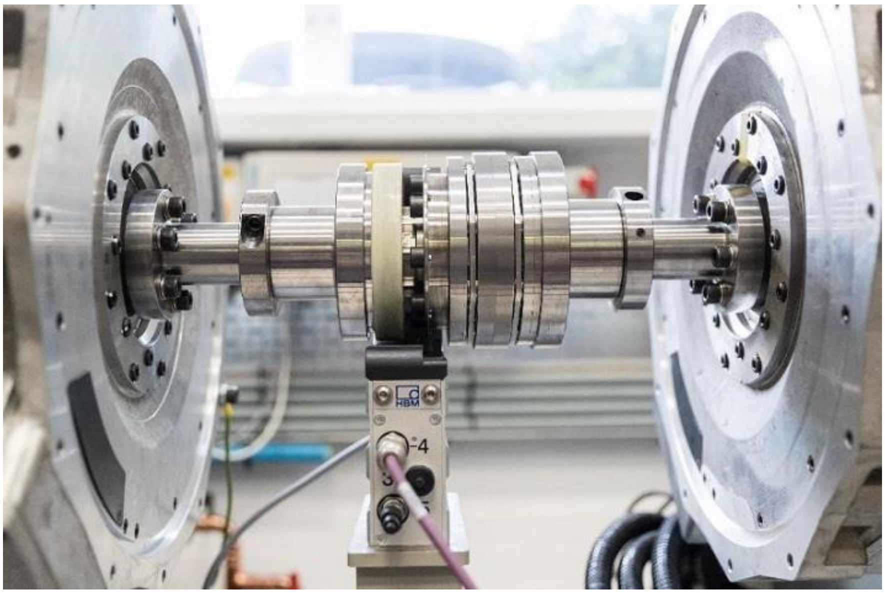
Power Electronics and Industrial Drives



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Lecture notes on Power Electronics and Industrial Drives

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INDEX

AIM

To introduce the application of electronic devices for conversion, control and conditioning of electric power.

COURSE OBJECTIVES

The course will enable the students to:

1. Have an overview of different types of power semi-conductor devices and their switching characteristics.
2. Understand the operation, characteristics and performance parameters of controlled rectifiers.
3. Study the operation, switching techniques of inverters and choppers.
4. Learn the different speed control techniques of drives and to understand the converter/chopper fed methods.
5. Understand the practical applications of power electronic drive converters.

PREREQUISITE: Electronic Devices and Circuits

SYLLABUS

UNIT I POWER SEMICONDUCTOR DEVICES

Power diodes – power transistor – characteristics of SCR, Triac, power MOSFET – IGBT – MCT – LASCR – SCR turn on, turn off characteristics – thyristor specifications – thyristor protection circuits. Thyristor trigger circuits

UNIT II CONVERTERS

Operation of 1ϕ half wave rectifiers with R, RL & RLE load.- 1ϕ Full wave rectifier with R, RL, & RLE load (fully controlled and half controlled) - Effect of source inductance & load inductance – Introduction to Cyclo Converters - Single phase mid - point cyclo-converters with Resistive and inductive load – Bridge configuration of single phase cyclo-converter – Waveforms. AC voltage controllers – Integral Cycle Control – Single Phase Voltage controller with R, RL load.

UNIT III INVERTERS & CHOPPERS

Voltage source inverters – series, parallel & bridge inverters – Current source inverters – PWM inverters. Commutation – Choppers – Control strategies – DC chopper – AC Chopper – Applications.

UNIT IV DC DRIVES

Advantages, types & selection of electrical drives, Methods of speed control of DC motors – Armature control & Field control – Ward Leonard drives –Converter fed & Chopper fed DC drives - Two quadrant & Four quadrant chopper drives.

UNIT V INDUCTION MOTOR DRIVES

Induction Motor fundamentals – Speed control of Induction motors – Stator control: Voltage, Frequency, V/F control (AC chopper, Inverter fed drives) – Rotor resistance control – slip power recovery scheme – Introduction – Synchronous motor drive.

UNIT I – POWER SEMICONDUCTOR DEVICES

Power diodes – power transistor – characteristics of SCR, Triac, power MOSFET – IGBT – MCT – LASCR – SCR turn on, turn off characteristics – thyristor specifications – thyristor protection circuits. Thyristor trigger circuits

THEORY

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 Thyristorised 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 to a form that is suitable for user loads. The most desirable power electronic system is one whose efficiency and reliability is 100%.

2. 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

3. Types of power electronic converters

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

Power semiconductor devices

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

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

Linear operation	**Switching operation**
Active zone selected: Good linearity between input/output	Active zone avoided : High losses, encountered only during transients
Saturation & cut-off zones avoided: poor linearity	Saturation & cut-off (negative bias) zones selected: low losses
Transistor biased to operate around quiescent point	No concept of quiescent point
Common emitter, Common collector, common base modes	Transistor driven directly at base - emitter and load either on collector or emitter
Output transistor barely protected	Switching-Aid-Network (SAN) and other protection to main transistor

4. POWER SEMICONDUCTOR DEVICES

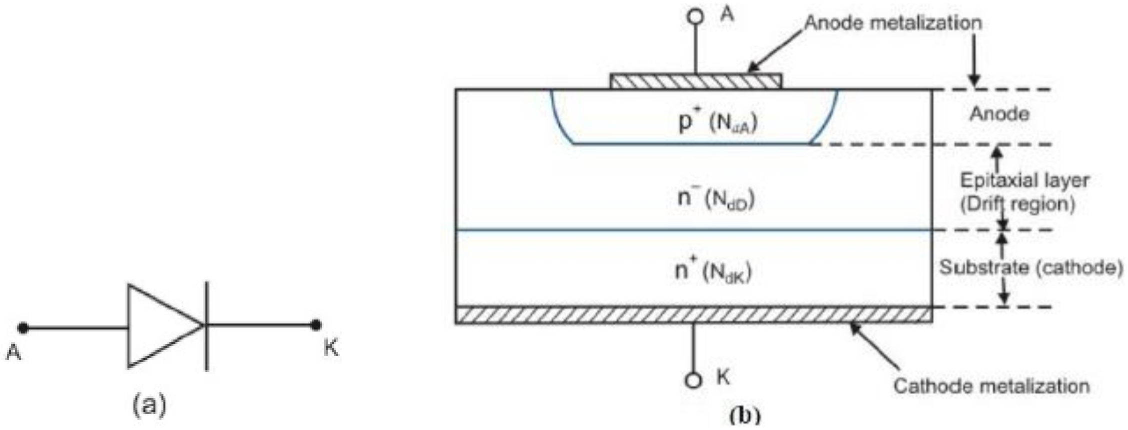
The first SCR was developed in late 1957. Power semiconductor devices are broadly categorized into 3 types:

