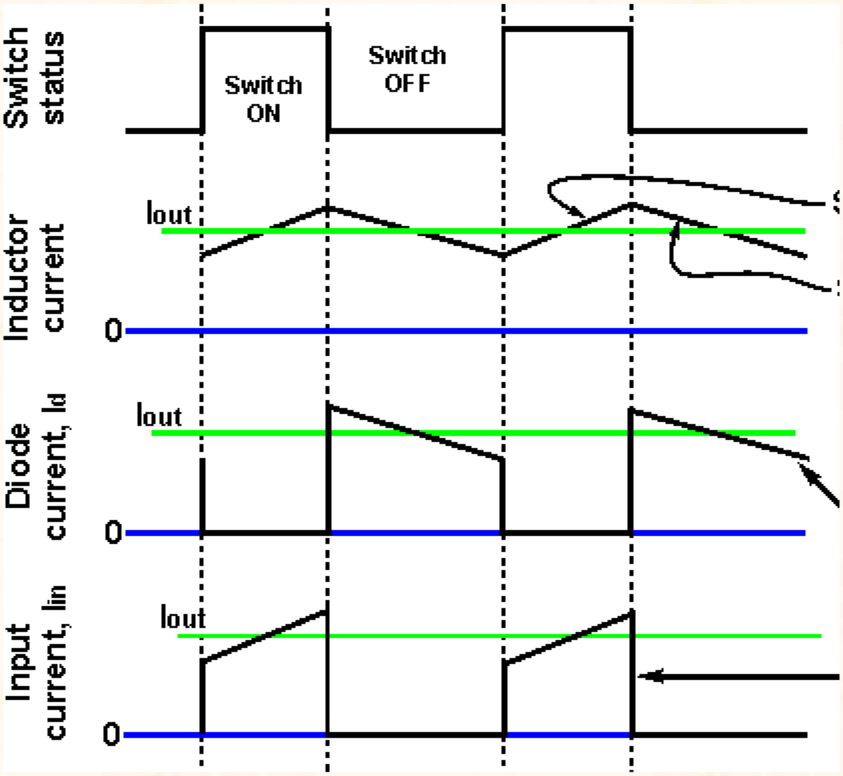


Figure: 3.23 Input and output waveforms of Buck regulator

In the diagram of the current waveforms for the buck converter / switching regulator, it can be seen that the inductor current is the sum of the diode and input / switch current. Current either flows through the switch or the diode.

It is also worth noting that the average input current is less than the average output current. This is to be expected because the buck converter circuit is very efficient and the input voltage is greater than the output voltage. Assuming a perfect circuit, then power in would equal power out, i.e. Vin · In = Vout · Iout. While in a real circuit there will be some losses, efficiency levels greater than 85% are to be expected for a well-designed circuit.

It will also be seen that there is a smoothing capacitor placed on the output. This serves to ensure that the voltage does not vary appreciable, especially during and switch transition times. It will also be required to smooth any switching spikes that occur.

4.11 BOOST REGULATOR

One of the advantages of switch mode power supply technology is that it can be used to create a step up or boost converter / regulator.

Boost converters or regulators are used in many instances from providing small supplies where higher voltages may be needed to much higher power requirements.

Often there are requirements for voltages higher than those provided by the available power supply - voltages for RF power amplifiers within mobile phones is just one example.

4.12 STEP-UP BOOST CONVERTER BASICS

The boost converter circuit has many similarities to the buck converter. However the circuit topology for the boost converter is slightly different. The fundamental circuit for a boost converter or step up converter consists of an inductor, diode, capacitor, switch and error amplifier with switch control circuitry.

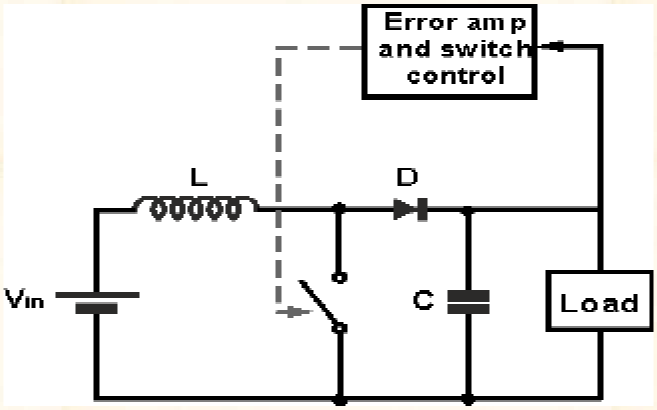


Figure: 3.24 Circuit diagram of Boost regulator

The circuit for the step-up boost converter operates by varying the amount of time in which inductor receives energy from the source.

In the basic block diagram the operation of the boost converter can be seen that the output voltage appearing across the load is sensed by the sense / error amplifier and an error voltage is generated that controls the switch.

Typically the boost converter switch is controlled by a pulse width modulator, the switch remaining on of longer as more current is drawn by the load and the voltage tends to drop and often there is a fixed frequency oscillator to drive the switching.

4.13 BOOST CONVERTER OPERATION

The operation of the boost converter is relatively straightforward.

When the switch is in the ON position, the inductor output is connected to ground and the voltage Vin is placed across it. The inductor current increases at a rate equal to Vin/L.

When the switch is placed in the OFF position, the voltage across the inductor changes and is equal to Vout-Vin. Current that was flowing in the inductor decays at a rate equal to (Vout-Vin)/L.

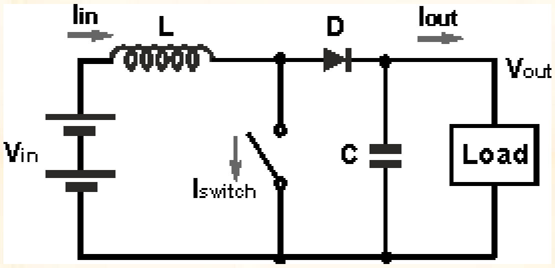


Figure: 3.25 Circuit diagram of Boost regulator during switch off condition

Referring to the boost converter circuit diagram, the current waveforms for the different areas of the circuit can be seen as below.

