Lecture Notes

on

"23EE501 - POWER ELECTRONICS"

Submitted by

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SECUNDERABAD-14

(2025-2026)

SYLLABUS

23EE501: Power Electronics

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Prerequisites: Analog Electronics, Digital Electronics.

Course Objectives:

- To Design/develop suitable power converter for efficient control or conversion of power in drive applications
- To Design / develop suitable power converter for efficient transmission and utilization of power in power system applications.

Course Outcomes: Students will be able to

- Apply the basic operation and characteristics of various power semiconductor devices and intelligent power module.
- Design AC/DC rectifier circuit
- Evaluate chopper circuits
- Examine three phase inverter circuits
- Create AC voltage controller circuits

UNIT- I

Power Switching Devices:

Concept of power electronics, scope and applications, types of power converters; Power semiconductor switches and their V-I characteristics - Power Diodes, Power BJT, SCR, Power MOSFET, Power IGBT; Thyristor ratings and protection, Series and parallel connections of SCRs, Two transistor analogy of SCR, methods of SCR commutation, UJT as a trigger source, gate drive circuits for BJT and MOSFETs.

UNIT-II

AC-DC Converters(Phase Controlled Rectifiers):

Principles of single-phase fullycontrolled converter with R, RL, and RLE load, Principles of single- phase half-controlled converter with RL and RLE load, Principles of three-phase fully-controlled converter operation with RLE load, Effect of load and source inductances, General idea of gating circuits, Single phase and Three phase dual converters.

UNIT-III

DC-DC Converters (Chopper/SMPS):

Introduction, elementary chopper with an active switch and diode, concepts of duty ratio, average inductor voltage, average capacitor current. Buck converter -Power circuit, analysis and waveform at steady state, duty ratio control of output voltage. Boost converter - Power circuit, analysis and waveforms at steady state, relation between duty ratio and average output voltage. Buck-Boost converter-Power circuit, analysis and waveforms at steady state, relation between duty ratio and average output voltage

UNIT-IV

AC-DC Inverters:

Introduction, principle of operation, performance parameters, single phase bridge inverters with R, RL loads, 3-phase bridge inverters - 120- and 180- degrees mode of operation, Voltage control of single-phase inverters–single pulse width modulation, multiple pulse width modulation, sinusoidal pulse width modulation.

UNIT-V

AC-AC Converters:

Phase Controller (AC Voltage Regulator) - Introduction, modes of operation of Triac, principle of operation of single-phase voltage controllers for R, R-L loads and its applications. Cyclo-converter-Principle of operation of single phase cyclo-converters, relevant waveforms, circulating current mode of operation, Advantages and disadvantages.

TEXT BOOKS:

1. M. H. Rashid, "Power electronics: circuits, devices, and applications", Pearson Education India, 2009.
2. N. Mohan and T. M. Undeland, "Power Electronics: Converters, Applications and Design", John Wiley & Sons, 2007.

REFERENCES:

1. R. W. Erickson and D. Maksimovic, "Fundamentals of Power Electronics" Springer Science &Business Media, 2007.
2. L. Umanand, "Power Electronics: Essentials and Applications", Wiley India, 2009.

UNIT – I
Power Switching 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 may be defined as the subject of applications of solid state power semiconductor devices (Thyristors) for the control and conversion of electric power. Power electronics deals with the study and design of thyristor based power controllers for variety of application like Heat control, Light/Illumination control and Motor control - AC/DC motor drives used in industries, High voltage power supplies, Vehicle propulsion systems, High voltage direct current (HVDC) transmission.

Power Electronics refers to the process of controlling the flow of current and voltage and converting it toa form that is suitable for user loads. The most desirable power electronic system is one whose efficiencyand reliability is 100%.

Take a look at the following block diagram. It shows the components of a Power Electronic system and how they are interlinked.

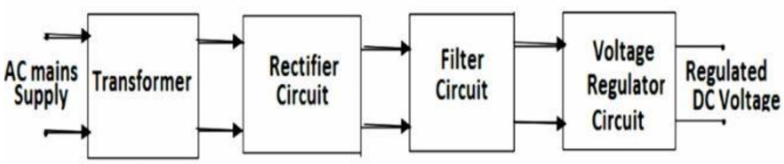


Figure: 1.1. Block diagram of DC power supply

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

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

Applications of Power Electronics are classified into two types − Static Applications and Drive Applications.

StaticApplications

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

DC Power Supply

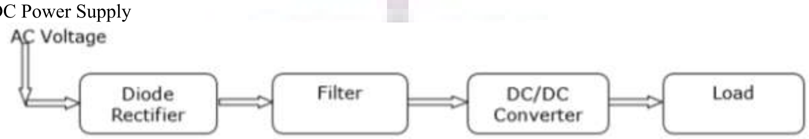


Figure: 1.2. Block diagram of DC power supply

DriveApplications

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

Air Conditioning System

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

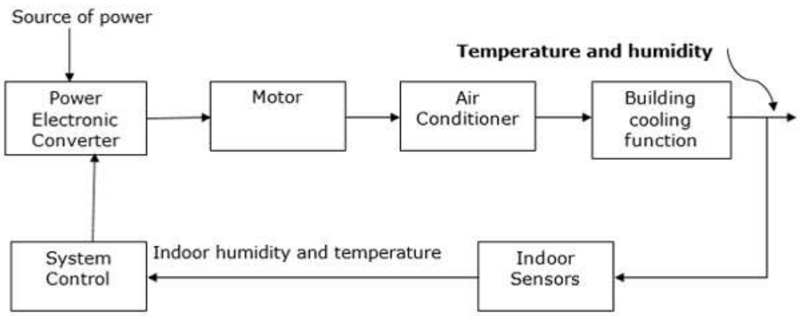


Figure: 1.3. Block diagram of Air Conditioning System

Power electronic applications

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

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

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

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

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

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

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

1.2 Types of power electronic converters

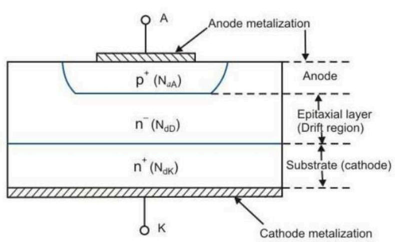
1. Rectifiers (AC to DC converters): These converters convert constant ac voltage to variable dc output voltage.
2. Choppers (DC to DC converters): Dc chopper converts fixed dc voltage to a controllable dc output voltage.
3. Inverters (DC to AC converters): An inverter converts fixed dc voltage to a 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.

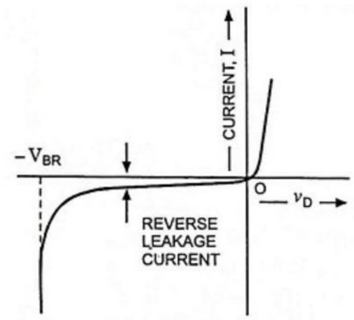
1.3 Power semiconductor switches

i. Power Diodes.
ii. Power transistors (BJT's).
iii. SCR
iv. Power MOSFET.
v. Power IGBT.

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.





V-I Characteristic of Practical Power Diode

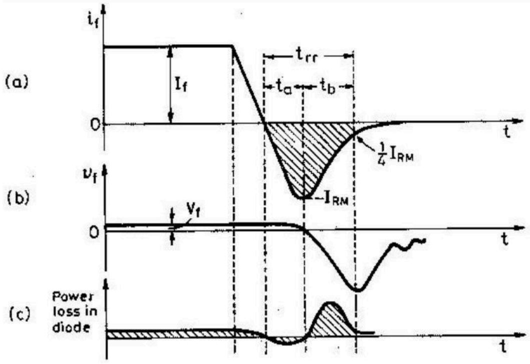
Circuit Symbol

The structure of power diode is slightly more complex than that of a signal diode. In a power diode a lightly doped N– expitaxial layer is grown on an heavily doped N+ substrate. The P-N junction is developed by alloying N– layer with heavily doped P+ region as shown in Fig. 8.51. The N– layer in the figure is termed as drift region which is not the part of the signal diodes. The function of drift region is to absorb depletion layer of the reversed biased P+ N– junction J1. The width of this region determines the reverse voltage that can be applied across the device under safe operation. The drawback of N– layer is to add significant ohmic resistance to the diode when it is conducting in forward mode. This leads to large power dissipation in the diode, requiring proper cooling arrangements in large rating diodes.

When the anode is positive w.r.t. cathode, the diode is said to be forward biased and the diode conducts. A conducting diode has a relatively small forward voltage drop across it; and the magnitude of this voltage drop depends on the manufacturing process and junction temperature. When the cathode is positive w.r.t. anode, the diode is said to be reverse biased. Under reverse-biased conditions, a small reverse current, called the leakage current, (in the range of micro- or milli-amperes) flows and this leakage current increases slowly in magnitude with the reverse voltage until the avalanche or zener voltage is reached. The volt-ampere characteristics of a diode are shown in Fig. For most practical purposes, a diode can be considered as an ideal switch, whose characteristics are shown in Fig. The V-I characteristics depicted in Fig. can be expressed by an equation, known as Shockley diode equation, and it is given under dc steady-state operation by

$$\text{Diode current, } I_D = I_s \left(e^{v_D/\eta V_T} - 1\right)$$

where v_D is diode voltage with anode positive w.r.t. to cathode, I_s is the leakage or reverse saturation current, typically in the range 10-6 to 10-15 A and η is empirical constant known as emission coefficient, or ideality factor.



(a)Variation of Forward Current If (b) Forward Voltage DropVf (c) Power loss in the Diode

Types of Power Diode

The classification of these diodes can be done based on the reverse recovery time, the process of manufacturing & the depletion region penetration in reversed bias condition. The power diodes depending on the reverse recovery time as well as the process of manufacturing are classified into three types such as

General Purpose Diodes

Fast Recovery Diodes

Schottky Diodes

General Purpose Diodes

These diodes have huge reverse recovery time around 25µs; therefore they are applicable in low frequency (up to 1 kHz) & low-speed operations (up to 1- kHz).

Fast Recovery Diodes

These diodes have quick recovery act due to their very small reverse recovery time less than 5µs, used in high-speed switching applications.

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 theirvoltage and current ratings are lower than those of thyristors and are therefore used in low to medium power applications. Power transistors are classified as follows o Bipolar junction transistors(BJTs) o Metal-oxide semiconductor filed-effect transistors(MOSFETs) o Static Induction transistors(SITs) o Insulated-gate bipolar transistors(IGBTs)

Advantages of BJT'S

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

Demerits of BJT

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

1.5 Thyristors – Silicon Controlled Rectifiers (SCR's)

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

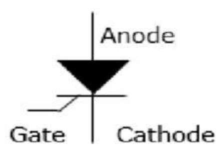


Figure: 1.4. Symbol of thyristor

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

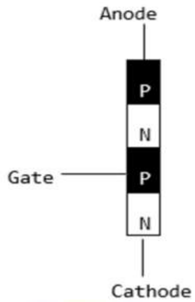


Figure: 1.5. Structure of thyristor

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.

ModesofOperationinSCR

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

Characteristics of Thyristor

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

V-I Characteristics of a Thyristor

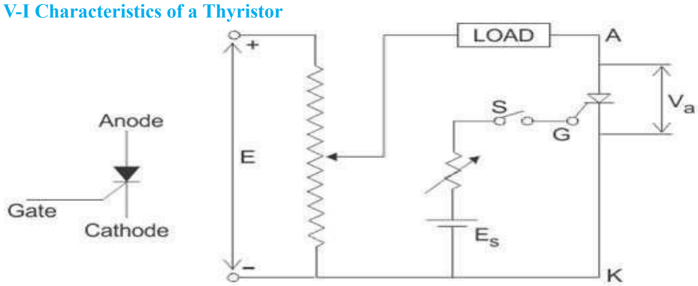


Figure: 1.6. Circuit diagram for characteristics of SCR

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

Reverse Blocking Mode of Thyristor

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

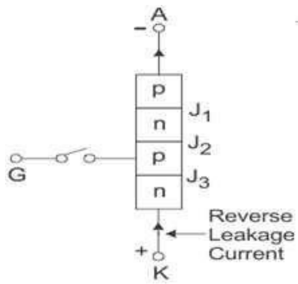


Figure: 1.7. Reverse blocking mode of SCR

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

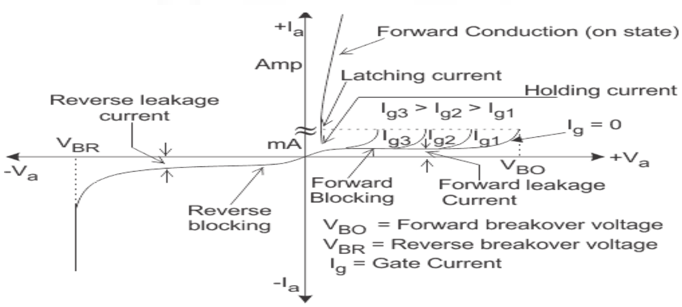


Figure: 1.8. V- I characteristics of SCR

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

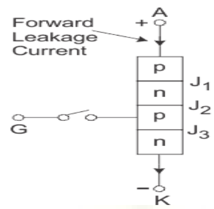


Figure: 1.9. Forward connection of SCR

As we can see the junctions J_1 and J_3 are now forward biased but junction J_2 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 J_2 will have an avalanche breakdown at a voltage called forward break over voltage V_{B0} of the thyristor. But, if we keep the forward voltage less than V_{BO}, we can see from the characteristics of thyristor, that the device offers high impedance. Thus even here the thyristor operates as an open switch during the forward blocking mode.