1. Power diodes (600V,4500A)
2. Transistors
3. Thyristors (10KV,300A,30MW)

5. **POWER DIODE**

Power Diodes of largest power rating are required to conduct several kilo amps of current in the forward direction with very little power loss while blocking several kilo volts in the reverse direction. Large blocking voltage requires wide depletion layer in order to restrict the maximum electric field strength below the impact ionization‖ level. Space charge density in the depletion layer should also be low in order to yield a wide depletion layer for a given maximum Electric fields strength. These two requirements will be satisfied in a lightly doped p-n junction diode of sufficient width to accommodate the required depletion layer. Such a construction, however, will result in a device with high resistively in the forward direction. Consequently, the power loss at the required rated current will be unacceptably high.

On the other hand if forward resistance (and hence power loss) is reduced by increasing the doping level, reverse break down voltage will reduce. This apparent contradiction in the requirements of a power diode is resolved by introducing a lightly doped drift layer‖ of required thickness between two heavily doped p and n layers as shown in Fig 1 (b). Fig 1 (a) and (b) shows the circuit symbol and the photograph of a typical power diode respectively



(a)

(b)

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Fig.1. a) Symbol b) Schematic diagram

To arrive at the structure shown in Fig 1 (b) a lightly doped n epitaxial layer of specified width (depending on the required break down voltage) and donor atom density (N) is grown on a heavily doped n+ substrate (NdK donor atoms Cm-3) which acts as the cathode. Finally the p-n junction is formed by defusing a heavily doped (NaA acceptor atoms.Cm-3) p+ region into the epitaxial layer. This p type region acts as the anode.

The different applications of Power Diode are in SMPs, Snubber, Chopper and freewheeling diode etc.

V-I characteristic curve of Power Diode

Power Diodes take finite time to make transition from reverse bias to forward bias condition (switch ON) and vice versa (switch OFF). Behavior of the diode current and voltage during these switching periods are important due to the following reasons.

i) Severe over voltage / over current may be caused by a diode switching at different points in the circuit using the diode.

ii) Voltage and current exist simultaneously during switching operation of a diode. Therefore, every switching of the diode is associated with some energy loss. At high switching frequency this may contribute significantly to the overall power loss in the diode.

Observed Turn ON behavior of a power Diode: Diodes are often used in circuits with di/dt limiting inductors. The rate of rise of the forward current through the diode during Turn ON has significant effect on the forward voltage drop characteristics. A typical turn on transient is shown in Fig. 2

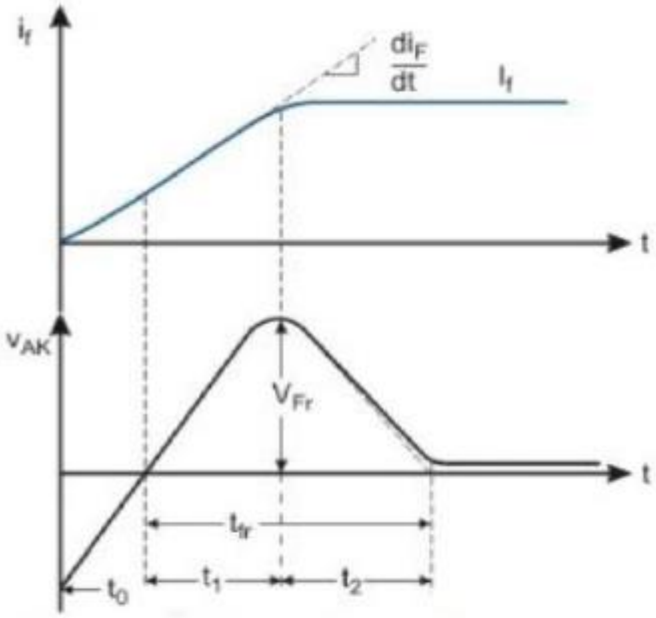


Fig 2 Forward current and voltage waveforms of a power diode during turn on operation

It is observed that the forward diode voltage during turn ON may transiently reach a significantly higher value V_{fr} compared to the steady slate voltage drop at the steady current I_F. V_{fr} (called forward recovery voltage) is given as a function of the forward di/dt in the manufacturer‘s data sheet. Typical values lie within the range of 10-30V. Forward recovery time (t_{fr}) is typically within 10 us.

Observed Turn OFF behavior of a Power Diode: Figure 3 shows a typical turn off behavior of a power diode assuming controlled rate of decrease of the forward current.

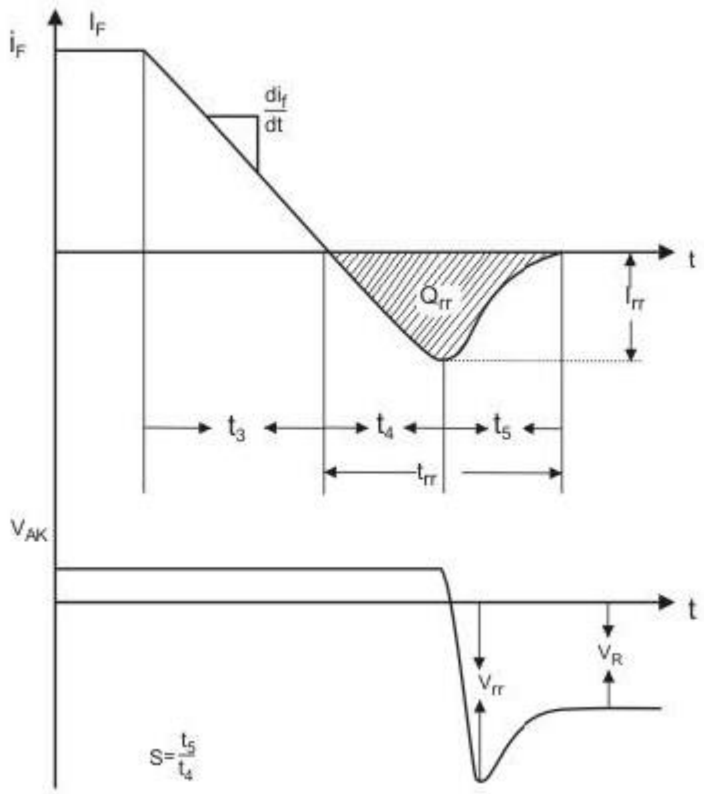


Fig.3 Reverse recovery characteristics of a power diode

Salient features of this characteristic are:

The diode current does not stop at zero; instead it grows in the negative direction to Irr called ―peak reverse recovery current‖ which can be comparable to I_F. In many power electronic circuits (e.g. choppers, inverters) this reverse current flows through the main power switch in addition to the load current. Therefore, this reverse recovery current has to be accounted for while selecting the main switch.