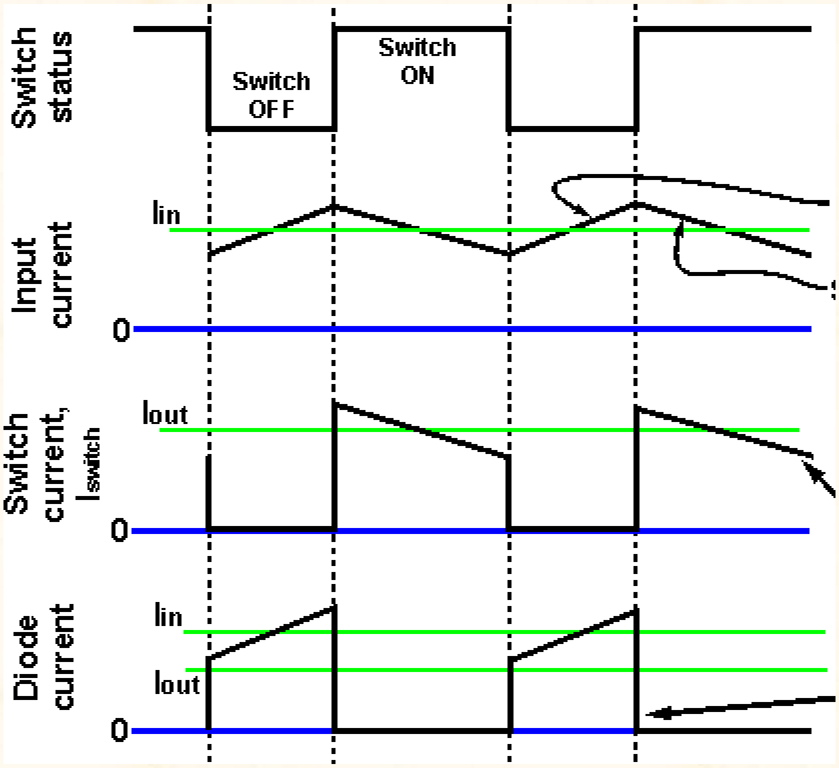


Figure: 3.26 Input and output waveforms of Boost regulator

It can be seen from the waveform diagrams that the input current to the boost converter is higher than the output current. Assuming a perfectly efficient, i.e. lossless, boost converter, the power out must equal the power in, i.e. Vin · Iin = Vout · Iout. From this it can be seen if the output voltage is higher than the input voltage, then the input current must be higher than the output current.

In reality no boost converter will be lossless, but efficiency levels of around 85% and more are achievable in most supplies.

4.14 BUCK BOOST REGULATOR

A simple buck converter can only produce voltages lower than the input voltage, and a boost converter, only voltages higher than the input. To provide voltages over the complete range a circuit known as a buck-boost converter is required.

There are many applications where voltages higher and lower than the input are required. In these situations a buck-boost converter is required.

BUCK-BOOST CONVERTER BASICS

The buck-boost DC-DC converter offers a greater level of capability than the buck converter of boost converter individually, it as expected it extra components may be required to provide the level of functionality needed.

There are several formats that can be used for buck-boost converters:

+Vin, -Vout:

This configuration of a buck-boost converter circuit uses the same number of components as the simple buck or boost converters. However this buck-boost regulator or DC-DC converter produces a negative output for a positive input. While this may be required or can be accommodated for a limited number of applications, it is not normally the most convenient format.

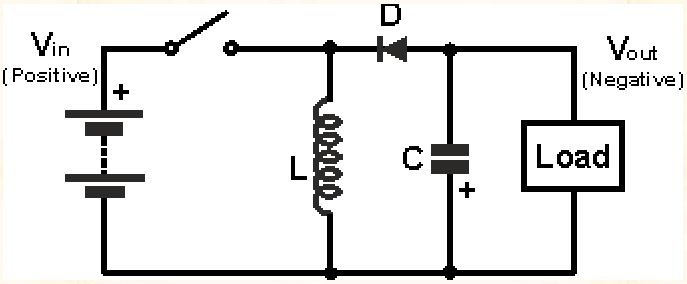


Figure: 3.27 Circuit diagram of buck boost regulator

- When the switch in closed, current builds up through the inductor. When the switch is opened the inductor supplies current through the diode to the load.
- Obviously the polarities (including the diode) within the buck-boost converter can be reversed to provide a positive output voltage from a negative input voltage.

+Vin, +Vout:

The second buck-boost converter circuit allows both input and output to be the same polarity. However to achieve this, more components are required. The circuit for this buck boost converter is shown below.

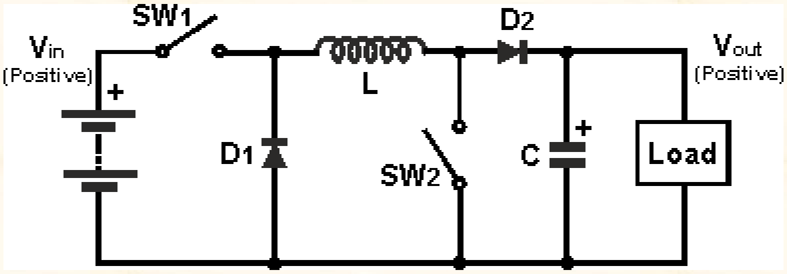


Figure: 3.28 Circuit diagram of buck boost regulator with two switches

In this circuit, both switches act together, i.e. both are closed or open. When the switches are open, the inductor current builds. At a suitable point, the switches are opened. The inductor then supplies current to the load through a path incorporating both diodes, D1 and D2.

UNIT V - INVERTERS

5.1 INTRODUCTION TO INVERTERS

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

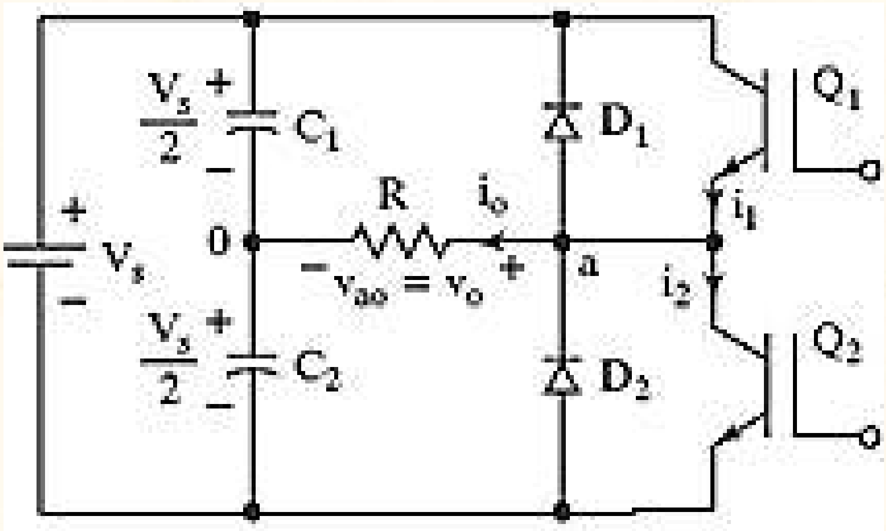


Figure: 5.1 Single phase Half Bridge DC-AC inverter with R load

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

1. The current entering node a is considered to be positive.
2. The switches S1 and S2 are unidirectional, i.e. they conduct current in one direction.
3. The current through S1 is denoted as i1 and the current through S2 is i2.

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 v o = Vin/ 2

When the switch S2 is only turned on, the voltage across the load is v o = Vin/ 2.