Forward Conduction Mode

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

1.6 Two transistor analogy of SCR

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

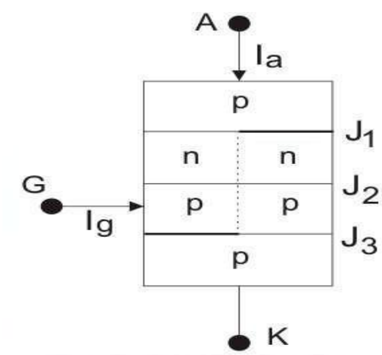


Figure: 1.10. Two transistor structure of SCR

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

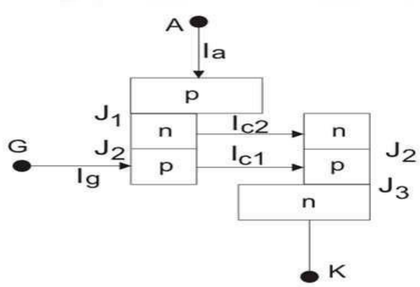


Figure: 1. 11. Two transistor structure of SCR

When the transistors are in off state, the relation between the collector current and emitter current is shown below

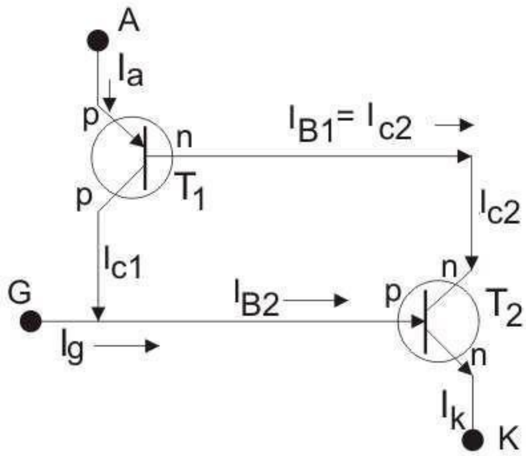


Figure: 1. 12. Two transistors connection of SCR

Here, I_C is collector current, I_E is emitter current, I_{CBO} is forward leakage current, α is common base forward current gain and relationship between I_C and I_B is $I_C = \beta I_B$ Where, I_B is base current and β is common emitter forward current gain. Let"s for transistor T_1 this relation holds

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

And that for transistor T_2

$I_{C2} = \alpha_2 I_k + I_{CBO2} \ldots\ldots (ii)\ again\ I_{C2} = \beta_2 I_{B2}$ Now, by the analysis of two transistors model we can get anode current,

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

From equation (i) and (ii), we get, $I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 I_k + I_{CBO2} \ldots\ldots (iii)$

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

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

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

From this relation we can assure that with increasing the value of $(\alpha_1 + \alpha_2)$ towards unity, corresponding anode current will increase. Now the question is how $(\alpha_1 + \alpha_2)$ increasing. Here is the explanation using two transistor model of SCR. At the first stage when we apply a gate current I_g, it acts as base current of T_2 transistor i.e. $I_{B2} = I_g$ and emitter current i.e. $I_k = I_g$ of the $T_{,2}$ transistor. Hence establishment of the emitter current gives rise α_2 as

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

Presence of base current will generate collector current as

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

This I_{C2} is nothing but base current I_{B1} of transistor $T_{,1}$, which will cause the flow of collector current,

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

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

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

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

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

This will lead to increase emitter current

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

and as a result α_2 also increases and this further increases

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

As

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

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

1.7 Turn on methods of SCR

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

The various SCR triggering methods are

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

(a) Forward Voltage Triggering:-

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

(b) Thermal (or) Temperature Triggering:-

- The width of depletion layer of SCR decreases with increase in junction temperature.

- Therefore in SCR when V_{AR} is very near its breakdown voltage, the device is triggered by increasing the junction temperature.

- By increasing the junction temperature the reverse biased junction collapses thus the device starts to conduct.

(c) Radiation Triggering (or) Light Triggering:-

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

(d) dv/dt Triggering:-

- When the device is forward biased, J1 and J3 are forward biased, J2 is reverse biased.
- Junction J2 behaves as a capacitor, due to the charges existing across the junction.
- If voltage across the device is V, the charge by Q and capacitance by C then,

$i_c = dQ/dt$

$Q = CV$

$i_c = d(CV)/dt$

$= CdV/dt + VdC/d$

t as $dC/dt = 0$

$i_c = CdV/dt$

- Therefore when the rate of change of voltage across the device becomes large, the device may turn ON, even if the voltage across the device is small.

(e) Gate Triggering:-

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

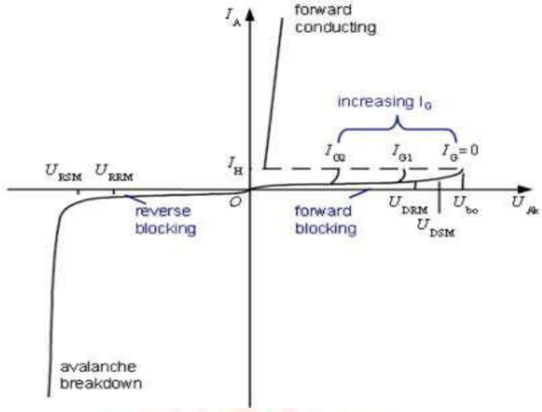


Figure: 1. 13. V - I characteristics of SCR

- Three types of signals are used for gate triggering.

1. DC gate triggering:-

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

1.8 AC Gate Triggering:-

- Here AC source is used for gate signals.
- This scheme provides proper isolation between power and control circuit.
- Drawback of this scheme is that a separate transformer is required to step down ac supply.

- There are two methods of AC voltage triggering namely (i) R Triggering (ii) RC triggering

(i) Resistance triggering:

The following circuit shows the resistance triggering.

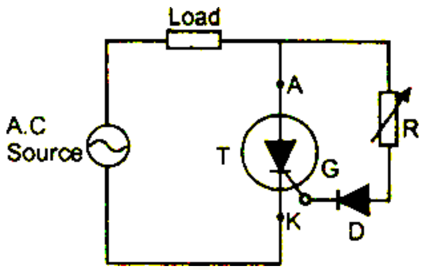


Figure: 1. 14. Resistance triggering circuit of SCR

- In this method, the variable resistance R is used to control the gate current.
- Depending upon the value of R, when the magnitude of the gate current reaches the sufficient value(latching current of the device) the SCR starts to conduct.
- The diode D is called as blocking diode. It prevents the gate cathode junction from getting damaged in the negative half cycle.
- By considering that the gate circuit is purely resistive, the gate current is in phase with the applied voltage.
- By using this method we can achieve maximum firing angle up to 90°.

(ii) RC Triggering

The following circuit shows the resistance-capacitance triggering.

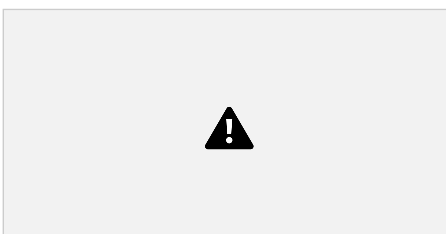


Figure: 1. 15. Resistance Capacitance triggering circuit of SCR

- By using this method we can achieve firing angle more than 90°.

- In the positive half cycle, the capacitor is charged through the variable resistance R up to the peak value of the applied voltage.

- The variable resistor R controls the charging time of the capacitor.
- Depends upon the voltage across the capacitor, when sufficient amount of gate current will flow in the circuit, the SCR starts to conduct.
- In the negative half cycle, the capacitor C is charged up to the negative peak value through the diode D2.
- Diode D1 is used to prevent the reverse break down of the gate cathode junction in the negative half cycle.

2. Pulse Gate Triggering:-

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

Advantages of pulse train triggering:

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

1.9 Turn off methods of SCR:

SCR can be turned ON by applying appropriate positive gate voltage between the gate and cathode terminals, but it cannot be turned OFF through the gate terminal. The SCR can be brought back to the forward blocking state from the forward conduction state by reducing the anode or forward current below the holding current level.

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

To turn OFF the conducting SCR the below conditions must be satisfied.

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

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

SCR Turn OFF Methods

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

Forced Commutation

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

This commutating circuit consists of components like inductors and capacitors called as commutating components. These commutating components cause to apply a reverse voltage across the SCR that immediately bring the current in the SCR to zero.

Based on the manner in which the zero current achieved and arrangement of the commutating components, forced commutation is classified into different types such as class A, B, C, D, and E. This commutation is mainly used in chopper and inverter circuits.

Class A Commutation

This is also known as self commutation, or resonant commutation, or load commutation. In this commutation, the source of commutation voltage is in the load. This load must be an under damped R-L-C supplied with a DC supply so that natural zero is obtained.

The commutating components L and C are connected either parallel or series with the load resistance R as shown below with waveforms of SCR current, voltage and capacitor voltage.

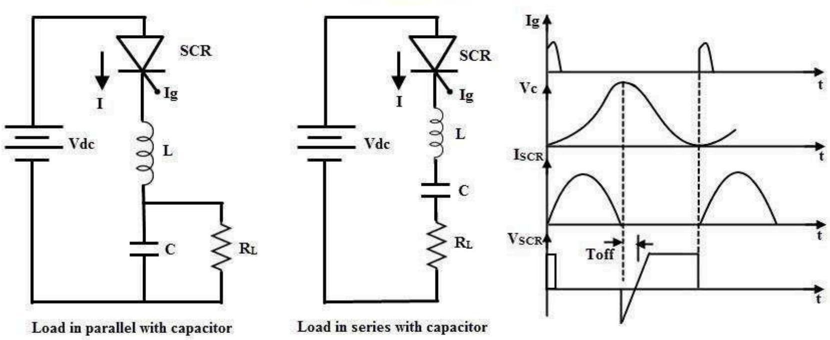


Figure: 1. 16. Class A Commutation circuit and waveforms

The value of load resistance and commutating components are so selected that they forms a under damped resonant circuit to produce natural zero. When the thyristor or SCR is triggered, the forward currents starts flowing through it and during this the capacitor is charged up to the value of E.

Once the capacitor is fully charged (more than the supply source voltage) the SCR becomes reverse biased and hence the commutation of the device. The capacitor discharges through the load resistance to make ready the circuit for the next cycle of operation. The time for switching OFF the SCR depends on the resonant frequency which further depends on the L and C components.

This method is simple and reliable. For high frequency operation which is in the range above 1000 Hz, this type of commutation circuits is preferred due to the high values of L and C components.

Class B Commutation

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

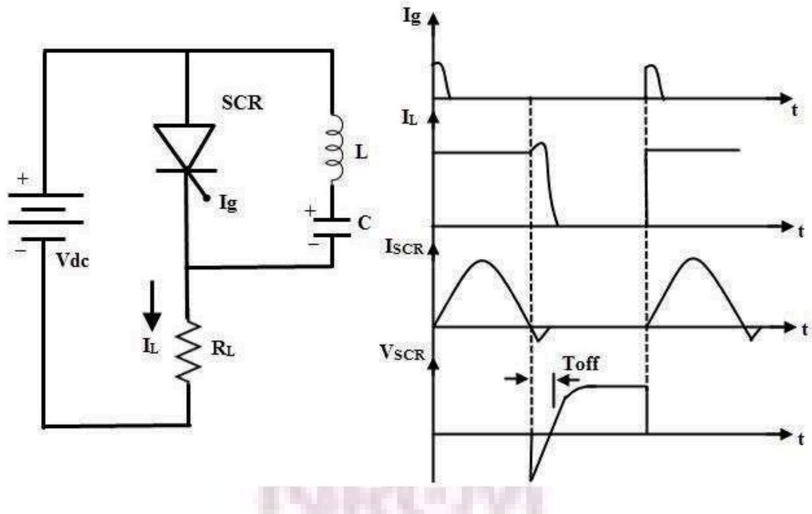


Figure: 1. 17. Class B Commutation circuit and waveforms

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

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

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

In the above process, the SCR is turned ON for some time and then automatically turned OFF for some time. This is a continuous process and the desired frequency of ON/OFF depends on the values of L and

C. This type of commutation is mostly used in chopper circuits.

Class C Commutation

In this commutation method, the main SCR is to be commutated is connected in series with the load and an additional or complementary SCR is connected in parallel with main SCR. This method is also called as complementary commutation.

In this , SCR turns OFF with a reverse voltage of a charged capacitor. The figure below shows the complementary commutation with appropriate waveforms.

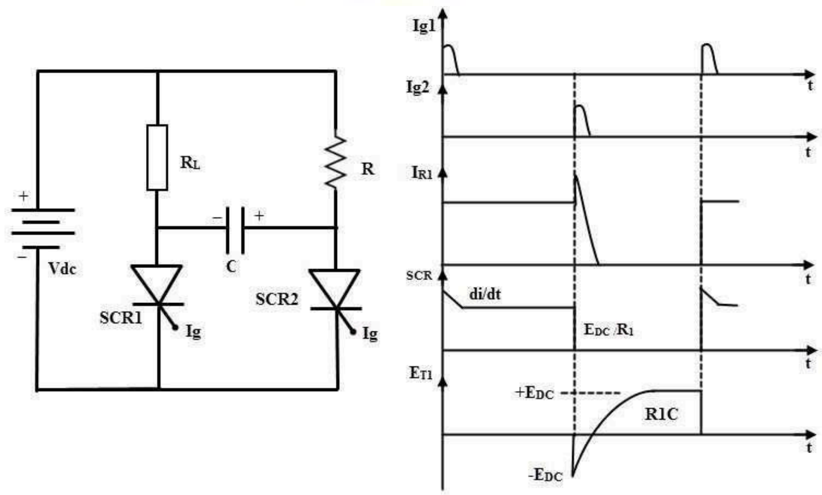


Figure: 1. 18. Class C Commutation circuit and waveforms

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

When the SCR2 is triggered, SCR is turned ON and simultaneously a negative polarity is applied across the SCR1. So this reverse voltage across the SCR1 immediately causes to turn OFF the SCR1. Now the capacitor starts charging with a reverse polarity through the path of E+ – R1- C+ – C- SCR2 – E-. And again, if the SCR 1 is triggered, discharging current of the capacitor turns OFF the SCR2.

This commutation is mainly used in single phase inverters with a centre tapped transformers. The Mc Murray Bedford inverter is the best example of this commutation circuit. This is a very reliable method of commutation and it is also useful even at frequencies below 1000Hz.