Voltage drop across the diode does not change appreciably from its steady state value till the diode current reaches reverse recovery level. In many power electric circuits (choppers, inverters) this may create an effective short circuit across the supply, current being limited only by the stray wiring inductance. Also in high frequency switching circuits (e.g, SMPS) if the time period t4 is comparable to switching cycle qualitative modification to the circuit behavior is possible. Towards the end of the reverse recovery period if the reverse current falls too sharply, (low value of S), stray circuit inductance may cause dangerous over voltage (Vrr) across the device. It may be required to protect the diode using an RC snubber. During the period t_5 large current and voltage exist simultaneously in the device. At high switching frequency this may result in considerable increase in the total power loss.

Power Transistor Characteristics

Power transistors are devices that have controlled turn-on and turn-off characteristics. These devices are used a switching devices and are operated in the saturation region resulting in low on-state voltage drop. They are turned on when a current signal is given to base or control terminal. The transistor remains on so long as the control signal is present. The switching speed of modern transistors is much higher than that of Thyristors and is used extensively in dc-dc and dc-ac converters. However, their voltage and current ratings are lower than those of thyristors and are therefore used in low to medium power applications.

Power transistors are classified as follows

Bipolar junction transistors (BJTs)
Metal-oxide semiconductor filed-effect transistors (MOSFETs)
Insulated-gate bipolar transistors (IGBT)

6. POWER BJT

The need for a large blocking voltage in the off state and a high current carrying capability in the on state means that a power BJT must have substantially different structure than its small signal equivalent. The modified structure leads to significant differences in the I-V characteristics and switching behavior between power transistors and its logic level counterpart.

BJT Structure

To form a three terminal device with the terminals named as Emitter, Base and Collector, thin p-layer is sandwiched between two n-layers as shown in fig.4 in the power BJT, the following differences over conventional one are obvious:

- A power transistor is a vertically oriented four layer structure of alternating p-type and n type. This is maximizing the cross-section area results in current rating of BJT, minimize the on-state resistance, and thus reduce the power losses.
- The doping of emitter layer and collector layer is quite large typically 1019 cm-3
- A special layer called the collector drift region (n-) has a light doping level of 1014.
- The thickness of the drift region determines the breakdown voltage of the transistor.
- The base thickness is made as small as possible in order to have good amplification capabilities, however if the base thickness is small the breakdown voltage capability of the transistor is compromised.

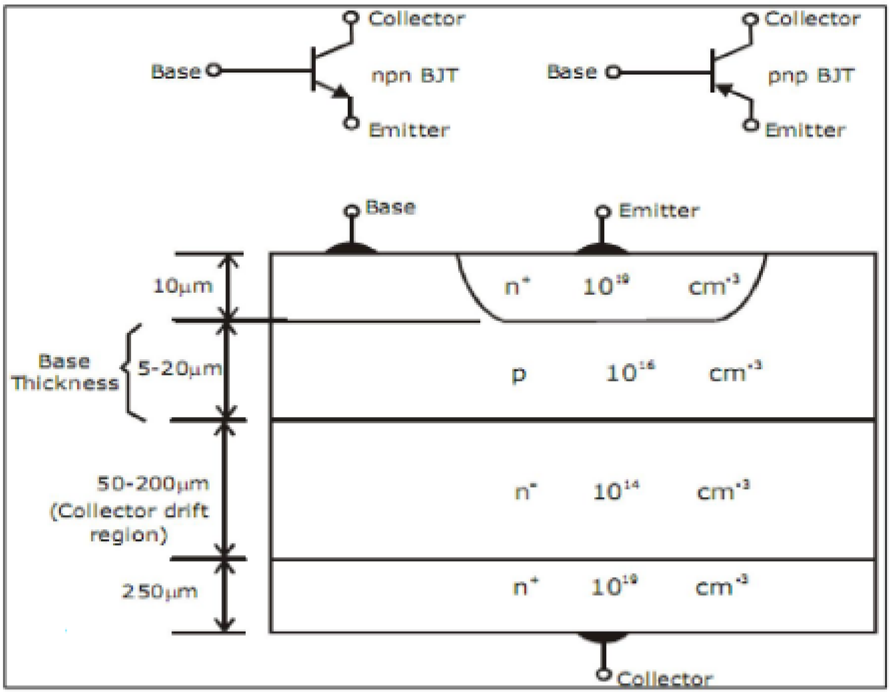


Fig 4. Power BJT

Steady State Characteristics

The power transistor has steady state characteristics almost similar to signal level transistors except that the V-I characteristics have a region of quasi saturation as shown by Fig.5/ Three regions of operation for a BJT can be recognized:

Cutoff Region: When the base current (IB) is zero, the collector current (IC) is insignificant and the transistor is driven into the cutoff region. The transistor is now in the **OFF state**. The collector–base and base–emitter junctions are reverse biased in the cutoff region or OFF state, and the transistor behaves as an open switch.

In this region:

IC= 0 and the collector–emitter voltage VCE is equal to the supply voltage VCC

Saturation Region: When the base current is sufficient to drive the transistor into saturation. During saturation, both junctions are forward-biased and the transistor acts like a **closed switch**. In the quasi saturation and hard saturation, the base drive is applied and transistor is said to be on.

In this region:

IC = VCC /RC and VCE = zero

Active Region: In the active region, the collector–base junction is reversed-biased and the base–emitter junction is forward-biased. The active region of the transistor is mainly used for amplifier applications and should be avoided for switching operation.

The power BJT is never operated in the active region (i.e. as an amplifier) it is always operated between cut-off and saturation.