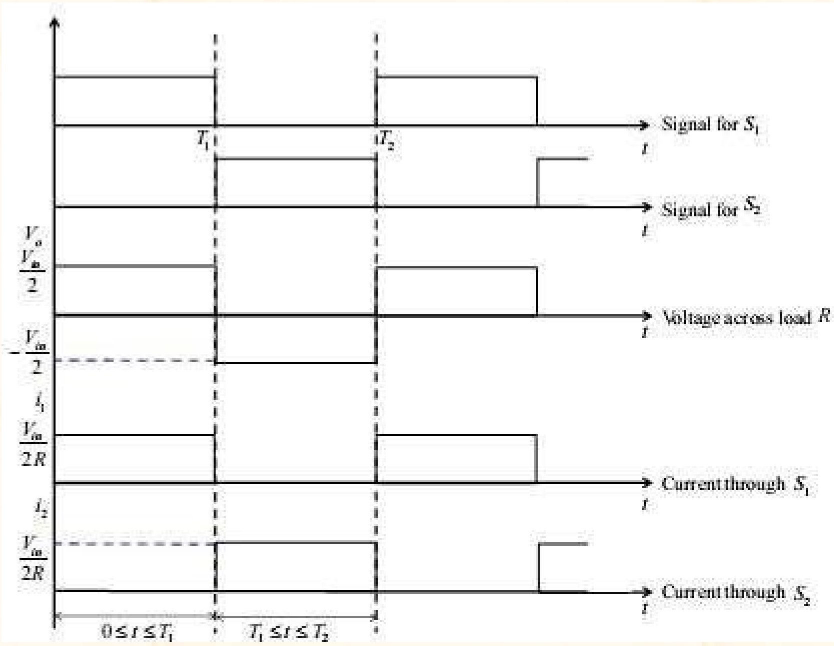


Figure: 5.2 Single phase Half Bridge DC-AC inverter output waveforms

The r.m.s 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 bn from above equation , we get

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

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

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

5.2 HALF BRIDGE DC-AC INVERTER WITH L LOAD AND R-L LOAD

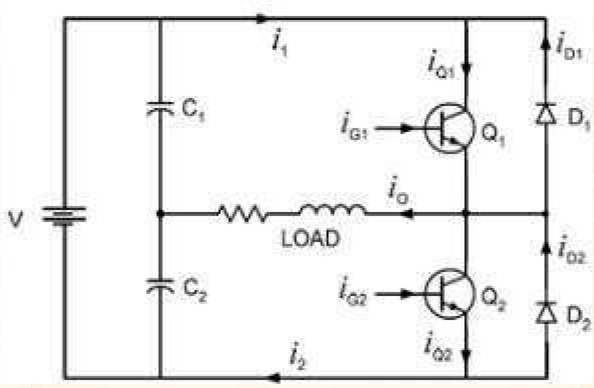


Figure: 5.3 Single phase Half Bridge DC-AC inverter with RL load

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.

The working of the DC-AC inverter with inductive load is as follow is:

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.

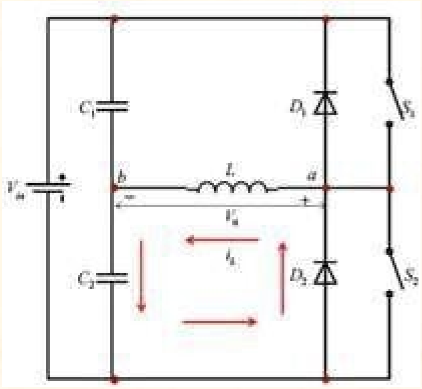


Figure: 5.4 Single phase Half Bridge DC-AC inverter with L load

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.

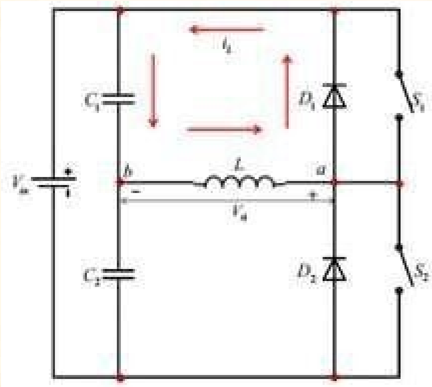


Figure: 5.5 Single phase Half Bridge DC-AC inverter with L load

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,

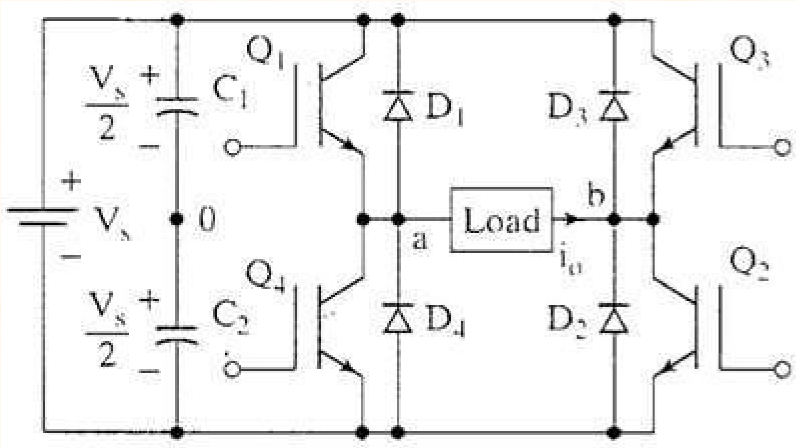
$$i_L = \sum_{n=1,3,5,...}^{\infty} \frac{2V_{in}}{n\pi\sqrt{R^2 + (n\omega L)^2}} \sin(n\omega t - \theta_n)$$

Where,

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

5.3 OPERATION OF SINGLE PHASE FULL BRIDGE INVERTER

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



1. The current entering node a in Figure 8 is considered to be positive.
2. The switches S1, S2, S3 and S4 are unidirectional, i.e. they conduct current in one direction.

Figure: 5.6 Single phase Full Bridge DC-AC 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 ==> $v_o = V_s$

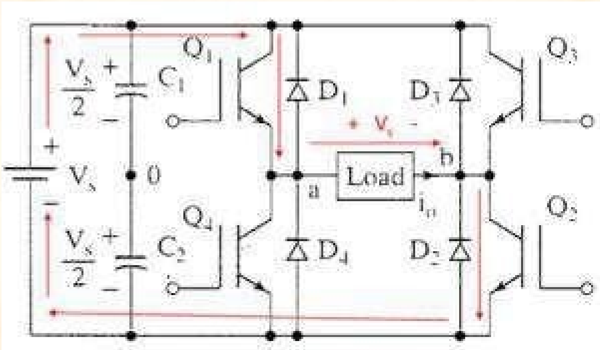


Figure: 5.7 Single phase Full Bridge DC-AC inverter with R load

If the switches S3 and S4 turned on duration T1 ≤ t ≤ 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 = -Vs

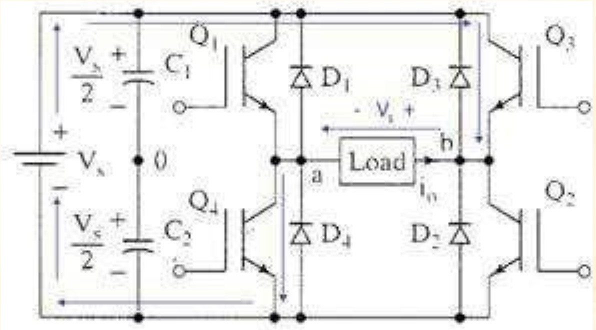


Figure: 5.8 Single phase Full Bridge DC-AC inverter with R load current directions