Class D Commutation

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

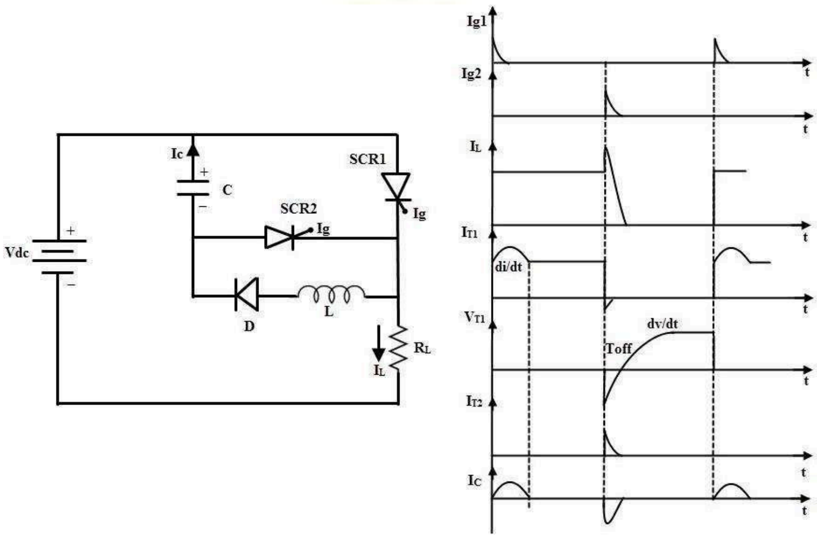


Figure: 1. 19. Class D Commutation circuit and waveforms

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

As soon as the capacitor completely discharges, its polarities will be reversed but due to the presence of diode the reverse discharge is not possible. When the SCR2 is triggered capacitor starts discharging through C+ – SCR2- SCR1- C-. When this discharging current is more than the load current the SCR1 becomes turned OFF. Again, the capacitor starts charging through the SCR2 to a supply voltage E and then the SCR2 is turned OFF. Therefore, both SCRs are turned OFF and the above cyclic process is repeated. This commutation method is mainly used in inverters and also used in the Jones chopper circuit.

Class E Commutation

This is also known as external pulse commutation. In this, an external pulse source is used to produce the reverse voltage across the SCR. The circuit below shows the class E commutation circuit which uses a pulse transformer to produce the commutating pulse and is designed with tight coupling between the primary and secondary with a small air gap. If the SCR need to be commutated, pulse duration equal to the turn OFF time of the SCR is applied. When the SCR is triggered, load current flows through the pulse transformer. If the pulse is applied to the primary of the pulse transformer, an emf or voltage is induced in the secondary of the pulse transformer. This induced voltage is applied across the SCR as a reverse polarity and hence the SCR is turned OFF. The capacitor offers a very low or zero impedance to the high frequency pulse.

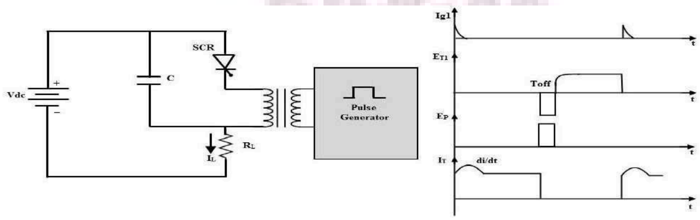


Figure: 1. 20. Class E Commutation circuit and waveforms

Natural Commutation

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

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

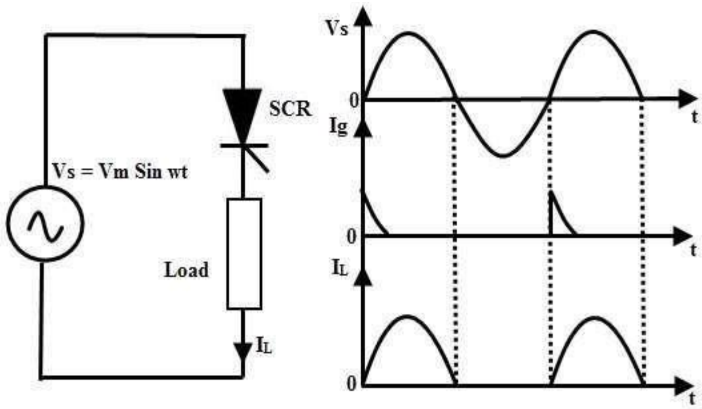


Figure: 1. 21. Natural Commutation circuit and waveforms

Dynamic Turn OFF Switching Characteristics

The transition of an SCR from forward conduction state to forward blocking state is called as turn OFF or commutation of SCR. As we know that once the SCR starts conducting, the gate has no control over it to bring back to forward blocking or OFF state.

To turn OFF the SCR, the current must be reduced to a level below the holding current of SCR. We have discussed various methods above to turn OFF the SCR in which SCR turn OFF is achieved by reducing the forward current to zero. But if we apply the forward voltage immediately after the current zero of SCR, it starts conducting again even without gate triggering.

This is due to the presence of charge carriers in the four layers. Therefore, it is necessary to apply the reverse voltage, over a finite time across the SCR to remove the charge carriers.

Hence the turn OFF time is defined as the time between the instant the anode current becomes zero and the instant at which the SCR retains the forward blocking capability. The excess charge carriers from the four layers must be removed to bring back the SCR to forward conduction mode.

This process takes place in two stages. In a first stage excess carriers from outer layers are removed and in second stage excess carriers in the inner two layers are to be recombined. Hence, the total turn OFF time t_q is divided into two intervals; reverse recovery time t_{rr} and gate recovery time t_{gr}.

$$\mathbf{t_q = t_{rr} + t_{gr}}$$

The figure below shows the switching characteristics of SCR during turn ON and OFF. The time t_1 to t_3 is called as reverse recovery time; at the instant $t_1$the anode current is zero and builds up in the reverse direction which is called as reverse recovery current. This current removes the excess charge carriers from outer layers during the time t_1 to t_3.

At instant t_3, junctions J_1 and J_3 are able to block the reverse voltage but, the SCR is not yet able to block the forward voltage due to the presence of excess charge carriers in junction J_2. These carriers can be disappeared only by the way of recombination and this could be achieved by maintaining a reverse voltage across the SCR.

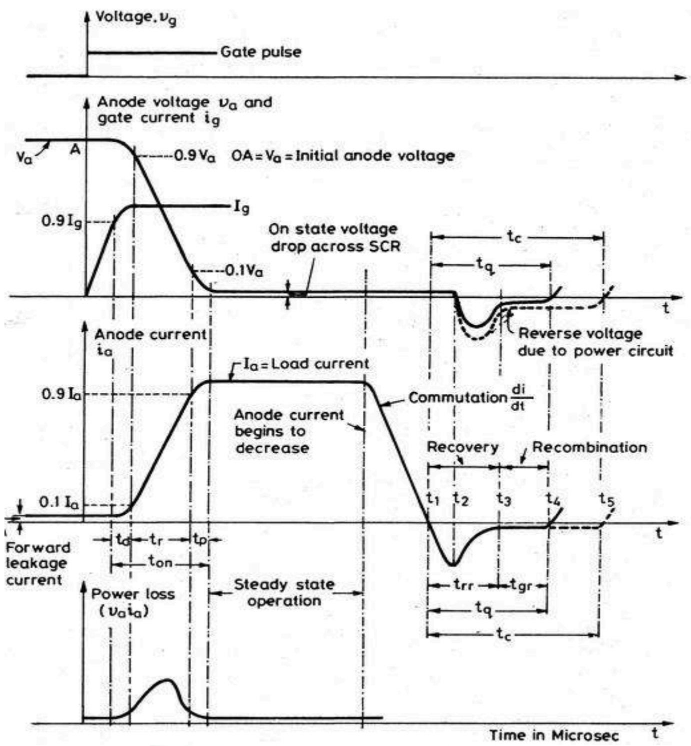


Figure: 1. 22. Dynamic characteristics of SCR

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

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

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

1.10 Resistance Firing Circuit

- The circuit below shows the resistance triggering of SCR where it is employed to drive the load from the input AC supply. Resistance and diode combination circuit acts as a gate control circuitry to switch the SCR in the desired condition.
- As the positive voltage applied, the SCR is forward biased and doesn"t conduct until its gate current is more than minimum gate current of the SCR.
- When the gate current is applied by varying the resistance R2 such that the gate current should be more than the minimum value of gate current, the SCR is turned ON. And hence the load current starts flowing through the SCR.
- The SCR remains ON until the anode current is equal to the holding current of the SCR. And it will switch OFF when the voltage applied is zero. So the load current is zero as the SCR acts as open switch.
- The diode protects the gate drive circuit from reverse gate voltage during the negative half cycle of the input. And Resistance R1 limits the current flowing through the gate terminal and its value is such that the gate current should not exceed the maximum gate current.
- It is the simplest and economical type of triggering but limited for few applications due to its disadvantages.
- In this, the triggering angle is limited to 90 degrees only. Because the applied voltage is maximum at 90 degrees so the gate current has to reach minimum gate current value somewhere between zero to 90 degrees.

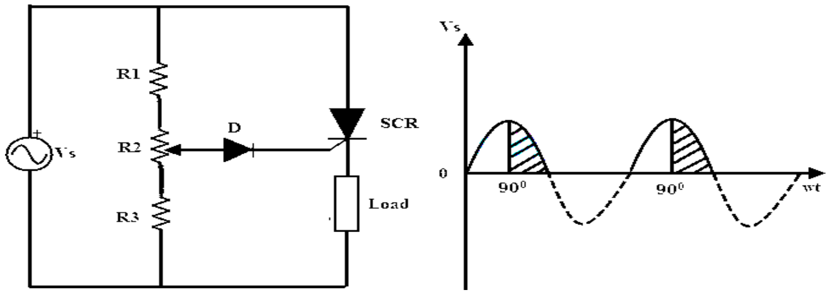


Figure: 1. 23. R Firing circuit for SCR and corresponding waveforms

Resistance – Capacitacne (RC) Firing Circuit

- The limitation of resistance firing circuit can be overcome by the RC triggering circuit which provides the firing angle control from 0 to 180 degrees. By changing the phase and amplitude of the gate current, a large variation of firing angle is obtained using this circuit.
- Below figure shows the RC triggering circuit consisting of two diodes with an RC network connected to turn the SCR.
- By varying the variable resistance, triggering or firing angle is controlled in a full positive half cycle of the input signal.
- During the negative half cycle of the input signal, capacitor charges with lower plate positive through diode D2 up to the maximum supply voltage Vmax. This voltage remains at -Vmax across the capacitor till supply voltage attains zero crossing.
- During the positive half cycle of the input, the SCR becomes forward biased and the capacitor starts charging through variable resistance to the triggering voltage value of the SCR.
- When the capacitor charging voltage is equal to the gate trigger voltage, SCR is turned ON and the capacitor holds a small voltage. Therefore the capacitor voltage is helpful for triggering the SCR even after 90 degrees of the input waveform.
- In this, diode D1 prevents the negative voltage between the gate and cathode during the negative half cycle of the input through diode D2.

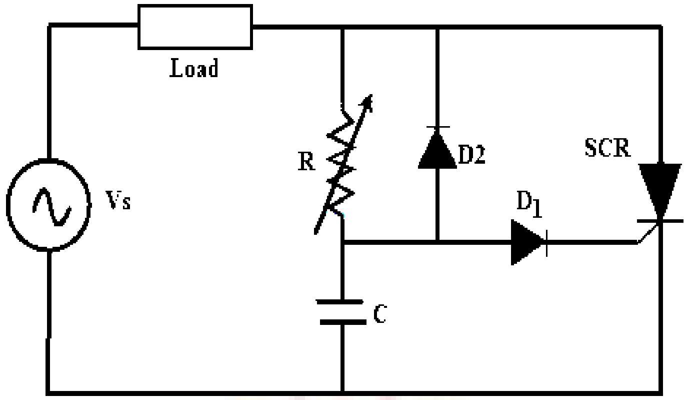


Figure: 1. 24. R Firing circuit for SCR

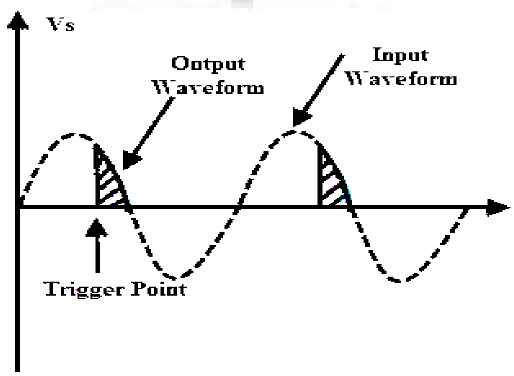


Figure: 1. 25. R Firing circuit waveforms of SCR

UJT Firing Circuit

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

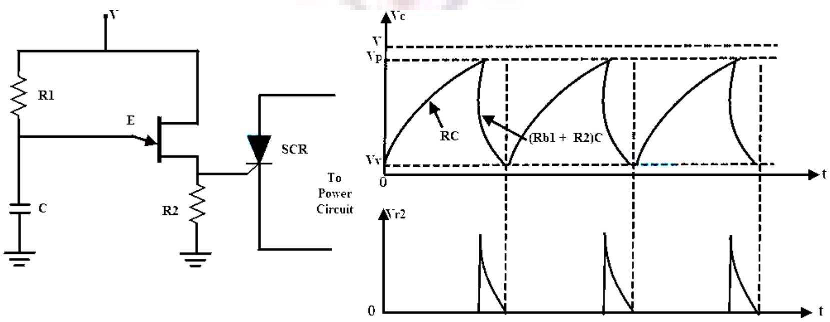


Figure: 1. 26. UJT Firing circuit for SCR and corresponding waveforms

1.11 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

(i) turn-on time

(ii) turn-off time

(iii) Leakage current in forward direction

(iv) Leakage current in reverse direction and

(v) Recovery voltage.

Series Connection of an SCR

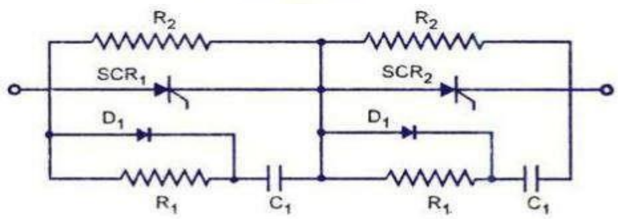


Figure: 1. 27. Series connection of SCRs

(i) Unequal distribution of voltage across SCRs

(ii) 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 = $\frac{\text{Voi or actual current rating of the whole string}}{\text{No of SCRs in string} \times \text{Voi or current rating of individual SCR}}$

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

DRF = 1- string efficiency

1.12 Parallel Connection of an SCR

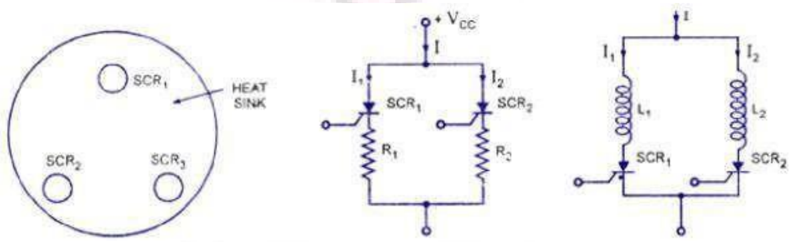


Figure: 1. 28. Parallel connection of SCRs

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.