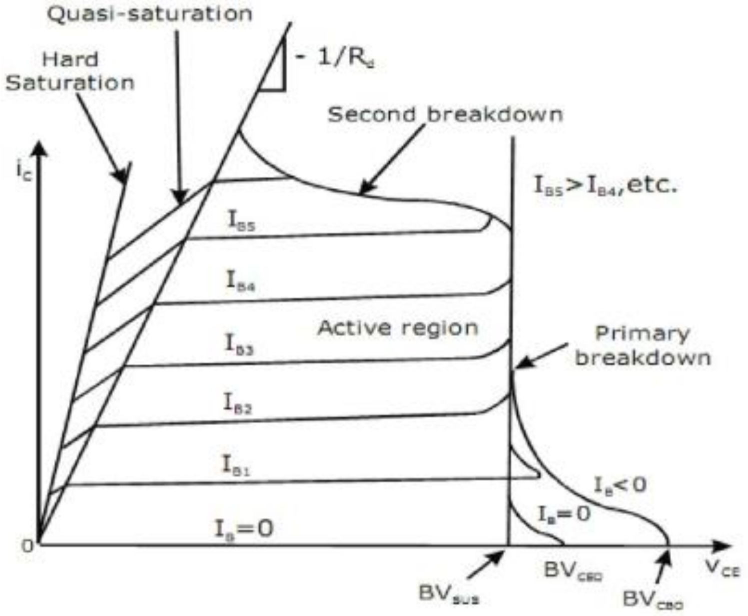


Fig 5 V-I characteristics of Power BJT

Power BJT as a Switch

The transistor is used as a switch therefore it is used only between saturation and cutoff.

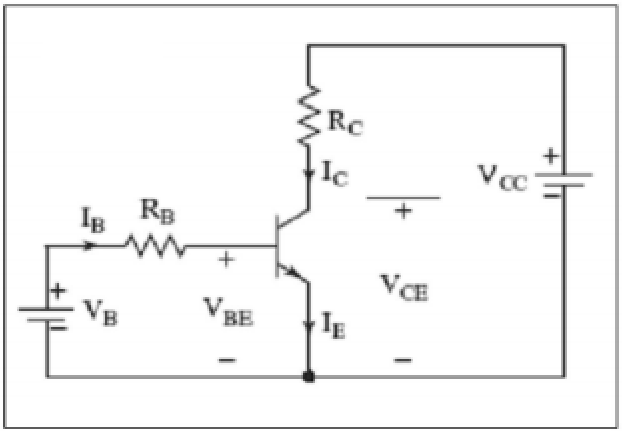


Fig 6 Transistor as a switch

The following equations can be written:

$$I_B = \frac{V_B - V_{BE}}{R_B}$$

$$V_C = V_{CE} = V_{CC} - I_C R_C = V_{CC} - \beta \frac{R_C \left(V_B - V_{BE} \right)}{R_B}$$

$$V_{CE} = V_{CB} + V_{BE} \Rightarrow \boxed{V_{CB} = V_{CE} - V_{BE} \qquad \dots(1)}$$

As long as VCE>VBE the Collector-Base junction is reverse biased and transistor is in active region,

The maximum collector current in the active region, for $V_{CB} = 0 \text{ and } V_{BE} = V_{CE}$

$$I_{CM} = \frac{V_{CC} - V_{CE}}{R_C} \qquad I_{BM} = \frac{I_{CM}}{\beta_F}$$

If IB > IBM → VBE↑, IC↑ and VCE falls below VBE. This continues until Collector-Base junction is forward biased and the BJT goes into saturation region.

NOTE: The transistor saturation may be defined as the point above which any increase in the base current does not increase the collector current significantly.

The collector current is

$$I_{CS} = \frac{V_{CC} - V_{CESAT}}{R_C} \quad I_{BS} = \frac{I_{CS}}{\beta}$$

The ratio of IB to IBS is called to overdrive factor ODF. $\boxed{ODF = \frac{I_B}{I_{BS}}}$

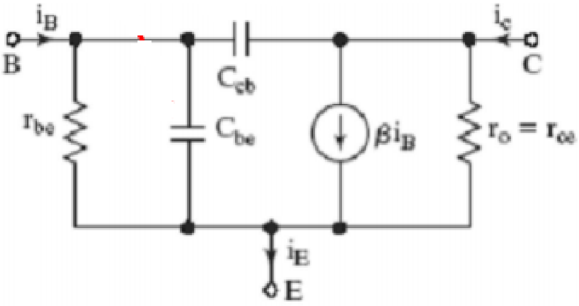
The ratio of IC to ICS is called forced β $\boxed{\beta_{forced} = \frac{I_{CS}}{I_B}}$

The total power loss in the two functions is $\boxed{P_T = V_{BE} I_B + V_{CE} I_C}$

Switching Characteristics

A forward biased p-n junction exhibits two parallel capacitances; a **depletion layer capacitance** and a **diffusion capacitance**

a reverse biased p-n junction has only depletion capacitance.



(a) Model with current gain

under transient conditions, they influence turn-on and turn-off behaviour of the transistor.