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

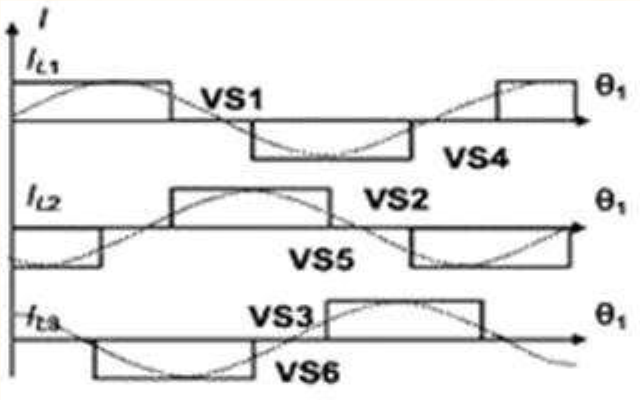


Figure: 5.9 Single phase Full Bridge DC-AC inverter waveforms

5.4 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.

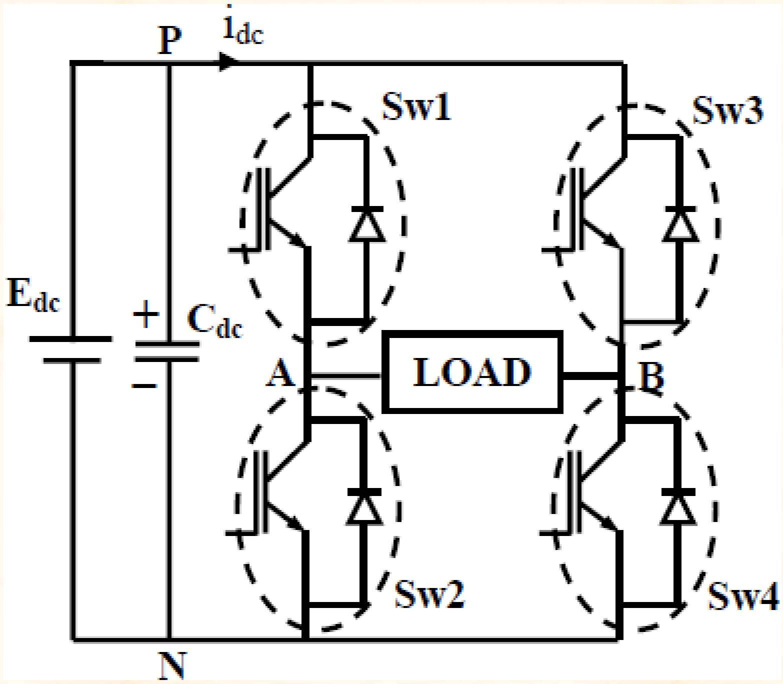


Figure: 5.10 Single phase Full Bridge DC-AC inverter with L load

The above topology is analyzed under the assumption of ideal circuit conditions. Accordingly, it is assumed that the input dc voltage (Edc) 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.

5.5 SERIES INVERTER:

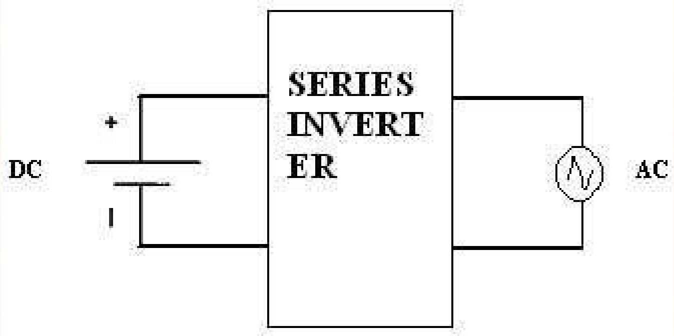


Figure: 5.11 Block diagram of series Inverter

In series inverter, the commutating elements L and C are connected in series with the load. This constitutes a series RLC resonant circuit. The Two SCRs are used to produce the halves (positive and negative half cycle) in the output.

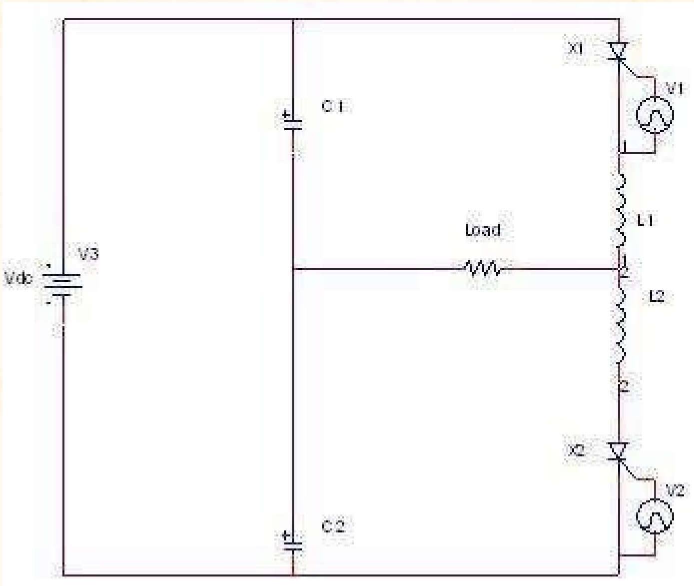


Figure: 5.12 Circuit diagram of series inverter

In the first half of the output currents when SCR T1 is triggered it will allow the current to flow through L1, and load, and C2 thus charging. The capacitor C1 which is already charged at these instant discharges through SCR1, L1 and the Load. Hence 50% of the current is drawn from the input source and 50% from the capacitor. Similarly in the second half of the output current C1 will be charged and C2 will discharge through the load, L2 and SCR2, Again 50% of the load current is obtained from the DC input source and rest from the capacitor. The SCRs T1 and T2 are alternatively fired to get AC voltage and current.

5.6 OPERATION OF PARALLEL INVERTER

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

The operation of this inverter can be explained in the following modes.

Mode I

In this mode, SCR T1 is conducting and a current flow in the upper half of primary winding. SCR T2 is OFF. As a result an emf Vs is induced across upper as well as lower half of the primary winding.

In other words total voltage across primary winding is 2 Vs. Now the capacitor C charges to a voltage of 2Vs with upper plate as positive.