Numerical Problems:

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

Solution:

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

ii. Here $V_g I_g = 0.4W$

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

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

$$120 I_g^2 - 15 I + 0.4 = 0$$

Its solution gives Ig = 38.56mA or 86.44 mA

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

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

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

2. For an SCR the gate-cathode characteristic has a straight line slope of 130. For trigger source voltage of 15V and allowable gate power dissipation of 0.5 watts, compute the gate source

resistance.

3. SCRs with a rating of 1000V and 200A are available to be used in a string to handle 6kV and 1kA. Calculate the number of series and parallel units required in case de-rating factor is 0.1 and 0.2

4. It is required to operate 250A SCR in parallel with 350A SCR with their respective on state voltage drops of 1.6V and 1.2V. Calculate the value of resistance to be inserted in series with each SCR so that the share the total load of 600A in proportion to their current ratings.

Snubber circuit

Due to overheating, over voltage, over current or excessive change in voltage or current switching devices and circuit components may fail. From over current they can be protected by placing fuses at suitable locations. Heat sinks and fans can be used to take the excess heat away from switching devices and other components. Snubber circuits are needed to limit the rate of change in voltage or current (**di/dt** or **dv/dt**) and over voltage during turn-on and turn-off. These are placed across the semiconductor devices for protection as well as to improve the performance. Static **dv/dt** is a measure of the ability of a thyristor to retain a blocking state under the influence of a voltage transient. These are also used across the relays and switches to prevent arcing.

Necessity of Using the Snubber Circuit

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

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

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

- Shape the load line of a bipolar switching transistor to keep it in its safe operating area.
- Reducing the voltages and currents during turn-ON and turn-OFF transient conditions.
- Removes energy from a switching transistor and dissipate the energy in a resistor to reduce junction temperature.
- Limiting the rate of change of voltage and currents during the transients.

- Reduce ringing to limit the peak voltage on a switching transistor and lowering their frequency.

Design of RC Snubber Circuits:

There are many kinds of snubbers like RC, diode and solid state snubbers but the most commonly used one is RC snubber circuit. This is applicable for both the rate of rise control and damping.

This circuit is a capacitor and series resistor connected across a switch. For designing the Snubber circuits. The amount of energy is to dissipate in the snubber resistance is equal to the amount of energy is stored in the capacitors. An RC Snubber placed across the switch can be used to reduce the peak voltage at turn-off and to lamp the ring. An RC snubber circuit can be polarized or non-polarized. If you assume the source has negligible impedance, the worst case peak current in the snubber circuit is

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

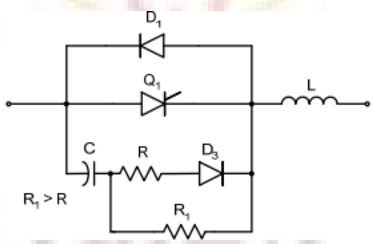


Figure: 1. 29. Forward-Polarized RC Snubber Circuit

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

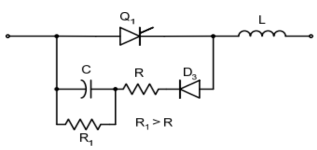


Figure: 1. 30. Reverse Polarized RC Snubber Circuit

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

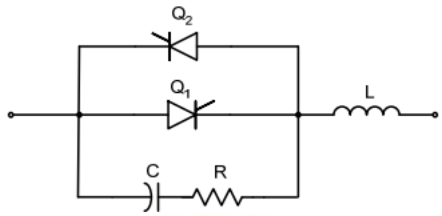


Figure: 1. 31. An un-polarized snubber circuit

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

Capacitors selection:

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

Resistors selection:

It is important that R in the RC snubber, have low self inductance. Inductance in R will increase the peak voltage and it will tend to defeat the purpose of the snubber. Low inductance will also be desirable for R in snubber but it is not critical since the effect of a small amount of inductance is to slightly increase the reset time of C and it will reduce the peak current in switch at turn-on. The normal choice of R is usually the carbon composition or metal film. The resistor power dissipation must be independent of the resistance R because it dissipates the energy stored in the snubber capacitor in each transition of voltage in the capacitor. If we select the resistor as that the characteristic impedance, the ringing is well damped. When comparing the Quick design to optimum design, the required snubber resistor's power capability will be reduced. Usually the "Quick" design is completely adequate for final design. Going to the "Optimum" approach is only if power efficiency and size constraints dictate the need for optimum design.

1.13 Power Bipolar Junction Transistor (BJT)

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

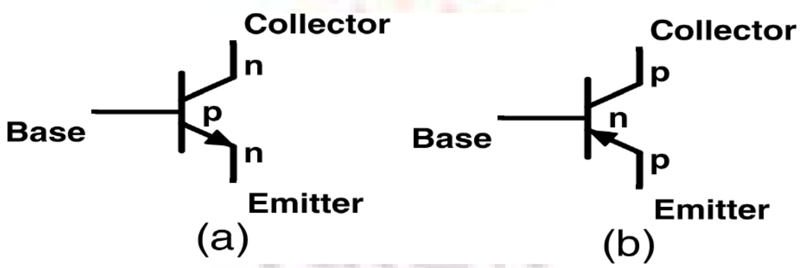


Figure: 1. 32. Symbol of transistor

The BJT is a three-layer and two-junction npn or pnp semiconductor device as given in Fig. 32. (a) and (b).

Although BJTs have lower input capacitance as compared to MOSFET or IGBT, BJTs are considerably slower in response due to low input impedance. BJTs use more silicon for the same drive performance.

In the case of MOSFET studied earlier, power BJT is different in configuration as compared to simple planar BJT. In planar BJT, collector and emitter is on the same side of the wafer while in power BJT it is on the opposite edges as shown in Fig. 33. This is done to increase the power-handling capability of BJT.

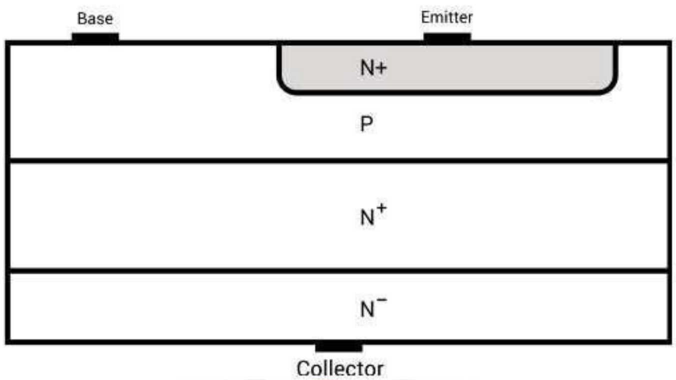


Figure: 1. 33. Structure of transistor

Power n-p-n transistors are widely used in high-voltage and high-current applications which will be discussed later.

Input and output characteristics of planar BJT for common-emitter configuration are shown in Fig. 34. These are current-voltage characteristics curves.

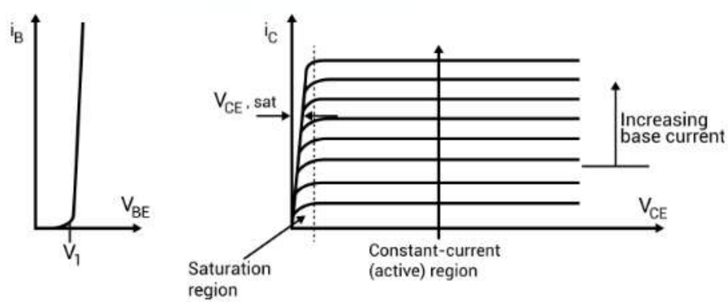
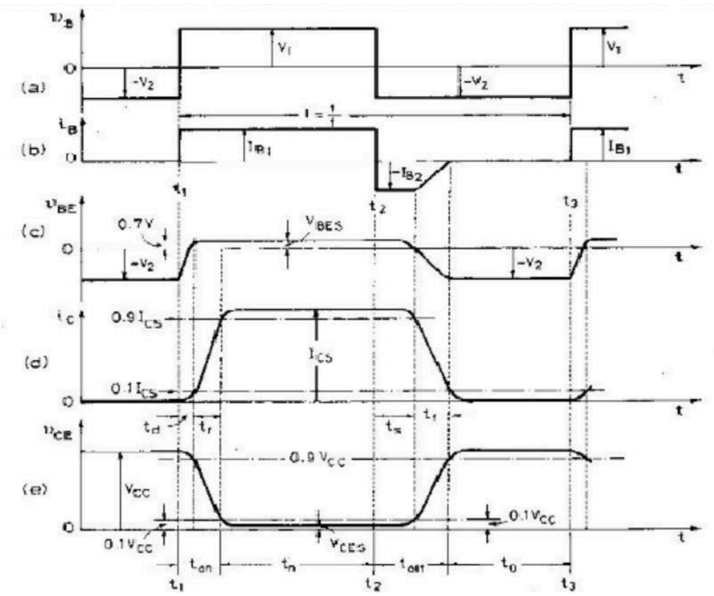


Figure: 1. 34. Input and output characteristics of BJT



Switching waveforms of Power BJT

1.14 Metal-Oxide Semiconductor Field-Effect Transistor (Power MOSFET)

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

N-channel enhancement type MOSFET is more common due to high mobility of electrons.

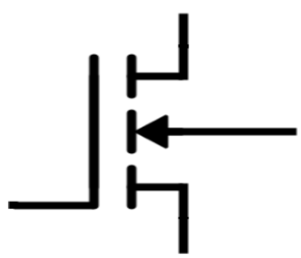


Figure: 1. 35. Symbol of MOSFET

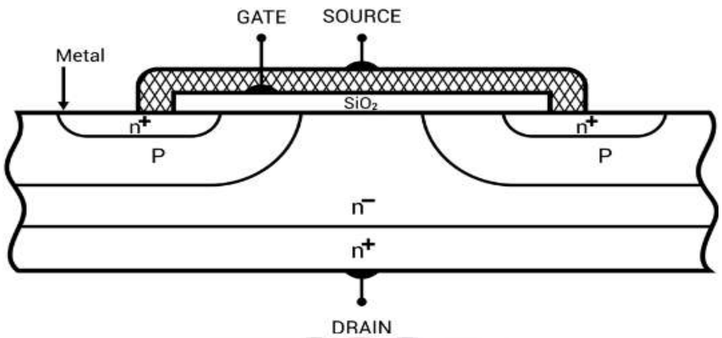
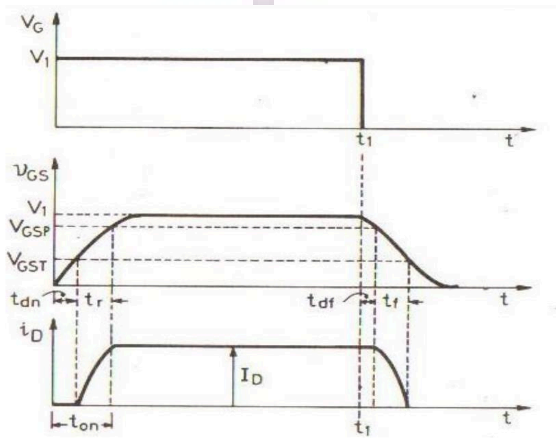


Figure: 1. 36. Structure of MOSFET



Switching Characteristics of MOSFET

Basic circuit diagram and output characteristics of an n-channel enhancement power MOSFET with load connected are in Fig. 37 and Fig. 38 respectively.

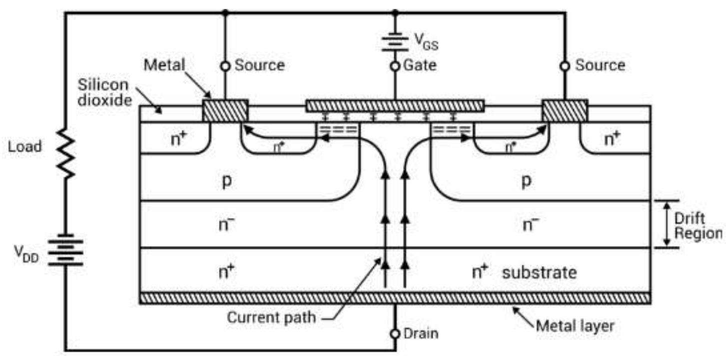


Figure: 1. 37. Basic circuit diagram of n-channel enhancement power MOSFET

Drift region shown in Fig. 37 determines the voltage-blocking capability of the MOSFET.

When $V_{GS} = 0$,

⇒ V_{DD} makes it reverse biased and no current flows from drain to source.

When $V_{GS} > 0$,

⇒ Electrons form the current path as shown in Fig. 37. Thus, current from the drain to the source flows. Now, if we will increase the gate-to-source voltage, drain current will also increase.

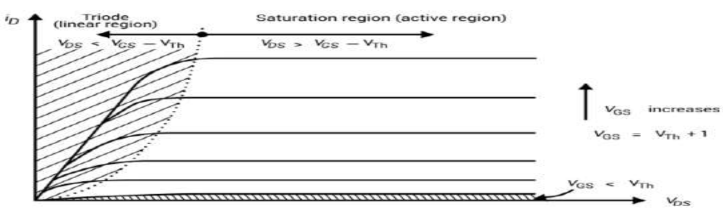


Figure: 1. 38. Output characteristics of an n-channel enhancement power MOSFET

For lower value of V_{DS}, MOSFET works in a linear region where it has a constant resistance equal to V_{DS} / I_D. For a fixed value of V_{GS} and greater than threshold voltage V_{TH}, MOSFET enters a saturation region where the value of the drain current has a fixed value.

Besides the output characteristics curves, transfer characteristics of power MOSFET is also shown in Fig. 39.