Fig 7 Equivalent circuit

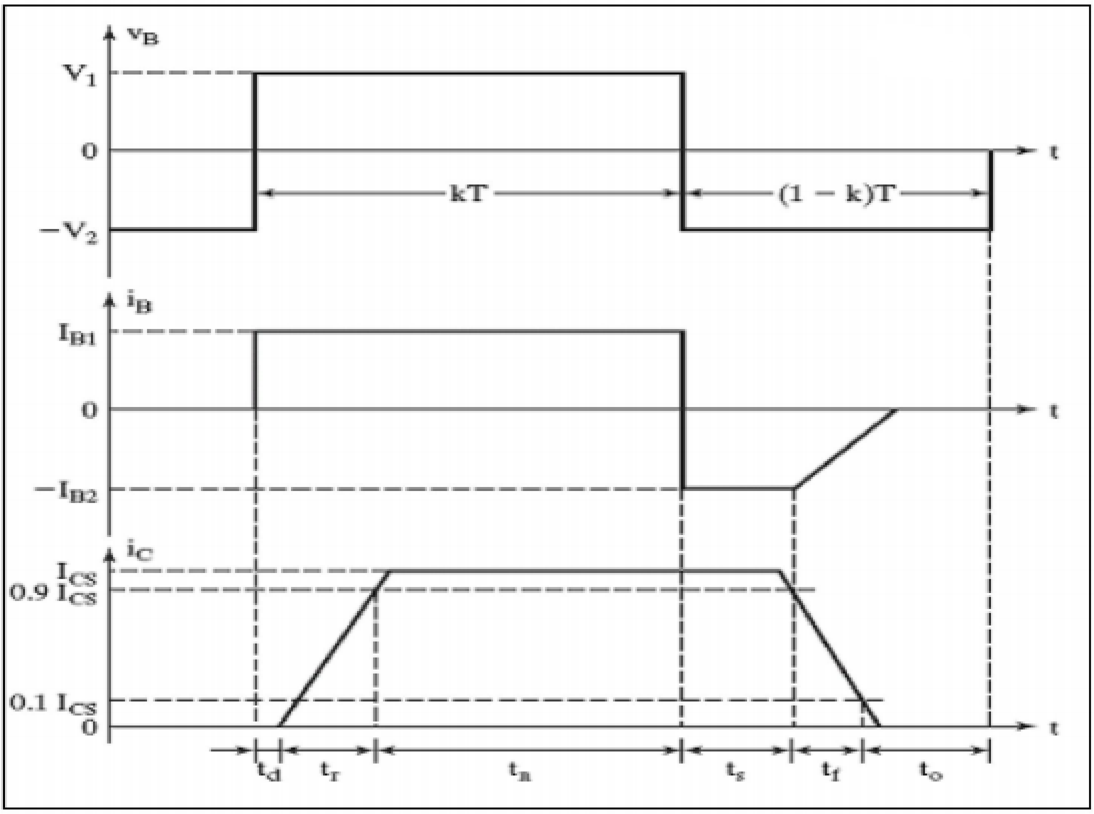


Fig 8 Switching characteristics of BJT

The Switching Times of BJT is shown in fig.8. From this figure it can be seen that:

- Due to internal capacitances, the transistor does not turn on instantly.
- VB rises from zero to V1 and the base current rises to IB1, the collector current does not respond immediately.
- The delay is due to the time required to charge up the BEJ to the forward bias voltage VBE(0.7V).
- The collector current rises to the steady value of ICS and this time is called rise time tr.

The base current is normally more than that required to saturate the transistor. As a result, excess minority carrier charge is stored in the base region. The higher the ODF, the greater is the amount of extra charge stored in the base. This extra charge which is called the saturating charge is proportional to the excess base drive.

This extra charge which is called the saturating charge is proportional to the excess base drive and the corresponding current Ie.

$$I_e = I_B - \frac{I_{CS}}{\beta} = ODF.I_{BS} - I_{BS} = I_{BS}\left(ODF - 1\right)$$

Saturating charge $Q_S = \tau_s I_e = \tau_s I_{BS}(ODF - 1)$ where τ_s is known as the storage time constant.

When the input voltage is reversed from V1 to -V2, the reverse current –IB2 helps to discharge the base. Without –IB2 the saturating charge has to be removed entirely due to recombination and the storage time ts would be longer. Once the extra charge is removed, BEJ charges to the input voltage

–V2 and the base current falls to zero. tf depends on the time constant which is determined by the reverse biased BEJ capacitance.

ADVANTAGES OF BJT

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

DEMERITS OF BJT

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

7. POWER MOSFETS

Unlike the device discussed so far, a power MOSFET is a unipolar, majority carrier, “zero junction,” voltage-controlled device. Figures (a) and (b) below show the symbol of an N type and P-type MOSFETs.

(a) n-channel **(b) p-channel**

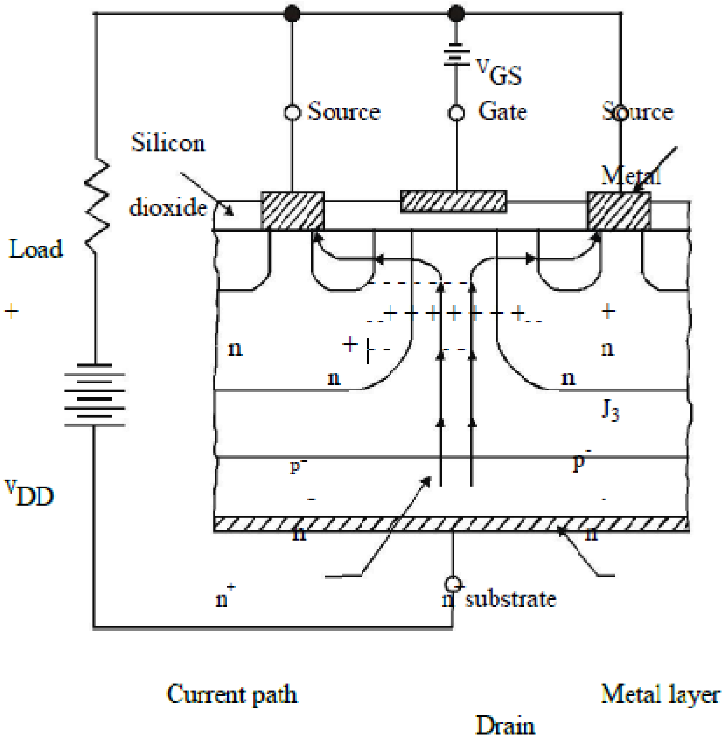


Fig 9 Power MOSFET

Enhancement Type MOSFET Construction

A slab of p-type material is formed and two n-regions are formed in the substrate. The source and drain terminals are connected through metallic contacts to n-doped regions, but the absence of a channel between the doped n regions. The SiO2 layer is still present like in conventional MOSFET to isolate the gate metallic platform from the region between drain and source, but now it is separated by a section of p-type material.