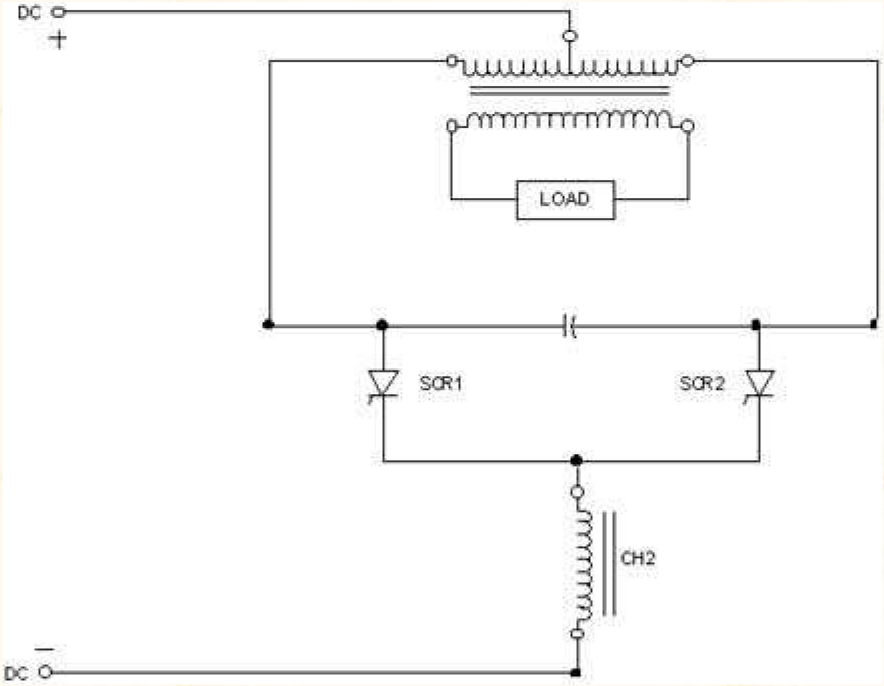


Figure: 5.13 Circuit diagram of parallel inverter

Mode II

At time to, T2 is turned ON by applying a trigger pulse to its gate. At this time t=0, capacitor voltage 2Vs appears as a reverse bias across T1, it is therefore turned OFF. A current Io begins to flow through T2 and lower half of primary winding. Now the capacitor has charged (upper plate as negative) from +2Vs to -2Vs at time t=t1. Load voltage also changes from Vs at t=0 to – Vs at t=t1.

Mode III

When capacitor has charged to –Vs, T1 may be tuned ON at any time When T1 is triggered, capacitor voltage 2Vs applies a reverse bias across T2, it is therefore turned OFF. After T2 is OFF, capacitor starts discharging, and charged to the opposite direction, the upper plate as positive.

5.7 PARALLELED COMMUTATED INVERTER

The above Fig 1: is a schematic of the classical parallel commutated square wave inverter bridge. It is being included here for illustrative purposes since most other circuits utilize this circuit or a variation there of. The waveform generated and supplied to the load is basically a square wave having a peak to peak amplitude of twice the DC supply voltage and a period that is determined by the relate at which SCRs 1 through 4 are gated on. The SCRs are turned on in pairs by simultaneously applying signals to the gate terminals of SCRs 1 and 4 or SCRs 2 and 3. If SCRs 1 and 4 happen to be the first two switched on a current will flow from the positive terminal of the source through negative terminal of the source. This will establish a left to right, plus to minus voltage relationship on the load.

Simultaneously, the left terminal of capacitor C1 will be charged positively with respect to the right negative terminal. The steady-state load current through the various components is determined nearly completely by the impedance of the load. Chokes 1 and 2 and SCRs 1 and 4 present very low steady-state drops and therefore nearly all the source voltage appears across the load. Conduction of SCRs 1 and 4 will continue to the end of the half cycle, at which point the gates are removed from SCRs 1 and 4 remain in conduction along with SCRs 2 and 3 that have now been turned on. If it were not for chokes 1 and 2, the action of turning on the second set of SCRs would place very low impedance and therefore momentarily prevent the source from being short-circuited.

Capacitor C1 now discharges with a current which flows into the cathode of SCR 1 through SCR 2 in a forward direction back to the negative terminal of the capacitor. This direction of current flow causes SCR 1 to become non-conductive provided that the reverse current through the SCR is of sufficient duration for the SCR to again become blocking. C1 simultaneously discharges through SCR 3 in a forward direction and through SCR 4 in a reverse direction. This will cause SCR 4 to become non-conductive just the same SCR 1. This entire sequence is referred to as commutation and typically in a modern inverter would occur in a period of time less than 50 microseconds. During this interval, chokes 1and 2 must have sufficient transient impedance to prevent a significant increase in current from the DC source.

Diodes 1, 2, 3 and 4 serve two functions. The first is to return any stored energy that may be "kicked back" from the load to the source. They also serve to prevent the choke from generating a high transient voltage immediately after commutation.