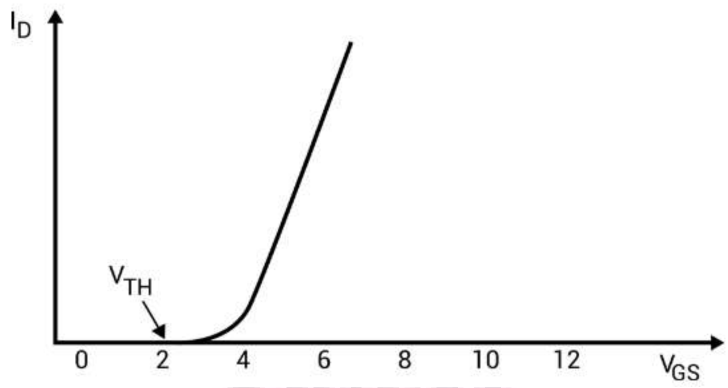


Figure: 1. 39. Transfer characteristics of an n-channel enhancement power MOSFET

1.15 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.

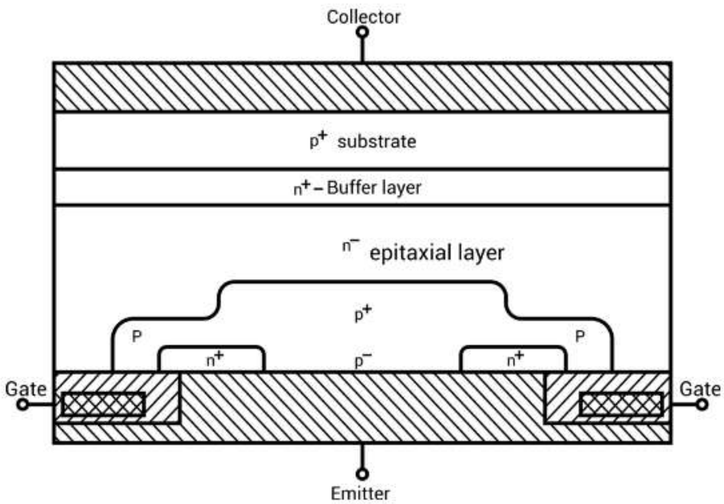


Figure: 1. 40. Cross -sectional structural diagram of IGBT

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:

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

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

(Note: ➔ means implies)

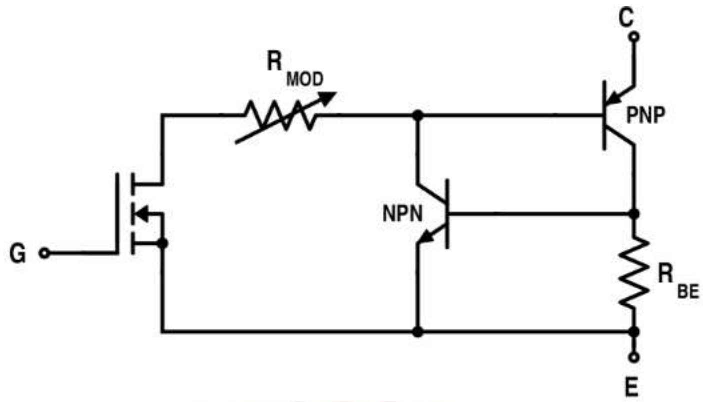


Figure: 1. 41. Equivalent diagram of IGBT

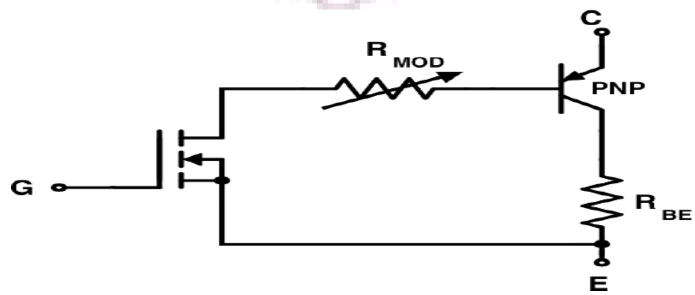


Figure: 1. 42. Simplified Equivalent diagram of IGBT

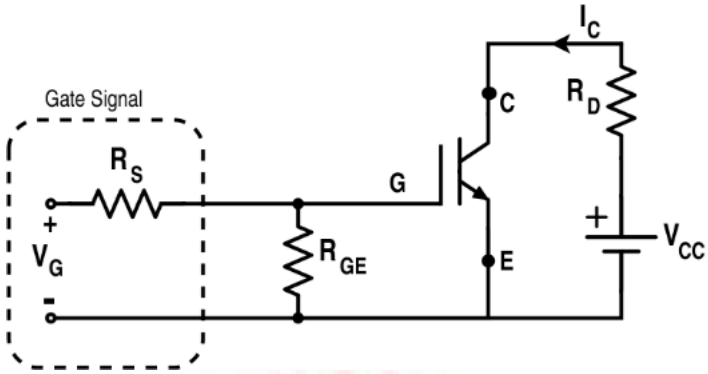


Figure: 43. Equivalent diagram of IGBT

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.

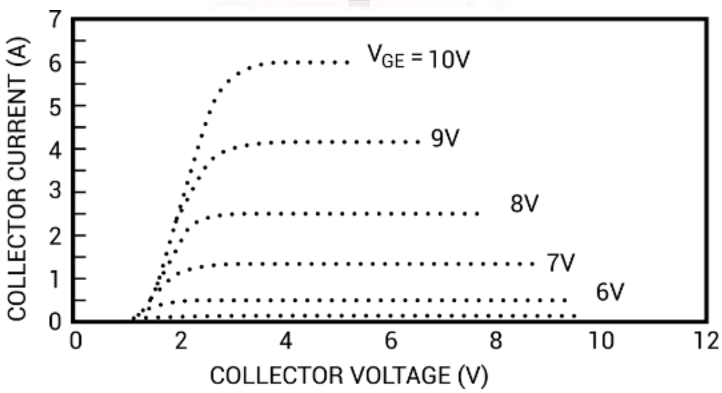


Figure: 1. 44. Forward characteristics of IGBT

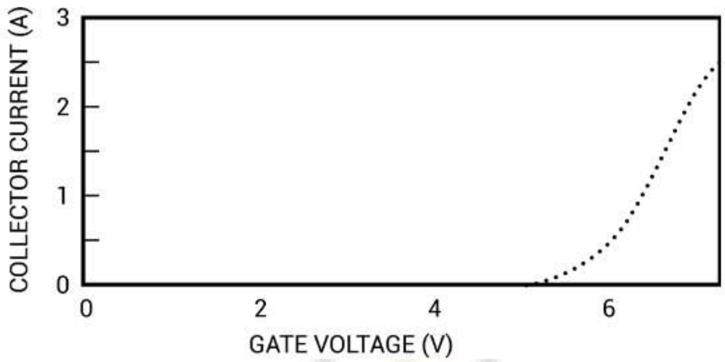


Figure: 1.45. Transfer characteristics of IGBT

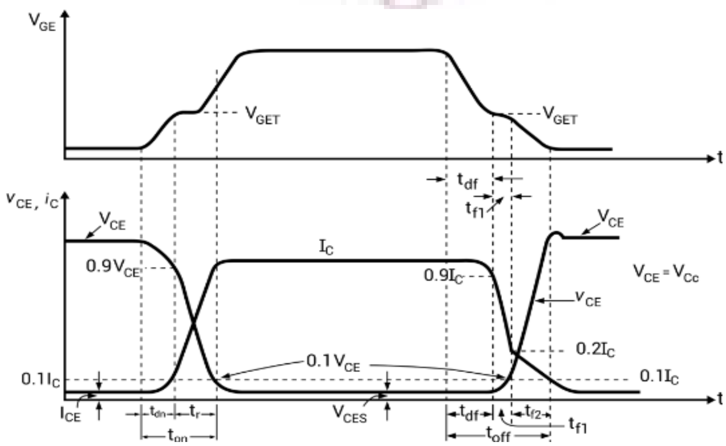


Figure: 1. 46. Dynamic characteristics of IGBT

(Note: T_{dn} : delay time ; T_r: rise time ; T_{df} : delay time ; T_{f1}: initial fall time ; T_{f2}: final fall time)

1.16 SCR Specifications and Ratings:

The main specifications of the SCR are its voltage rating and current rating. In this post, let us see various ratings of thyristor.

Voltage Ratings

Peak Invese Voltage (V_{PIV})

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

On State Voltage:

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

Finger Voltage:

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

Rate of Rise of Voltage (dV/dt)

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

Voltage Safety Factor:

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

V_f = Peak inverse voltage / (2 x RMS value of input voltage) Normally V_f
value lies between 2 and 2.5

Current Ratings:

The current carrying capacity of the device is known as its current rating.
It can be of two types.

1. Continuous
2. Intermittent

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

This is the average value of maximum continuous sinusoidal ON state current with conduction angle 180deg, at frequency 40 to 60Hz, which should not be exceeded even with intensive cooling.

Maximum rms ON-state current: (I_{mrc})

It is the rms value of the maximum continuous sinusoidal ON state current at the frequency 40 to 60 Hz and conduction angle 180deg, which should not be exceeded even with intensive cooling.

Maximum surge - ON state Current (I_{msc})

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

Latching Current (I_l)

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

Holding Current (I_H)

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

Gate Current:

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

Minimum Gate Current:

The minimum current required at the gate for triggering the device.

Maximum Gate Current:

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

Gate Power Loss:

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

Turn ON time:

The time taken by the device before getting latched from its OFF state to ON state. In other words, it is the time for which the device waits before achieving its full conduction. Usually it will be 150 to 200µsec.

Turn OFF time:

After applying reverse voltage, the device takes a finite time to get switched OFF. This time is called as turn-OFF time of the device. Usually it will be 200µsec.

Rate of rise of current (dI/dt)

The rate at which the current flowing in the device rises is known as its rate of rise (dI/dt) of current.

Parameter	IGBT	MOSFET
Full Form	IGBT stands for Insulated Gate Bipolar Transistor.	MOSFET stands for Metal Oxide Semiconductor Field Effect Transistor
Definition	IGBT is a three terminal semiconductor switching device used in the electronic circuits for switching and amplification of signals.	MOSFET is a four terminal semiconductor switching device which is also used as switching and amplification.
Terminals	IGBT has three terminals, which are: emitter (E), gate (G) and collector (C).	MOSFET has four terminals which are: source (S), gate (G), drain (D) and body (or substrate). Sometimes, the body terminal is merged with the source, making it a three terminal device.
PN junction	IGBT has PN junctions in its construction.	MOSFET does not have any PN junction in its construction.
Suitability	IGBT is suitable for medium to high current conduction and controlling.	MOSFET is suitable for low to medium current conduction and controlling.
Voltage and power handling capacity	IGBT has ability to handle very high voltage and high power.	MOSFET is capable of handling only low to medium voltage and power.
Operating frequency	IGBT can only be used for relatively low frequencies, up to a few kHz.	MOSFET can be used for very high frequency (of the order of MHz) applications.

Forward voltage drop	When IGBT is conducting current, it produces comparatively low forward voltage drop.	MOSFET produces higher forward voltage drop than IGBT.
Turn OFF time	For IGBT, the turn-off time is larger than MOSFET.	The turn-off time of a MOSFET is smaller than IGBT.
Switching speed	The switching speed of IGBT is relatively low.	The switching speed of MOSFET is very high.
Transient voltage & current handling ability	IGBT has ability to handle any transient voltage and current.	MOSFET cannot handle transient voltage and current. Thus, the operation of a MOSFET gets disturbed when the transient occurs.
Saturation	For IGBT, the saturation voltage	MOSFET has high saturation voltage.

Parameter	IGBT	MOSFET
voltage	is low.	
Cost	IGBT is costlier than MOSFET.	The cost of a MOSFET is relatively low.
Applications	IGBTs are extensively used in high power AC applications such as in inverter circuits.	MOSFETs are used in low power DC applications like in power supplies.

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.
10	Switching frequency is lower than MOSFET.	Switching frequency is high.

UNIT – II
Single phase and three phase controlled rectifiers

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.

What is a Phase Controlled Rectifier?

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

Types of Phase Controlled Rectifier

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

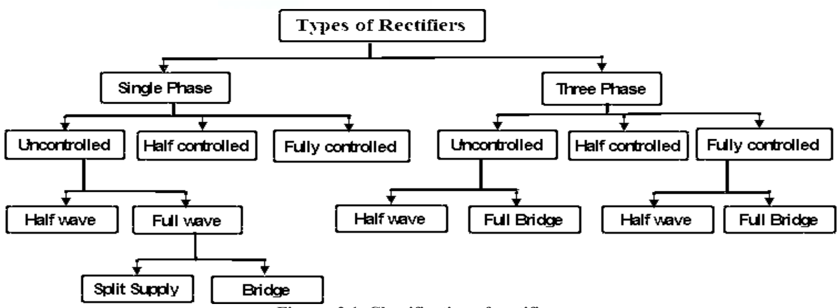


Figure: 2.1. Classification of rectifiers

2.2 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

Half wave 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.

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

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

Three-phase Controlled Rectifier

This type of rectifier which works from three phase AC i/p power supply

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

Operation of Phase Controlled Rectifier

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

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

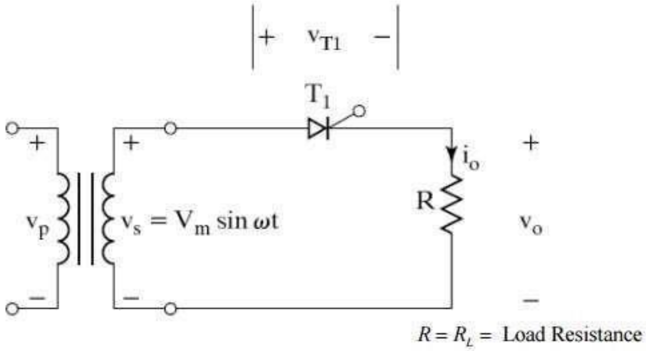


Figure: 2.2. Single phase half wave rectifier circuit

During the +ve half cycle of i/p supply when the upper end of the transformer secondary winding is at a +ve potential with respect to the lower end, the Thyristor is in a forward biased state.

The thyristor is activated at a delay angle of $\omega t = \alpha$, by applying an appropriate gate trigger pulse to the gate terminal of thyristor. When the thyristor is activated at a delay angle of $\omega t = \alpha$, the thyristor behaviors and assuming a perfect thyristor. The thyristor acts as a closed switch and the i/p supply voltage acts across the load when it conducts from $\omega t = \alpha$ to π radians For a purely resistive load, the load current io that flows when the thyristor T1 is on, is given by the expression.

$$I_o = v_o / R_L, \text{ for } \alpha \leq \omega t \leq \pi$$

Applications of Phase Controlled Rectifier

Phase controlled rectifier applications include paper mills, textile mills using DC motor drives and DC motor control in steel mills.