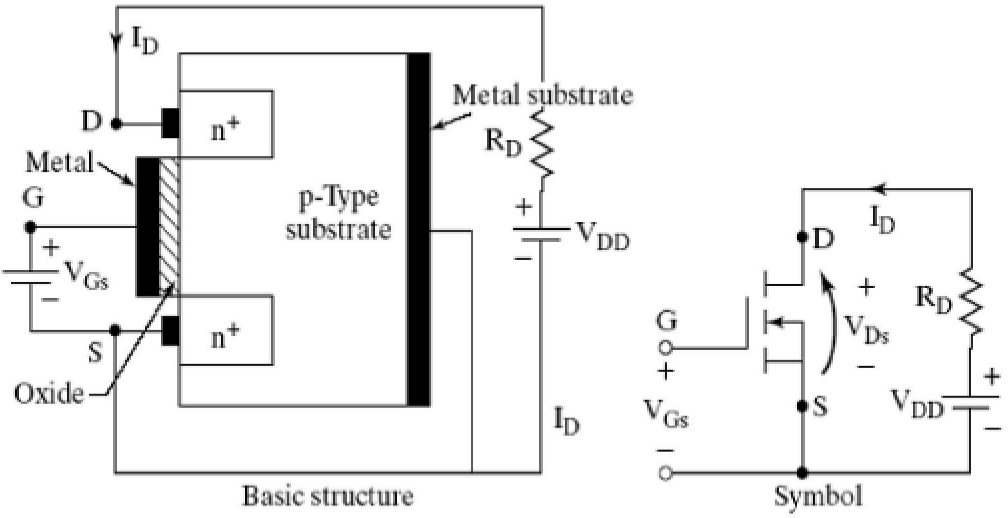


Fig 10. N channel enhancement MOSFET

With the normal forward polarity for VDD on the MOSFET, but with VGs = 0, the device is like an npn transistor with the drain to gate junction reverse-biased, and therefore no drain current flow. With VGs applied, making the gate positive with respect to the source, positive charge accumulates at the gate metallic surface, an electric field is created in the oxide layer, and negative charge accumulates at the p- structure surface in contact with the oxide layer.

This negative charge repels holes in the p-structure and leaves a virtual n-type channel through which electrons can flow from source to drain, i.e. conventional current low from drain to source. For the MOSFET to turn on, VGs must exceed the threshold voltage VT. The linearized transfer characteristic of the MOSFET is shown in Fig.11a, and the output, or drain-source, characteristic is shown in Fig.11b.

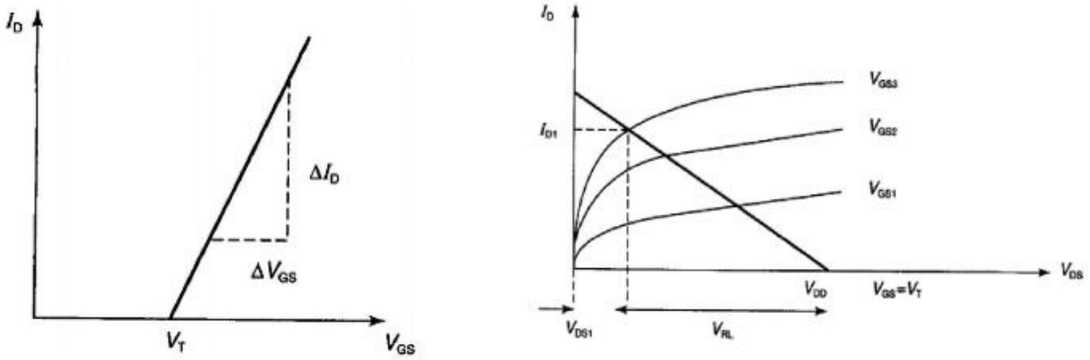


Fig. 11 Characteristics of power MOSFET

The load line can be superimposed on the output characteristic to give the operating point

$$V_{DD} = I_D R + V_{DS}$$

$$I_D = (V_{DD}/R) - (V_{DS}/R)$$

$$\text{At } I_D = 0,\ V_{DD} = V_{DS};\ \text{at } V_{DS} = 0,\ I_D = V_{DD}/R.$$

If the slope of the characteristic to the left of the intersection of the VGS (working) curve with the load line, the so-called 'ohmic region', is linearized then a much simpler solution is obtained.

SWITCHING CHARACTERISTICS

The switching model of MOSFET is as shown in the fig 9. The various inter electrode capacitance of the MOSFET which cannot be ignored during high frequency switching are represented by Cgs , Cgd & Cds . The switching waveforms are as shown in fig 12. The turn on time td is the time that is required to charge the input capacitance to the threshold voltage level. The rise time tr is the gate charging time from this threshold level to the full gate voltage Vgsp . The turn off delay time tdoff is the time required for the input capacitance to discharge from overdriving the voltage V1 to the pinch off region. The fall time is the time required for the input capacitance to discharge from pinch off region to the threshold voltage. Thus basically switching ON and OFF depend on the charging time of the input gate capacitance.

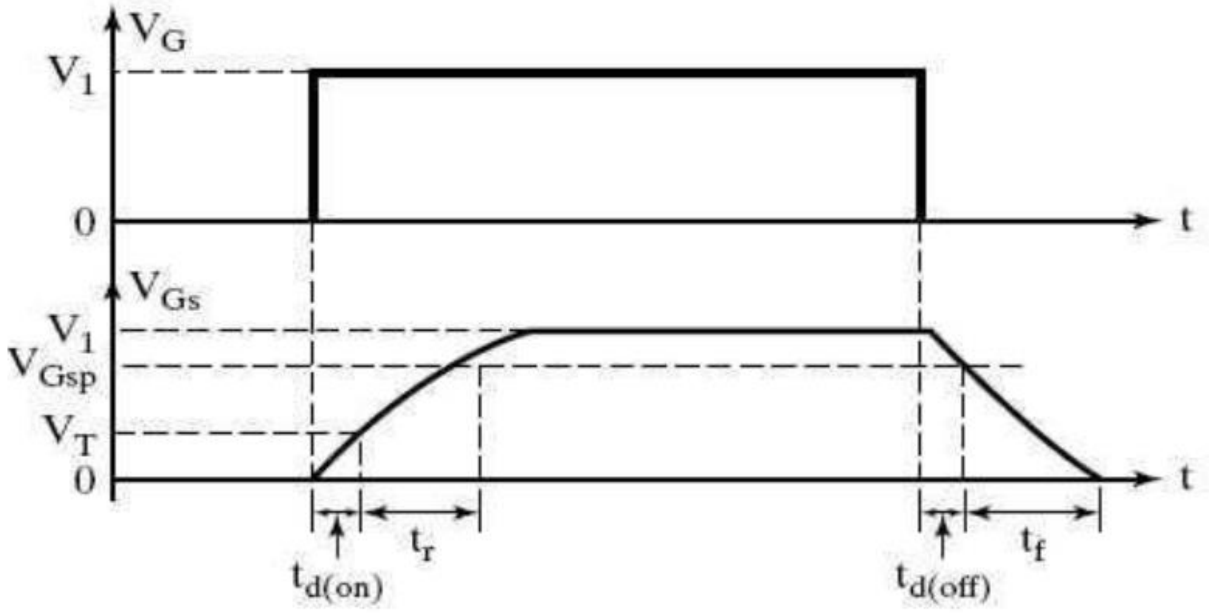


Fig.12. Switching waveforms of power MOSFET

Comparison between BJT and MOSFET

SlNo	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	Drive circuit is complex. It should provide constant current(Base current)	Drive 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.