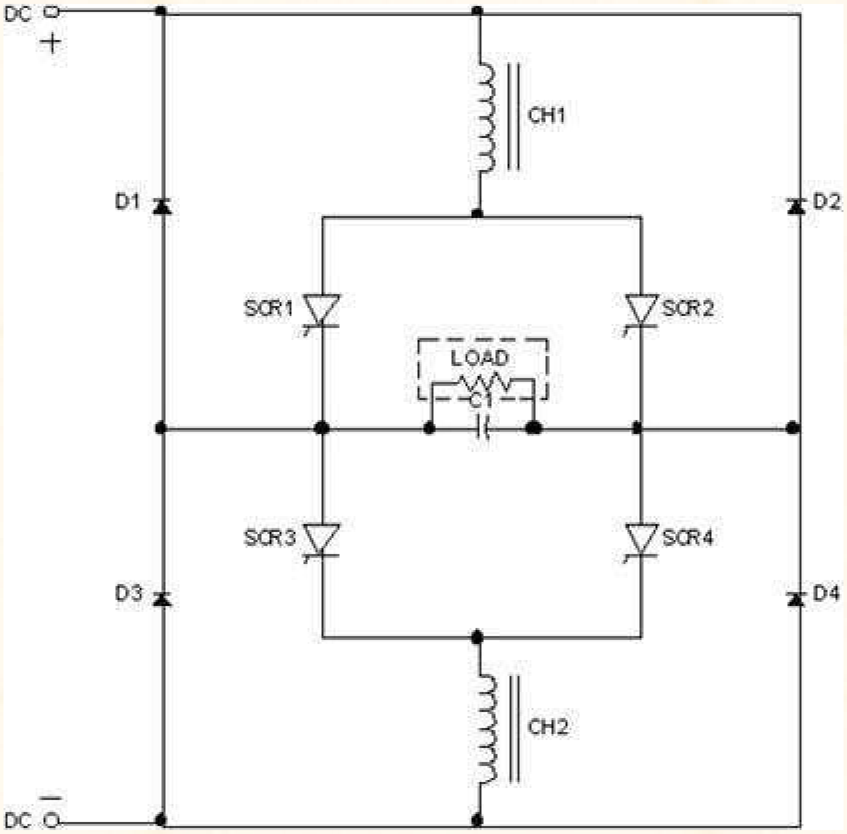


Figure: 5.14 Circuit diagram of parallel commutated inverter

5.8 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

5.9 VOLTAGE CONTROL TECHNIQUES FOR INVERTERS

5.9.1 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

$$y = \frac{1}{T}\int_{0}^{T} f(t)dt$$

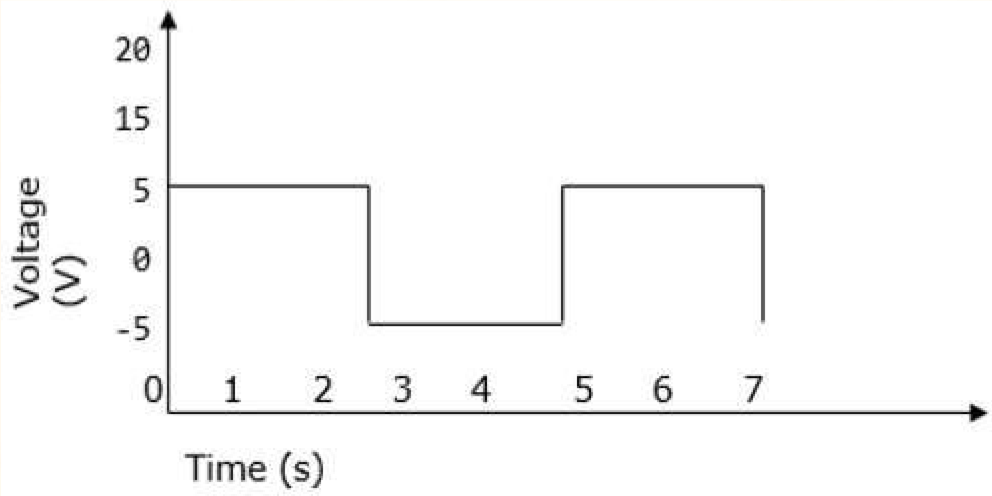


Figure: 5.27 Square waveform used for PWM technique

5.10 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.

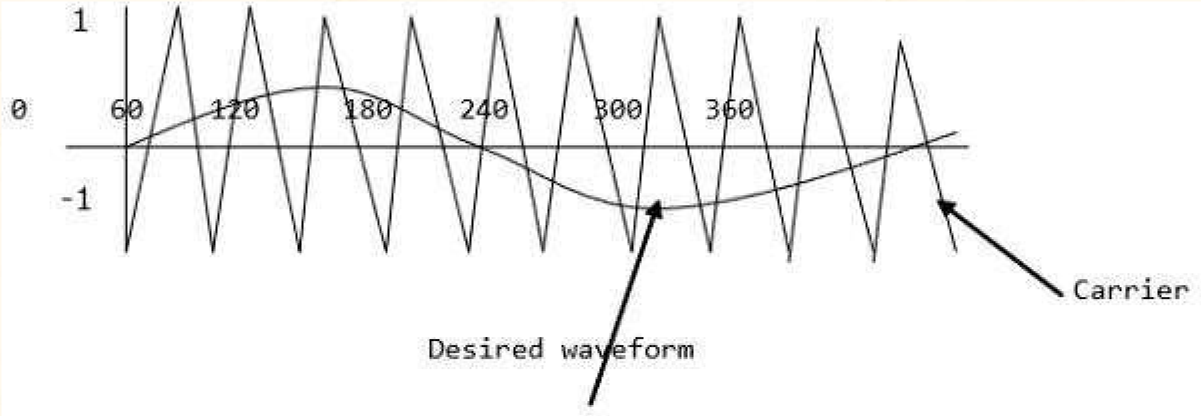


Figure: 5.28 Sinusoidal PWM waveform

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

5.11 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.

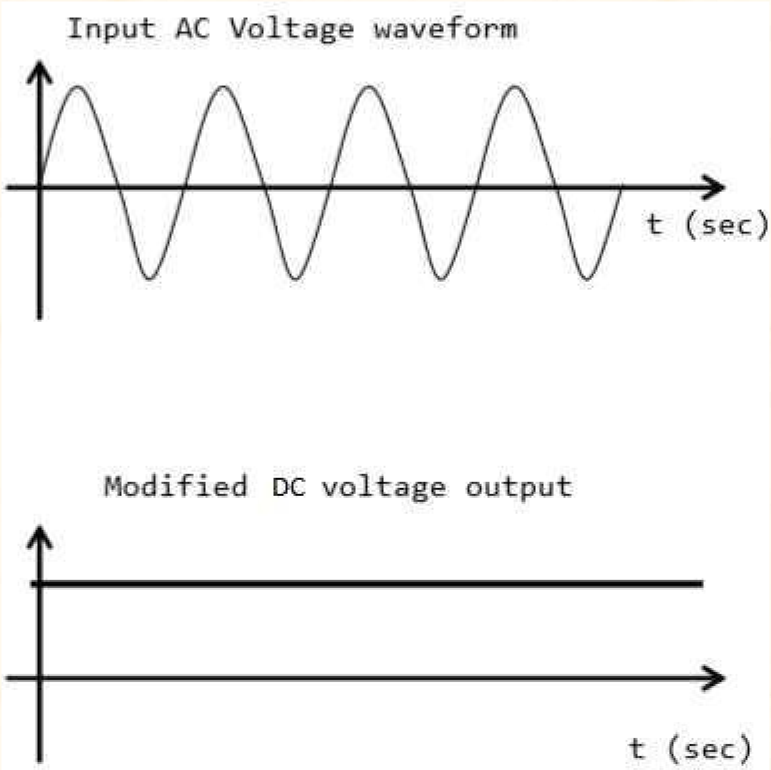


Figure: 5.29 Modified sinusoidal PWM waveform

5.12 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.