- AC fed traction system using a DC traction motor.
- Electro-metallurgical and Electrochemical processes.
- Reactor controls.
- Magnet power supplies.

- Portable hand instrument drives.
- Flexible speed industrial drives.
- Battery charges.
- High voltage DC transmission.
- UPS (Uninterruptible power supply systems).

2.3 Operation of half converter with R and RL loads

Single Phase Half Wave Controlled Rectifier with 'R' load:

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

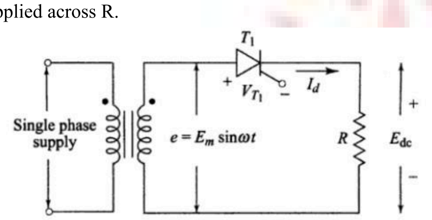


Fig.1 ***(a)** Halfwave-controlled rectifier with resistive load*

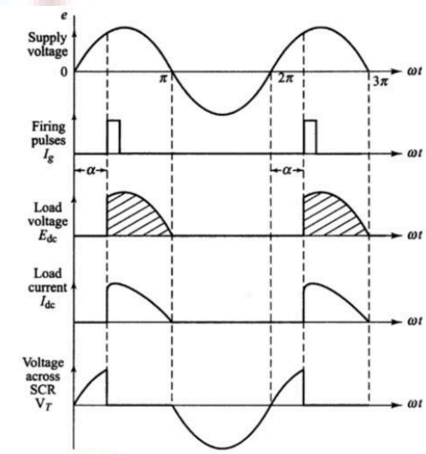


Fig.1 ***(b)** Waveforms for a half-wave circuit*

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

The load current i_0 flows through "R" the waveforms for voltage & current are as shown above.

As load is resistive,

Output current is given as,

$$I_o = \frac{V_o}{R}$$

Hence shape of output current is same as output voltage

As T1 conducts only in positive half cycle as it is reversed bias in negative cycle, the ripple frequency of output voltage is-f_{ripple}= 50 Hz (supply frequency) Average output voltage is given as,

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

i.e Area under one cycle.

Therefore T=2π&Vo(ωt) = Vm sinωt from α to π& for rest of the period Vo(ωt)=0

$$\therefore V_0(Avg) = \frac{1}{2\pi}\int_0^{2\pi} V_m sin(wt)\,dwt$$
$$= \frac{V_m}{2\pi}[-coswt]_\alpha^\pi$$
$$= \frac{V_m}{2\pi}(1+cos\alpha)$$

Power transferred to load,

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

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

$$RMS\ Value = \sqrt{(1/T)\int_0^T [f(x)]^2 dx}$$

RMS Value of Load output Voltage

$$= \sqrt{(1/2\pi)\int_0^{2\pi} [VmSin\omega t]^2 d(\omega t)}$$

$$= \sqrt{(Vm/4\pi)\int_0^{2\pi} [2Sin\omega t]^2 d(\omega t)}$$

$$= \sqrt{(Vm/4\pi)\int_0^{2\pi} [1 - Cos2\omega t] d(\omega t)}$$

Since the value of load output voltage is zero from $0 \leq \omega t \leq \alpha$ and $\pi < \omega t < 2\pi$, therefore

$$= \sqrt{(Vm/4\pi)\int_\alpha^{\pi} [1 - Cos2\omega t] d(\omega t)}$$

$$= \left(\frac{Vm}{2\sqrt{\pi}}\right)\sqrt{(\pi - \alpha) + (1/2)Sin2\alpha}$$

RMS Value of Load output Voltage

$$= \left(\frac{Vm}{2\sqrt{\pi}}\right)\sqrt{(\pi - \alpha) + (1/2)Sin2\alpha}$$

2.4 Single Phase Half Wave Controlled Rectifier with 'RL' load:

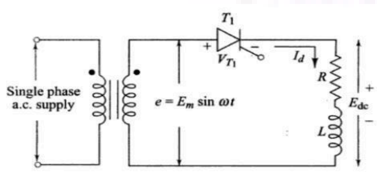


Fig.1(a) *Half-wave controlled rectifier with R-L load*

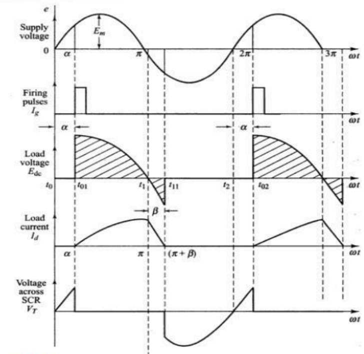


Fig.1(b) *Waveforms for a half-wave controlled rectifier with RL load*

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

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

- Normally motors are inductive

loads L= armature of field coil

inductance

R= Resistance of coil.

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

$$Avg.Voltage, Vo = \frac{1}{2\pi}\int_{\alpha}^{\beta} Vm\sin(\omega t)d(\omega t)$$

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

$$RMS\ Voltage, Vo = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\beta}(Vm\sin\omega t)^2\, d(\omega t)}$$

$$= \frac{Vm}{2\sqrt{\pi}}\sqrt{[(\beta-\alpha) - 1/2\{\sin 2\beta - \sin 2\alpha\}]}$$

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

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

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

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

2.4 Single phase half controlled converter with RLE load

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

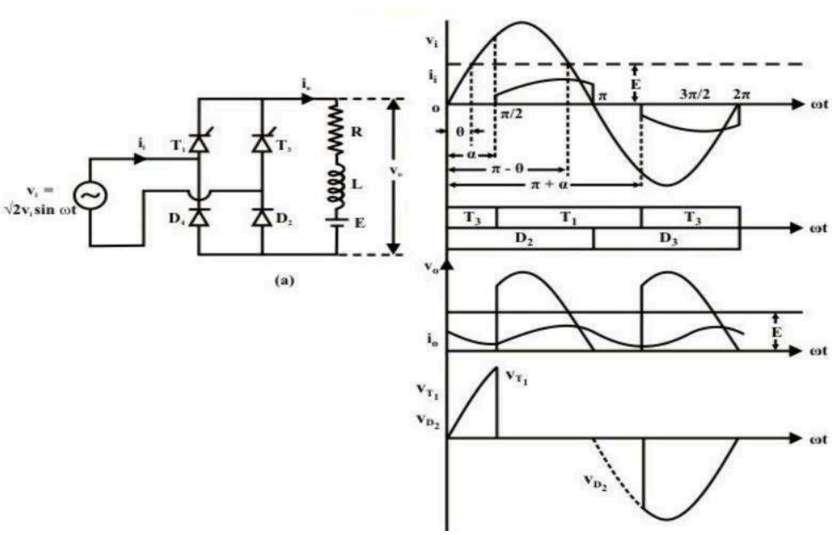


Figure: 2.5 single phase half controlled converter with RLE load

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

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

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

2.5 Single phase half controlled converter with RLE load and freewheeling diode

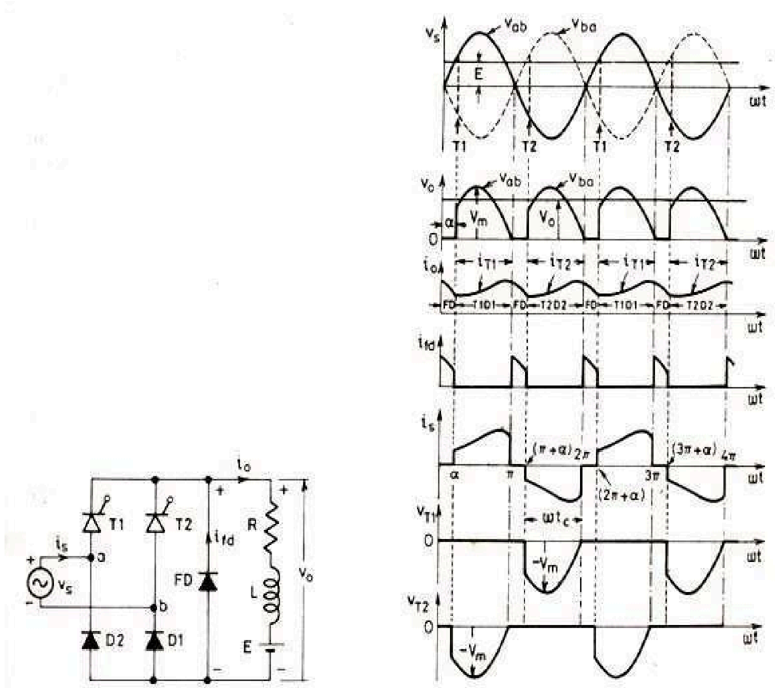


Figure: 2.6 single phase half controlled converter with RLE load and freewheeling diode

Numerical problems

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

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

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

   $1/2$ = 155.071V

   $2\sqrt{\pi}$ 4 2

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

   $$\frac{V_{or}^2}{R} = [\frac{155.071}{230}]^2 \times 1000 = 454.57W$$

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

   V_{or} = $\sqrt{2}$ × 2

$$\frac{30}{2\sqrt{\pi}}\left[\left(\pi - \frac{\pi}{2}\right) + \frac{1}{2}\sin 180\right]^{1/2} = 115V$$

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

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

2. A resistive load of 10Ω is connected through a half-wave controlled rectifier circuit to 220V, 50 Hz, single phase source. Calculate the power delivered to the load for a firing angle of 60°. Find also the value of input power factor
3. A single phase semi converter delivers to RLE load with R=5Ω, L = 10mH and E = 80V. The source voltage is 230V, 50Hz. For continuous conduction, Find the average value of output current for firing angle = 50°.

2.6 Single phase full wave controlled rectifier

Single Phase Full Wave Controlled Rectifier with 'R' load:

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

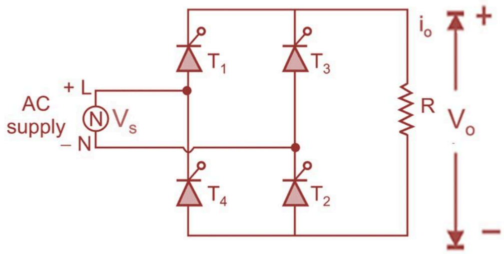


Figure: 2.7 single phase full converter circuit with R load

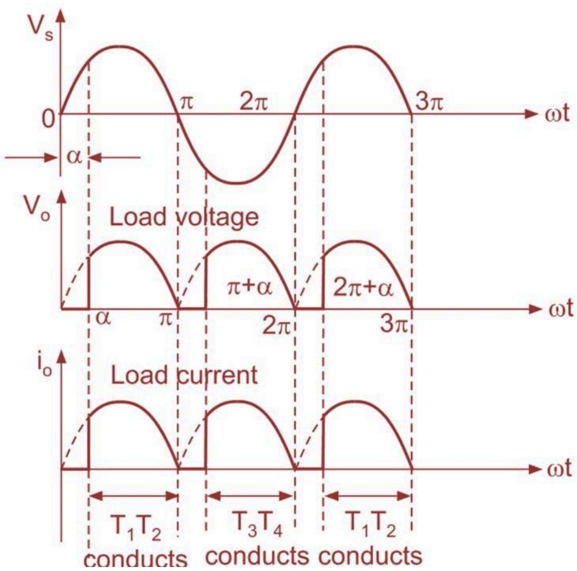


Figure: 2.8 single phase full converter circuit with R load input and output waveforms

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

• All four devices used are Thyristors. The turn-on instants of these devices are dependent on the firing signals that are given. Turn-off happens when the current through the device reaches zero and it is reverse

biased at least for duration equal to the turn-off time of the device specified in the data sheet.

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

• When T1 & T2

conducts Vo=Vs

IO=is=Vo/R=Vs/R

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

• Here output current & supply current are in opposite direction

∴ is=-io

T3 & T4 becomes off at 2π.

The average output voltage Vo is given by

$$V_o = \frac{1}{\pi}\int_{\alpha}^{\pi} \mathrm{V_m} sin\omega t \, d\omega t$$

$$\therefore V_o = \frac{V_s\sqrt{2}}{\pi}(1 + \cos\alpha)$$

The RMS value of output current I_{orms} is given by

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

$$or, I_{orms} = \frac{V_S}{r}\left[\frac{1}{\pi}\int_{\alpha}^{\pi}(1 - cos2\omega t) \; d\omega t\right]^{\frac{1}{2}}$$

$$\therefore I_{orms} = \frac{V_S}{R}\left[\frac{1}{\pi}\left\{(\pi - \alpha) + \frac{1}{2} sin2\alpha\right\}\right]^{\frac{1}{2}}$$

2.7 Single Phase Full Wave Controlled Rectifier with 'RL' load:

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

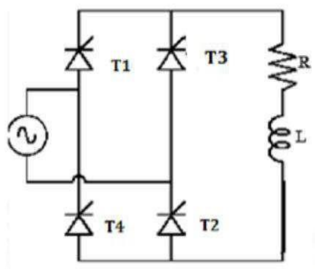


Figure: 2.9 single phase full converter circuit with RL load

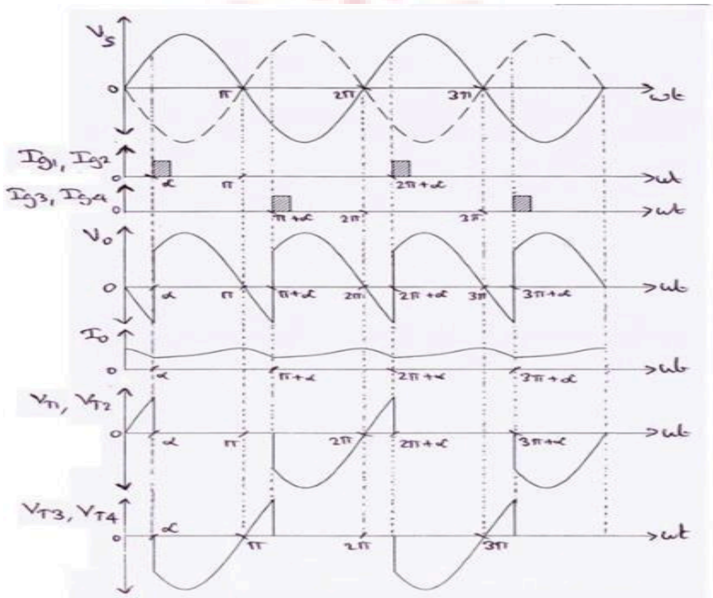


Figure: 2.10 single phase full converter circuit with RL load input and output waveforms

Operation of this mode can be divided between four modes

Mode 1 (α toπ)

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

Mode 2 (π toπ+α)

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

Mode 3 (π+α to 2π)

- At wt=π+α SCR‟s T3 & T4 are turned on & T1, T2 are reversed bias.
- Thus , process of conduction is transferred from T1,T2 to T3,T4.
- Load voltage again becomes positive & energy is stored in inductor
- T3, T4 conduct in negative half cycle from (π+α) to 2π
- With positive load voltage & load current energy gets stored

Mode 4 (2π to 2π+α)

- At wt=2π, input voltage passes through zero.
- Inductive load will try to oppose any change in current if in order to maintain load current constant & in the same direction.
- Induced emf is positive & maintains conducting SCR‟s T3 & T4 with reverse polarity also.
- Thus VL is negative & equal to instantaneous ac supply voltage. Whereas load current continues to be positive.
- Thus load acts as source & stored energy in inductance is returned back to ac supply
- At wt=α or 2π+α, T3 & T4 are commutated and T1,T2 are turned on.