8. 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.

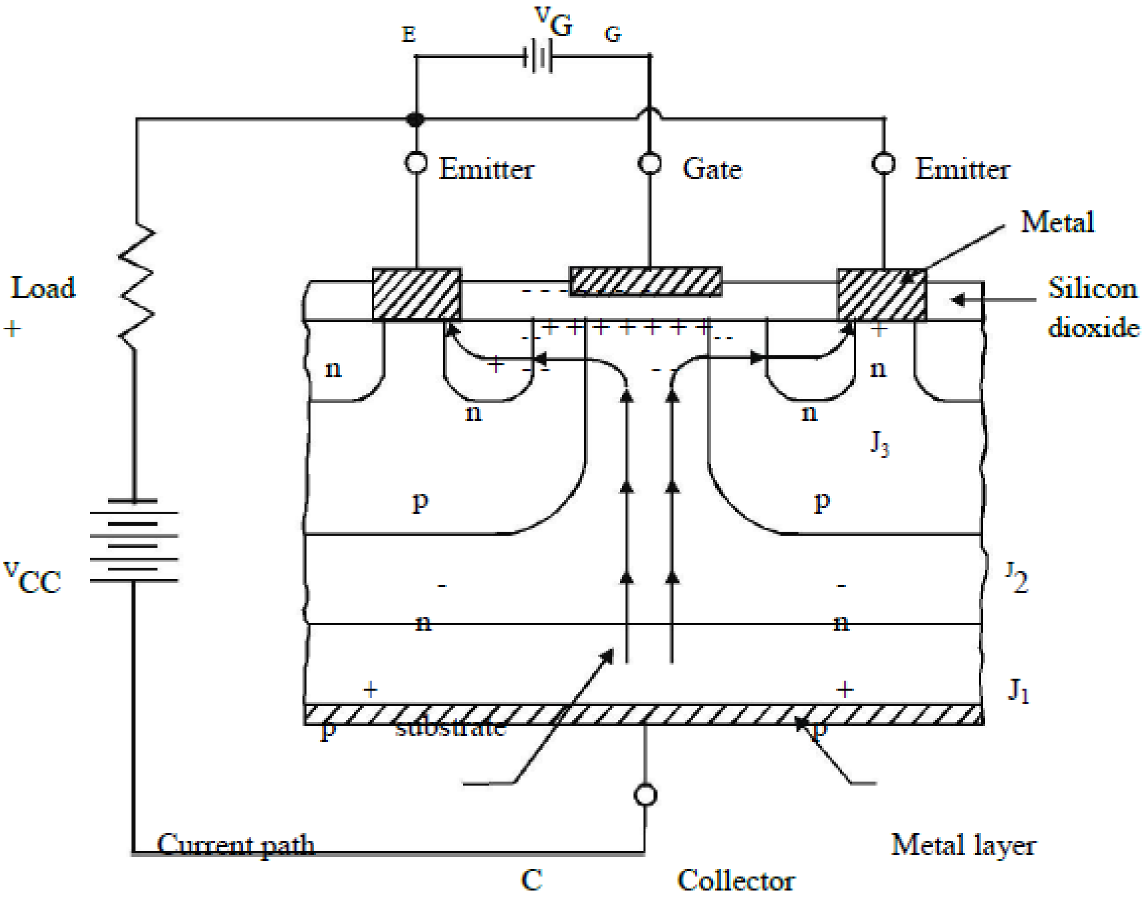


Fig. 13. Cross -sectional structural diagram of IGBT

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. 13 to Fig. 14. It has three terminals called collector, emitter and gate. 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

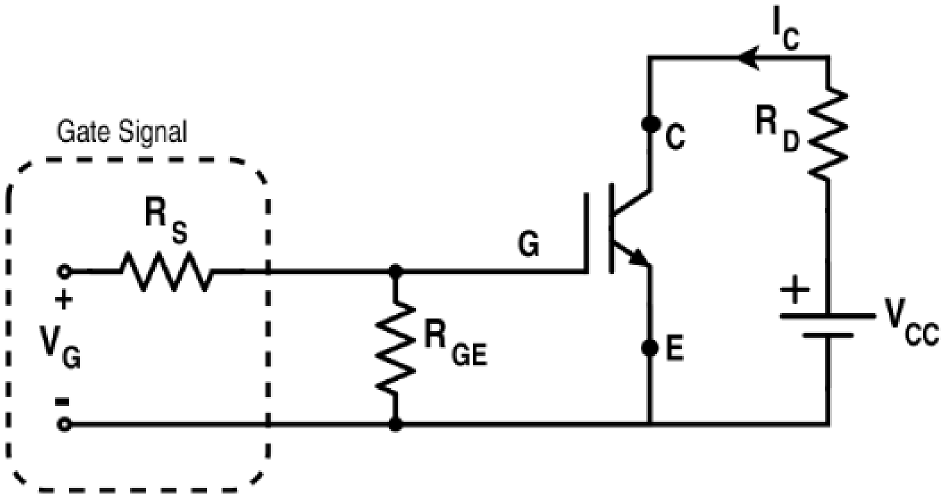


Fig. 14. Equivalent diagram of IGBT

Based on this circuit diagram given in Fig. 13, forward characteristics and transfer characteristics are obtained which are given in Fig. 15 and Fig. 16. Its switching characteristic is also shown in Fig. 17