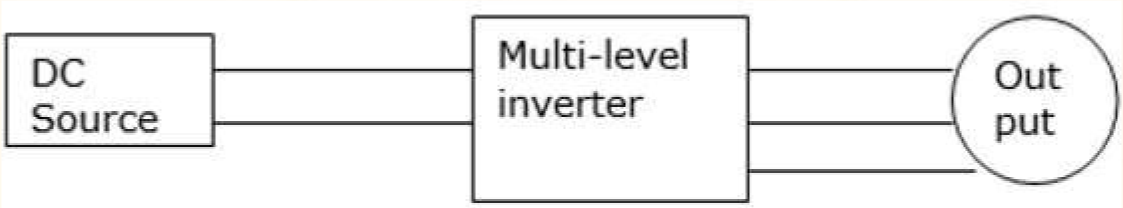


Figure: 5.30 Block diagram of multiple PWM technique

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

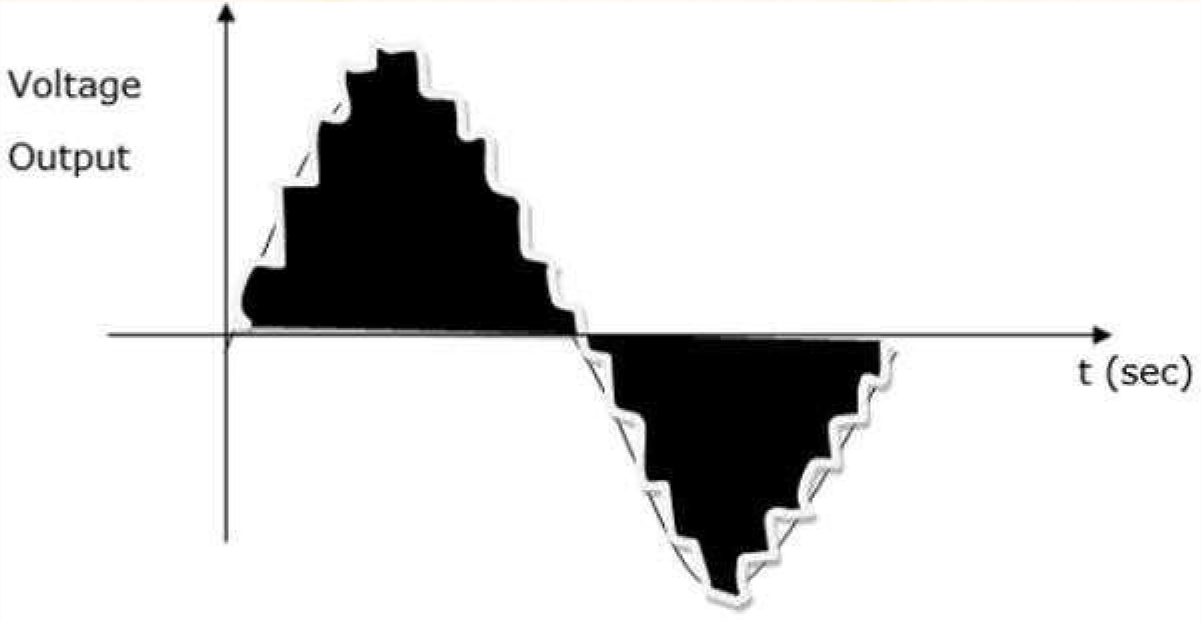


Figure: 5.31 Waveform of multiple PWM technique

5.13 VOLTAGE AND HARMONIC CONTROL

A periodic waveform that has frequency, which is a multiple integral of the fundamental power with frequency of 60Hz is known as a harmonic. Total harmonic distortion (THD) on the other hand refers to the total contribution of all the harmonic current frequencies.

Harmonics are characterized by the pulse that represents the number of rectifiers used in a given circuit.

It is calculated as follows $h=(n \times P)+1 or -1$

Where **n** – is an integer 1, 2, 3, 4….n

P – Number of rectifiers

Harmonics have an impact on the voltage and current output and can be reduced using isolation transformers, line reactors, redesign of power systems and harmonic filters.

5.14 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.

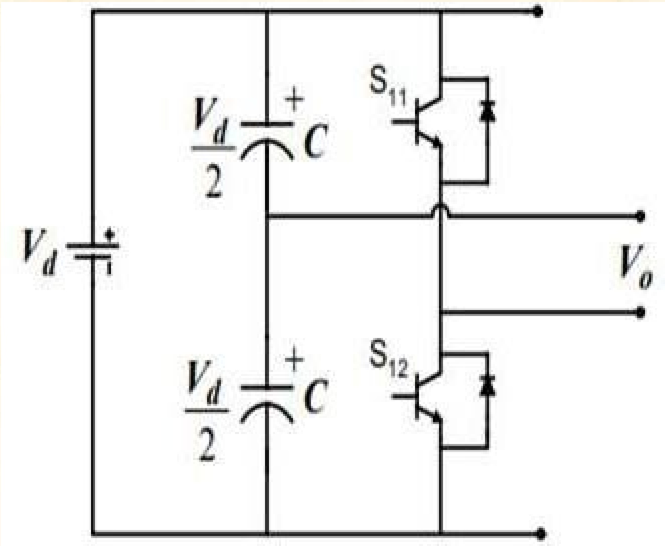


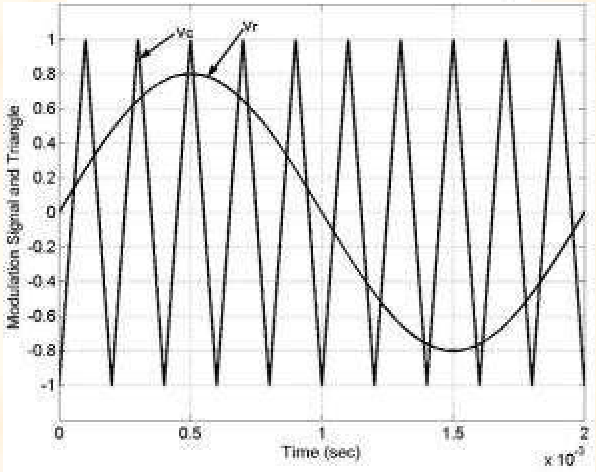
Figure: 5.32 Schematic diagram of Half bridge PWM inverter

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 vc the peak value of triangular carrier wave and VR is that of the reference, or modulating signal. The figure shows the triangle and modulation signal with some arbitrary frequency and magnitude. In the inverter of Figure 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.

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

and

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



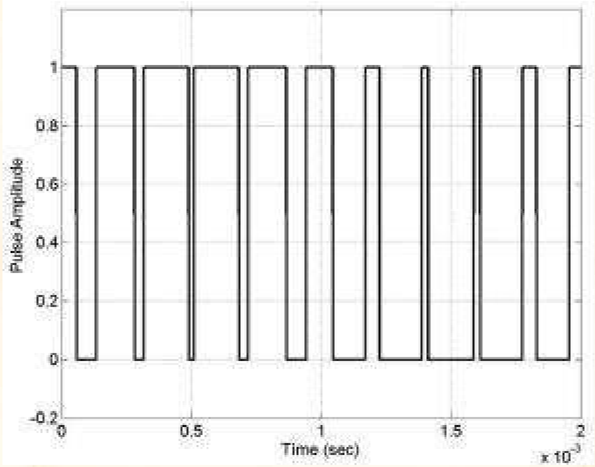


Figure: 5.33 Sine-Triangle Comparison and switching pulses of half bridge PWM inverter