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

2.8 Single phase fully controlled converters with RLE load

The circuit diagram of a full wave bridge rectifier using thyristors in shown in figure below. It consists of four SCRs which are connected between single phase AC supply and a load.

This rectifier produces controllable DC by varying conduction of all SCRs.

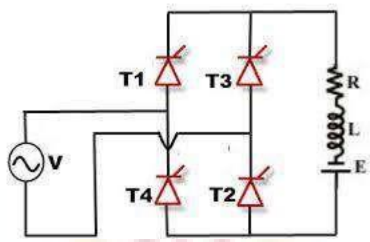


Figure: 2.11 single phase full converter circuit with RLE load

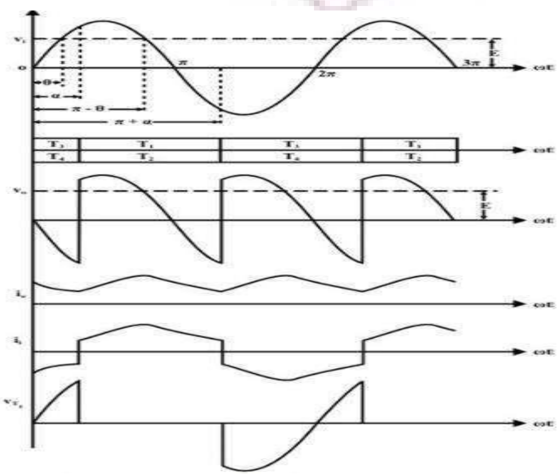


Figure: 2.12 single phase full converter circuit with RLE load input and output waveforms

In positive half-cycle of the input, Thyristors T1 and T2 are forward biased while T3 and T4 are reverse biased. Thyristors T1 and T2 are triggered simultaneously at some firing angle in the positive half cycle, and T3 and T4 are triggered in the negative half cycle.

The load current starts flowing through them when they are in conduction state. The load for this converter can be RL or RLE depending on the application.

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

The average output voltage is

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

For continuous load current, we may write

$$V_{dc} = \frac{2V_{max}}{\pi}\cos\alpha = RI_{dc} + E$$

2.9 Line commutated converters

For single phase half wave converter

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

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

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

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

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

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

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

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

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

2. Average DC load current is given as

$$I_{oavg} = \frac{V_{0avg}}{R}$$

$$I_{oavg} = \frac{V_m}{2\pi R}[1 + \cos\alpha]$$

3. RMS load voltage

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

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

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

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

4. Power delivered to the resistive load is given

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

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

$= \frac{V_{rms}^2}{R} = I_{rms}^2 X R$

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

$= V_s I_{rms}$

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

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

$$\text{Form Factor} = \frac{V_{rms}}{V_{avg}}$$

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

$$V_{ac} = [V_{rms}^2 - V_{avg}^2]^{1/2}$$

8. Ripple factor (R_f)

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

$$R_f = \frac{V_{ac}}{V_{avg}} = \frac{[V_{rms}^2 - V_{avg}^2]^{1/2}}{V_{avg}} = \left[\left(\frac{V_{rms}}{V_{avg}}\right)^2 - 1\right]^{1/2} = \sqrt{FF^2 - 1}$$

9. Transformer Utilization Factor (TUF):

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

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

10. Rectifier efficiency:

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

$$\eta = \frac{V_{avg} I_{avg}}{V_{rms} I_{rms}}$$

11. Peak inverse voltage (PIV):

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

In the case of Half wave rectifier it is V_m

2.10 Effect of source inductance in single phase rectifier

Fig. below shows a single phase fully controlled converter with source inductance. For simplicity it has been assumed that the converter operates in the continuous conduction mode. Further, it has been assumed that the load current ripple is negligible and the load can be replaced by a dc current source the magnitude of which equals the average load current. Fig. shows the corresponding waveforms

It is assumed that the Thyristors T3 and T4 were conducting at t = 0. T1 and T2 are fired at $\omega t = \alpha$. If there were no source inductance T3 and T4 would have commutated as soon as T1 and T2 are turned ON.

The input current polarity would have changed instantaneously. However, if a source inductance is present the commutation and change of input current polarity cannot be instantaneous. s. Therefore, when T1 and T2 are turned ON T3 T4 does not commutate immediately. Instead, for some interval all four Thyristors continue to conduct as shown in Fig. 2.14. This interval is called "overlap" interval.

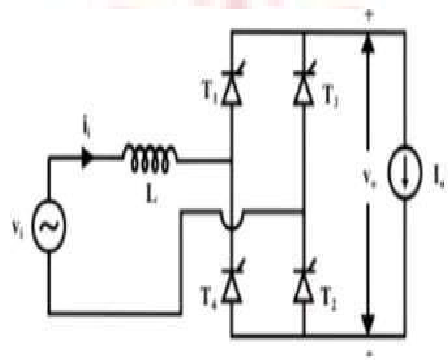


Figure: 2.13 single phase full converter circuit with source inductance

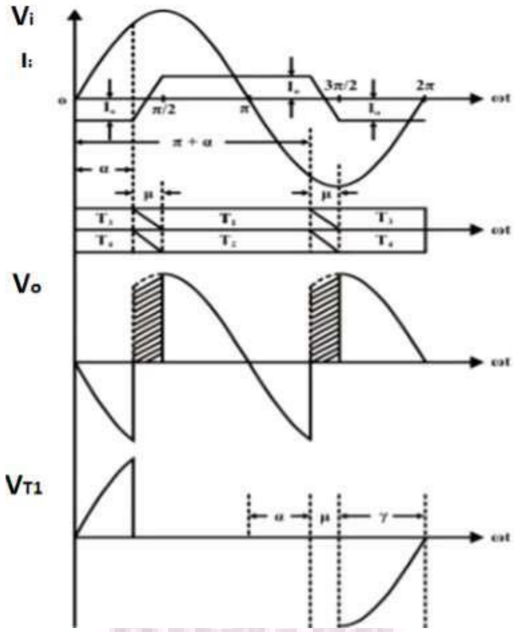


Figure: 2.14 single phase full converter output waveforms with source inductance

1. During overlap interval the load current freewheels through the thyristors and the output voltage is clamped to zero. On the other hand, the input current starts changing polarity as the current through T1 and T2 increases and T3 T4 current decreases. At the end of the overlap interval the current through T3 and T4 becomes zero and they commutate, T1 and T2 starts conducting the full load current
2. The same process repeats during commutation from T1 T2 to T3T4 at $\omega t = \pi + \alpha$. From Fig. 2.14 it is clear that, commutation overlap not only reduces average output dc voltage but also reduces the extinction angle γ which may cause commutation failure in the inverting mode of operation if α is very close to 180º.
3. In the following analysis an expression of the overlap angle "μ" will be determined. From the equivalent circuit of the converter during overlap period.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The Equation can be represented by the following equivalent circuit

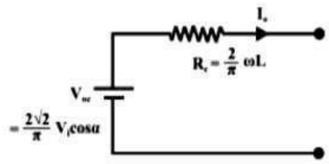


Figure: 2.15 Equivalent circuit of the given equation

Equivalent circuit representation of the single phase fully controlled rectifier with source inductance

The simple equivalent circuit of Fig. 2.15 represents the single phase fully controlled converter with source inductance as a practical dc source as far as its average behavior is concerned. The open circuit voltage of this practical source equals the average dc output voltage of an ideal converter (without source inductance) operating at a firing angle of α. The voltage drop across the internal resistance "RC" represents the voltage lost due to overlap shown in Fig. 2.14 by the hatched portion of the Vo waveform. Therefore, this is called the "Commutation resistance". Although this resistance accounts for the voltage drop correctly there is no power loss associated with this resistance since the physical process of overlap does not involve any power loss. Therefore this resistance should be used carefully where power calculation is involved.

Numerical problems

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

   Solution:

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

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

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

$\alpha = 53.21^0$

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

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

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

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

$\alpha = 124.1^0$

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

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

$I_{or} = I_o = 10A$

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

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

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

2. A single phase two pulse converter feeds power to RLE load with R= 6Ω, L= 6mH, E= 60V, AC source voltage is 230V, 50Hz for continuous condition. Find the average value of load current for a firing angle of 50°. In case one of the 4 SCRs gets open circuited. Find the new value of average load current assuming the output current as continuous.
3. For the single phase fully controlled bridge converter having load of „R", determine the average output voltage, rms output voltage and input power factor if the supply is 230V, 50 Hz, single phase AC and the firing angle is 60 degrees

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

Figure: 2.17 input and output waveforms of three phase half wave rectifier

Three phase supply voltage equations

We define three line neutral voltages (3 phase voltages) as follows V_{RN}

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

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

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

The 3-phase half wave converter combines three single phase half wave controlled rectifiers in one single circuit feeding a common load. The thyristor T_1 in series with one of the supply phase windings *'a-n'* acts as one half wave controlled rectifier The second thyristor T_2 in series with the supply phase winding *'b-n'* acts as the second half wave controlled rectifier. The third thyristor T_3in series with the supply phase winding acts as the third half wave controlled rectifier.

The 3-phase input supply is applied through the star connected supply transformer as shown in the figure. The common neutral point of the supply is connected to one end of the load while the other end of the load connected to the common cathode point.

When the thyristor T_1 is triggered at $\omega t=(\prod/6 + \alpha)=(30° + \alpha)$, the phase voltage V_{an} appears across the load when T_1 conducts. The load current flows through the supply phase winding *'a- n'* and through thyristor T_1 as long as T_1 conducts.
When thyristor T_2 is triggered at $\omega t=(5\prod/6\alpha)$, T_1 becomes reverse biased and turns-off. The load current flows through the thyristor and through the supply phase winding *'b-n'* . When T_2 conducts the phase voltage v_{bn} appears across the load until the thyristor T_3 is triggered .
When the thyristor T_3 is triggered at $\omega t=(3\prod/2 + \alpha)=(270°+\alpha)$, T_2 is reversed biased and hence T_2turns-off. The phase voltage V_{an} appears across the load when T_3 conducts.
When T_1 is triggered again at the beginning of the next input cycle the thyristor T_3 turns off as it is reverse biased naturally as soon as T_1 is triggered. The figure shows the 3-phase input supply voltages, the output voltage which appears across the load, and the load current assuming a constant and ripple free load current for a highly inductive load and the current through the thyristor T_1.
For a purely resistive load where the load inductance „L = 0‟ and the trigger angle $\alpha >(\prod/6)$, the load current appears as discontinuous load current and each thyristor is naturally commutated when the polarity of the corresponding phase supply voltage reverses. The frequency of output

ripple frequency for a 3-phase half wave converter is f_s, where f_s is the input supply frequency.

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

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

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

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

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

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

$$2\pi \quad cos\alpha$$

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

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

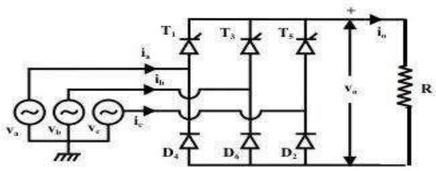


Figure: 2.18 circuit diagram three phase half controlled rectifier

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

Figure: 2.19 input and output waveforms of three phase half controlled rectifier with R load

Three single phase half wave converters can be connected to form a three phase half wave converter.

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

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

Figure: 2.19 Input and output waveforms of three phase half controlled rectifier with RL load

Numerical Problems on three phase rectifiers:

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

Solution:

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

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

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

For $\alpha = 30^0$

$P = V^2/R$

$$5000x10 = \frac{2V_s^2}{4\pi}\left[\frac{2\pi}{3} + \frac{\sqrt{3}}{2}(1 + \cos 60)\right]$$

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

2. A three-phase half-wave controlled rectifier has a supply of 200V/phase. Determine the average load voltage for firing angle of 0^o, $30^o$and 60^o assuming a thyristor volt drop of 1.5V and continuous load current
3. A three phase half wave converter is supplying a load with a continuous constant current of 50A over a firing angle from 0^o to 60^0. What will be the power dissipated by the load at these limiting values of firing angle. The supply voltage is 415V (line).

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

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

The three phase full converter is extensively used in industrial power applications upto about 120kW output power level, where two quadrant operations is required. The figure shows a three phase full converter with highly inductive load. This circuit is also known as three phase full wave bridge or as a six pulse converter.

The thyristors are triggered at an interval of ($\prod/3$) radians (i.e. at an interval of 30°). The frequency of output ripple voltage is $6f_s$ and the filtering requirement is less than that of three phase semi and half wave converters**.**

Figure: 2.20 circuit diagram three phase fully controlled rectifier with R and RL load

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

At $\omega t=(\prod/2 +\alpha)$, the thyristor T_2 is triggered and T_6 is reverse biased immediately and T_6 turns off due to natural commutation. During the time period $\omega t=(\prod/ +\alpha)$ *to* $(5\prod/6 +\alpha)$, thyristor T_1 and T_2 conduct together and the line to line supply voltage appears across the load.

The thyristors are numbered in the circuit diagram corresponding to the order in which they are triggered. The trigger sequence (firing sequence) of the thyristors is 12, 23, 34, 45, 56, 61, 12, 23, and so on. The figure shows the waveforms of three phase input supply voltages, output voltage, the thyristor current through T_1 and T_4, the supply current through the line "a".

We define three line neutral voltages (3 phase voltages) as follows V_{RN}

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

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

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

The corresponding line to line voltages are

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

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

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

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

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

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

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

2.15 Operation of three phase half wave rectifier with RLE loads

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

Figure: 2.22 circuit diagram of three phase fully controlled rectifier with RLE load

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

Then from symmetry consideration it can be argued that each thyristor conducts for 120° of the input cycle. Now the thyristors are fired in the sequence T1 → T2 → T3 → T4 → T5 → T6 → T1 with 60° interval between each firing. Therefore thyristors on the same phase leg are fired at an interval of 180° and hence cannot conduct simultaneously. This leaves only six possible conduction mode for the converter in the continuous conduction mode of operation. These are T1T2, T2T3, T3T4, T4T5, T5T6, T6T1. Each conduction mode is of 60° duration and appears in the sequence mentioned. Each of these line voltages can be associated with the firing of a thyristor with the help of the conduction table-1. For example the thyristor T1 is fired at the end

of T5 T6 conduction interval. During this period the voltage across T1 was vac. Therefore T1 is fired α angle after the positive going zero crossing of vac. similar observation can be made about other thyristors.

Fig. 2.23 shows the waveforms of different variables. To arrive at the waveforms it is necessary to draw the conduction diagram which shows the interval of conduction for each thyristor and can be drawn with the help of the phasor diagram of fig. 2.22. If the converter firing angle is α each thyristor is fired "α" angle after the positive going zero crossing of the line voltage with which it‟s firing is associated. Once the conduction diagram is drawn all other voltage waveforms can be drawn from the line voltage waveforms and from the conduction table of fig. 2.22. Similarly line currents can be drawn from the output current and the conduction diagram. It is clear from the waveforms that output voltage and current waveforms are periodic over one sixth of the input cycle. Therefore this converter is also called the “six pulse” converter. The input current on the other hand contains only odds harmonics of the input frequency other than the triplex (3rd, 9th etc.) harmonics. The next section will analyze the operation of this converter in more details.

Figure: 2.23 Input and output waveforms of three phase fully controlled rectifier in rectifier mode

Figure: 2.24 Input and output waveforms of three phase fully controlled rectifier in inversion mode

2.16 Effect of source inductance in three phase rectifiers

Figure: 2.25 circuit diagram for three phase rectifier with source inductance

The three phase fully controlled converter was analyzed with ideal source with no internal impedance. When the source inductance is taken into account, the qualitative effects on the performance of the converter is similar to that in the case of a single phase converter. Fig. 2.25 shows such a converter. As in the case of a single phase converter the load is assumed to be highly inductive such that the load can be replaced by a current source.

Figure: 2.26 waveforms for three phase rectifier with source inductance

As in the case of a single phase converter, commutations are not instantaneous due to the presence of source inductances. It takes place over an overlap period of "μ_1" instead. During the overlap period three thyristors instead of two conducts. Current in the outgoing thyristor gradually decreases to zero while the incoming thyristor current increases and equals the total load current at the end of the overlap period. If the duration of the overlap period is greater than 60º four thyristors may also conduct clamping the output voltage to zero for some time. However, this situation is not very common and will not be discussed any further in this lesson. Due to the conduction of two devices during commutation either from the top group or the bottom group the instantaneous output voltage during the overlap period drops (shown by the hatched portion of Fig. 2.26 resulting in reduced average voltage. The exact amount of this reduction can be calculated as follows.

In the time interval $\alpha < \omega t \leq \alpha + \mu$, T_6 and T_2 from the bottom group and T_1 from the top group conducts. The equivalent circuit of the converter during this period is given by the circuit diagram of Fig. 2.27

2.17 Introduction to dual converters

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

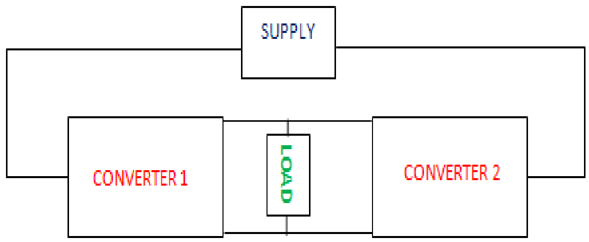


Figure: 2.28 Block diagram of dual converter

Modes of Operation of Dual Converter

There are two functional modes: Non-circulating current mode and circulating mode.

Non Circulating Current Mode

- One converter will perform at a time. So there is no circulating current between the converters.
- During the converter 1 operation, firing angle (α_1) will be $0<\alpha_1< 90^o$; V_{dc} and I_{dc} are positive.
- During the converter 2 operation, firing angle (α_2) will be $0<\alpha_2< 90^o$; V_{dc} and I_{dc} are negative.

Circulating Current Mode

- 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 (α_1) + firing angle of converter 2 (α_2) = 180^o.
- Converter 1 performs as a controlled rectifier when firing angle be $0<\alpha_1< 90^o$ and Converter 2 performs as an inverter when the firing angle be $90^o<\alpha_2< 180^o$. In this condition, V_{dc} and I_{dc} are positive.
  - Converter 1 performs as an inverter when firing angle be $90^o<\alpha_1< 180^o$ and Converter 2 performs as a controlled rectifier when the firing angle be $0<\alpha_2< 90^o$ In this condition, V_{dc} and I_{dc} are negative.
  - The four quadrant operation is shown below

Figure: 2.29 Four quadrant operations of dual converter

Ideal Dual Converter

The term „ideal‟ refers to the ripple free output voltage. For the purpose of unidirectional flow of DC current, two diodes (D_1 and D_2) are incorporated between the converters. However, the direction of current can be in any way. The average output voltage of the converter 1 is V_{01} and converter 2 is V_{02}. 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

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.

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

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

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

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

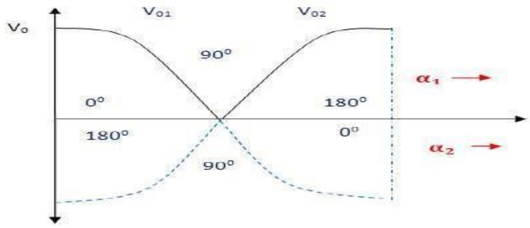


Figure: 2.32 output voltage variation with firing angle

Three Phase Dual Converter

Here, 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
DC – DC converters

3.1 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 choppers ON and OFF state times, respectively.

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

Symbol of a Chopper

Figure: 3.1 symbol of chopper

3.2 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:

1. Time Ratio Control

2. Current Limit Control

In this post we shall look upon both the ways of varying the duty cycle. Duty Cycle is the ratio of „On Time" to „Time Period of a pulse".

Time Ratio Control: As the name suggest, here the time ratio (i.e. the duty cycle ratio Ton/T) is varied. This kind of control can be achieved using 2 ways:

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

Pulse Width Modulation (PWM)

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

Figure: 3.2 pulse width modulation waveforms

Frequency Modulation Control (FMC)

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

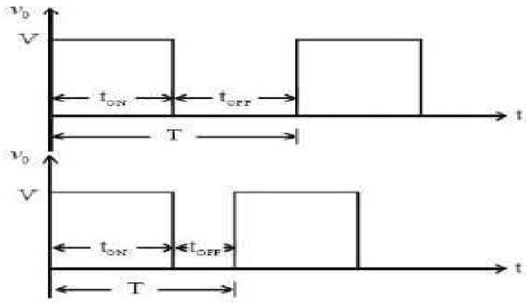


Figure: 3.3 Frequency modulation waveforms

Current Limit Control:

As is obvious from its name, in this control strategy, a specific limit is applied on the current variation.

In this method, current is allowed to fluctuate or change only between 2 values i.e. maximum current (I max) and minimum current (I min). When the current is at minimum value, the chopper is switched ON. After this instance, the current starts increasing, and when it reaches up to maximum value, the chopper is switched off allowing the current to fall back to minimum value. This cycle continues again and again.

Figure: 3.4 current limit control waveforms

3.3 Classification of Choppers

Depending on the voltage output, choppers are classified as −

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

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

Depending upon the direction of the output current and voltage, 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]

3.4 StepDownChopper

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

When the chopper is ON −

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

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

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

$$0\ VS=(VL+V0),$$

$$VL=VS-V0,$$

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

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

$$0$$

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

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

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,

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

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

$$L\Delta i/TOFF=V0$$

$$\Delta i=V0TOFF/L$$

From the above equations

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

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

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

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

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

3.5 StepUpChopper

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

Current and Voltage Waveforms

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

Figure: 3.8 Input and output waveforms of step up chopper

Where

T_{ON} – time interval when chopper is ON

T_{OFF} – time interval when chopper is OFF

V_L – Load voltage

V_s – Source voltage

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

V_o is given by −

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

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

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

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

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

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

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

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

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

Equating Δi from on state to off state $\frac{TVs}{Toff}$

$$Vo =$$

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

3.6 StepUp/StepDownChopper

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

Figure: 3.9 circuit diagram of step up / Steep down chopper

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

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

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

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

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

Hence,

$$V0 = -VL$$

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

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

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

By comparing the above equations

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

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

3.7 Principle of operation of class A chopper

Class A Chopper is a first quadrant chopper

• When chopper is ON, supply voltage V is connected across the load.

• When chopper is OFF, vO = 0 and the load current continues to flow in the same direction through the FWD.

• The average values of output voltage and current are always positive. Class A Chopper is a first quadrant chopper

• When chopper is ON, supply voltage V is connected across the load.

• When chopper is OFF, vO = 0 and the load current continues to flow in the same direction through the FWD.

• The average values of output voltage and current are always positive.

• Class A Chopper is a step-down chopper in which power always flows form source to load.

• It is used to control the speed of dc motor.

• The output current equations obtained in step down chopper with R-L load can be used to study the performance of Class A Chopper.

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

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

Taking Inverse Laplace Transform

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

The expression is valid for $0 \le t \le t_{OFF}$, i.e., during the period chopper is OFF. At the instant the chopper is turned ON or at the end of the off period, the load current is

$$i_O(t_{OFF}) = I_{min}$$

3.8 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.

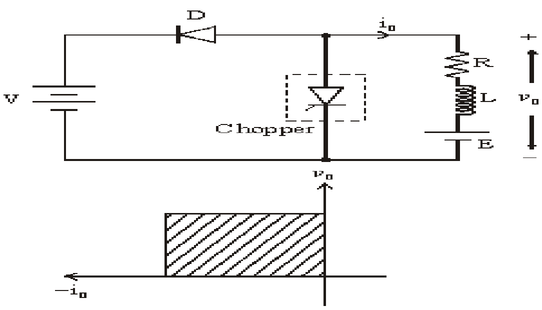


Figure: 3.12 circuit diagram and quadrant operation of Type B chopper

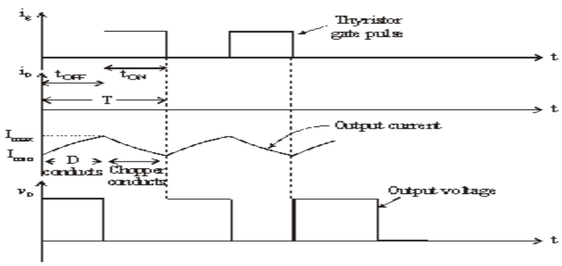


Figure: 3.13 Output voltage and current waveforms of type B chopper

3.9 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: 3.15 Output voltage and current waveforms of type C chopper

3..10 Class D chopper

• Class D is a two quadrant chopper.

• When both CH1 and CH2 are triggered simultaneously, the output voltage $v_O = V$ 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 $v_O = -V$.

• Average load voltage is positive if chopper ON time is more than the OFF time

• Average output voltage becomes negative if $t_{ON} < t_{OFF}$.

• Hence the direction of load current is always positive but load voltage can be positive or negative.

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

3.11 Class E Chopper

• Class E is a four quadrant chopper

• When CH1 and CH4 are triggered, output current iO flows in positive direction through CH1 and CH4, and with output voltage vO = V.

• This gives the first quadrant operation.

• When both CH1 and CH4 are OFF, the energy stored in the inductor L drives iO through D2 and D3 in the same direction, but output voltage vO = -V.

• Therefore the chopper operates in the fourth quadrant.

• When CH2 and CH3 are triggered, the load current iO flows in opposite direction & output voltage vO = -V.

• Since both iO and vO are negative, the chopper operates in third quadrant.

• When both CH2 and CH3 are OFF, the load current iO continues to flow in the same direction D1 and D4 and the output voltage vO = V.

• Therefore the chopper operates in second quadrant as vO is positive but iO is negative.

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

Numerical problems

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

Solution −

The chopping frequency (f)

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

Halving the pulse width gives −

2. In a type A chopper, the input supply voltage is 230 V the load resistance is 10Ω and there is a voltage drop of 2 V across the chopper thyristor when it is on. For a duty ratio of 0.4, calculate the average and rms values of the output voltage. Also find the chopper efficiency
3. A step-up chopper supplies a load of 480 V from 230 V dc supply. Assuming the non conduction period of the thyristor to be 50 microsecond, find the on time of the thyristor

Buck regulator

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

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

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

Linear step down

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

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.

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.

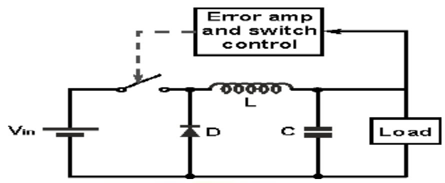


Figure: 3.20 circuit diagram of Buck regulator

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.

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.

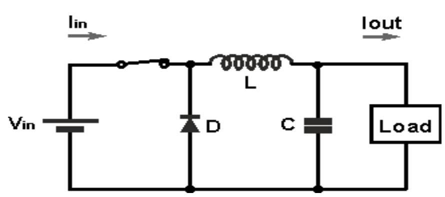


Figure: 3.21 circuit diagram of Buck regulator during switch on condition

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 Idiode equal to Iout 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: 3.23 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.

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.

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.

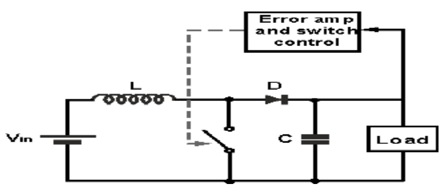


Figure: 3.24 circuit diagram of Boost regulator

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.

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.