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 Vr/VC 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

fr

M

F = *fm*

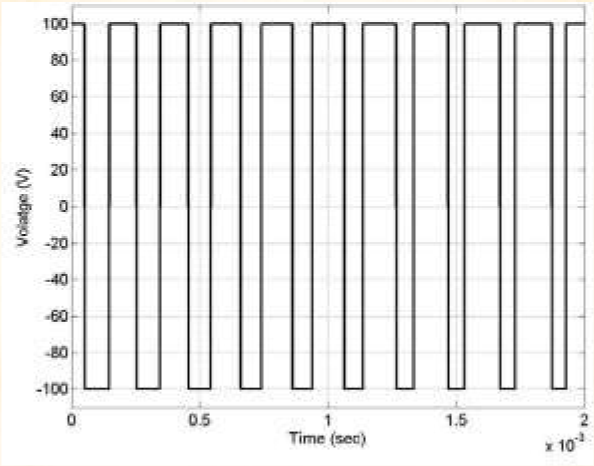


Figure: 5.34 Output voltage of the Half-Bridge inverter

5.15 OPERATION OF CURRENT SOURCE INVERTER WITH IDEAL SWITCHES

5.15.1 SINGLE-PHASE CURRENT SOURCE INVERTER

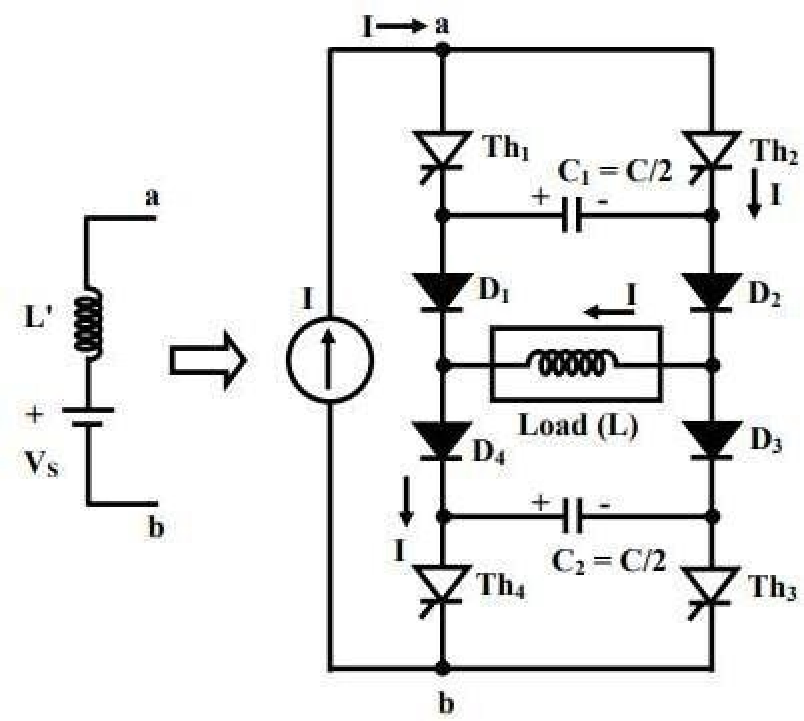


Figure: 5.35 Single phase current source inverter (CSI) of ASCI type

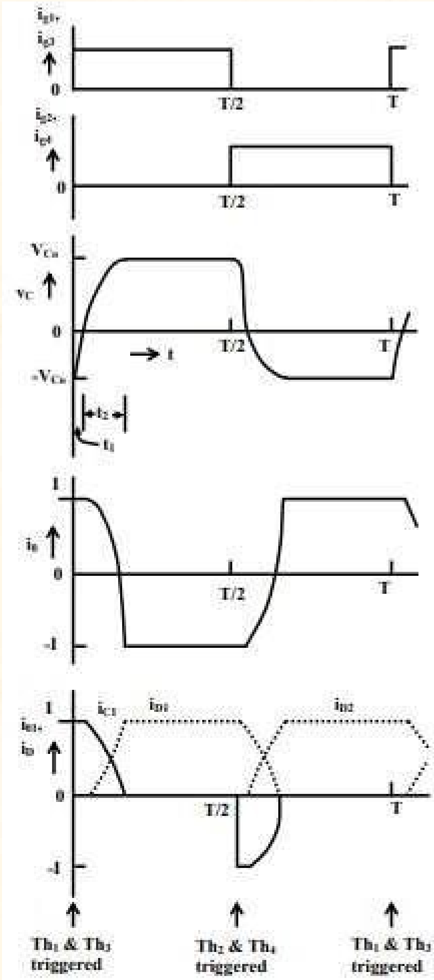


Figure: 5.36 Output waveforms of Single phase current source inverter

The circuit of a Single-phase Current Source Inverter (CSI) is shown in Fig. 5.35. 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. 5.36). 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.

Mode I:

The circuit for this mode is shown in Fig. 5.37. 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.

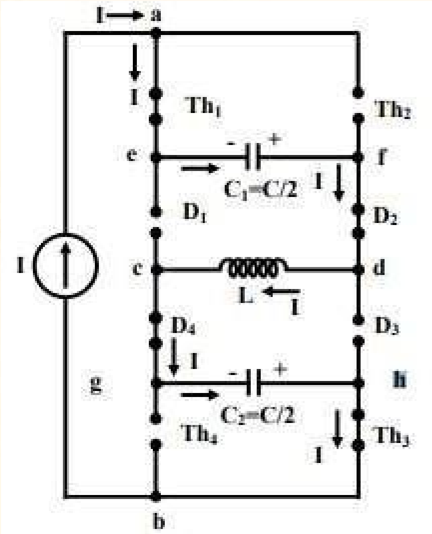


Figure: 5.37 Mode I operation of CSI

Mode II:

The circuit for this mode is shown in Fig. 5.38. Diodes, D2 & D4, are already conducting, but at = tt 1 , 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).

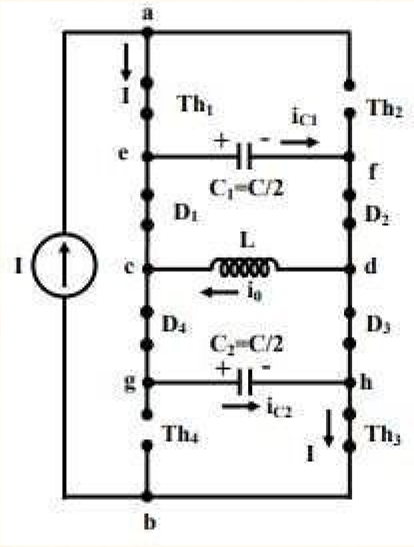


Figure: 5.38 Mode II operation of CSI

வையத்தலைமை கொள் - Lead the World

Ananda Chaitanya Foundation's Skill Development Initiative About the Initiative: Vaiya Thalamai Kol (Lead the World) is a skill development initiative by the Ananda Chaitanya Foundation, aimed at empowering individuals with essential technical and soft skills. Conducted under ACTA (Ananda Chaitanya Training Academy), this program bridges the gap between academic knowledge and industry requirements, providing hands-on training in cutting-edge technologies and professional development. Industry Collaboration: These programs are conducted in association with top industries like MAK Controls, Suntech, FX Multi-tech, etc., as part of their CSR activities. Unique aspects: We offer expert-led programs in:

Unique aspects:

- Training sessions led by industry experts with 15-20 years of experience
- Professionals volunteer their time to mentor and guide participants.
- This ensures high-quality, practical learning directly from professionals who have deep domain expertise.

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Our Mission:

This initiative nurtures talent, enhance employability, and create a future-ready workforce through industry-relevant skill development.

SUMMARY

Power electronics a subfield of electrical engineering that deals with the design, control, and conversion of electrical power from one form to another. It involves the use of solid-state electronics, such as transistors and diodes, to control and manipulate high-power electrical energy.

Note: This e-book has been compiled from various resources of Internet and by the personal knowledge of the team involved. It covers the basic topics as required by the Industries.

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