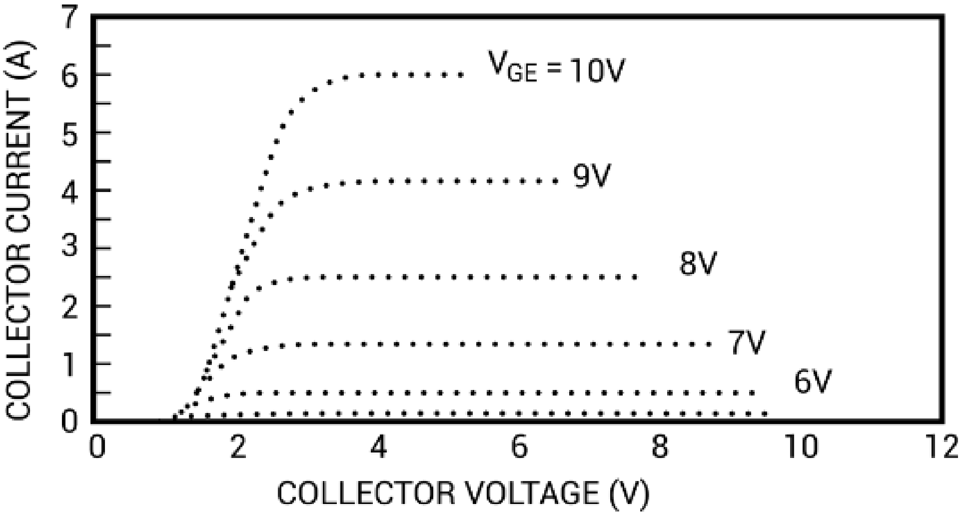


Fig: 15. Forward characteristics of IGBT

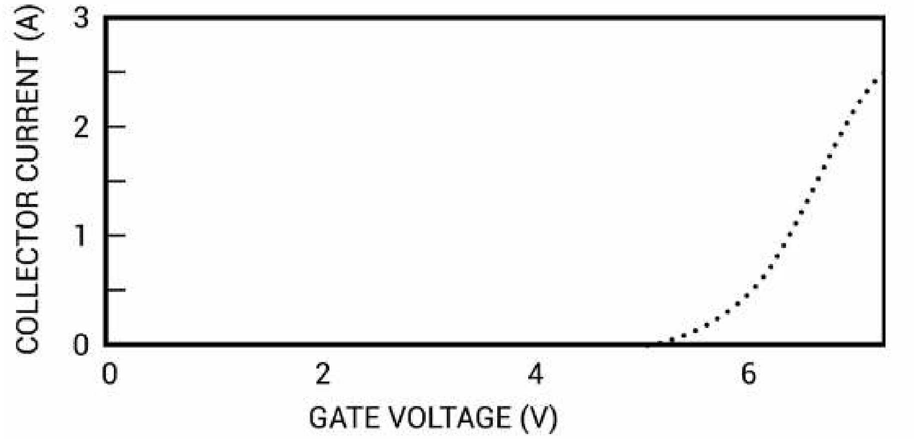


Fig: 16. Transfer characteristics of IGBT

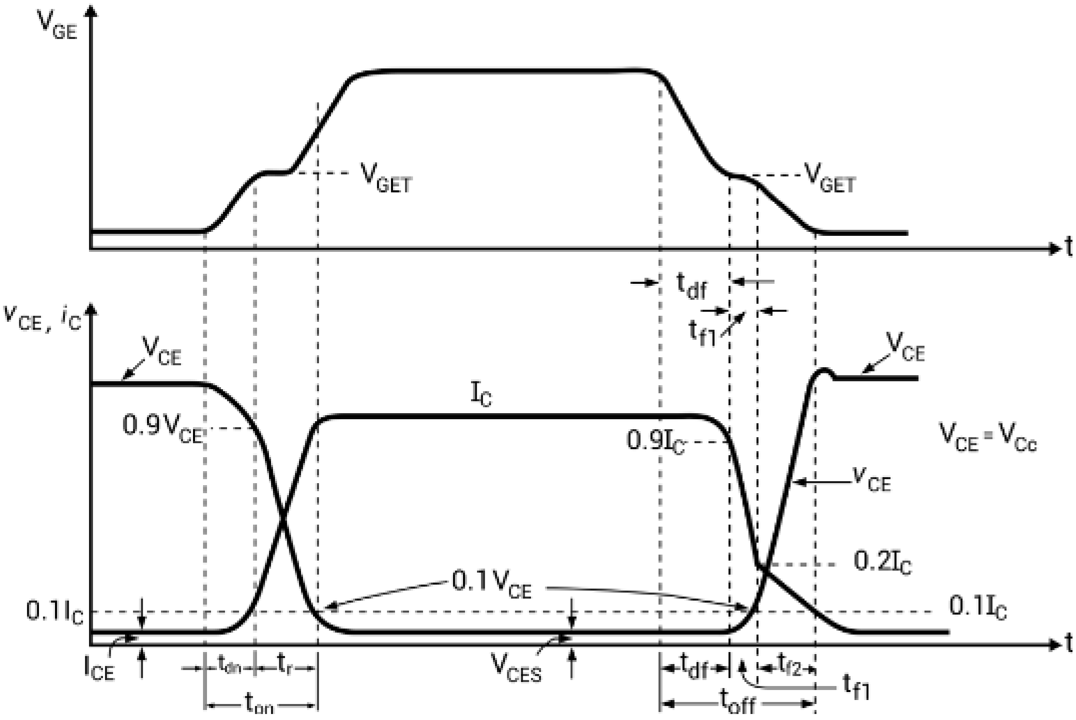


Fig: 17. Switching characteristics of IGBT

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

Applications of IGBT

IGBTs are used in high power applications such as:

- Appliance motor drives
- Electric vehicle motor drives
- Power factor correction converters
- Uninterruptible power supplies
- Solar inverters
- High frequency welders
- Inductive heating cookers

In what way IGBT is more advantageous than BJT and MOSFET?

- It has high input impedance of the MOSFET and has low on-state voltage drop.
- The turn off time of an IGBT is greater than that of MOSFET.
- It has low onstage conduction losses and there is no problem of second Breakdown as in case of BJT.
- It is inherently faster than a BJT.

9. DIAC

Operation, construction of DIAC and V-I characteristics curve

A DIAC is a two-terminal, three layer bidirectional device which can be switched from its OFF state to ON state for either polarity of applied voltage. The DIAC can be constructed in either npn or pnp form. Fig. (i) shows the basic structure of a DIAC in pnp form. The two leads are connected to p-regions of silicon separated by an n-region. The structure of DIAC is very much similar to that of a transistor. However, there are several important differences: (i) There is no terminal attached to the base layer. (ii) The three regions are nearly identical in size. (iii) The doping concentrations are identical (unlike a bipolar transistor) to give the device symmetrical properties. Fig. (ii) shows the symbol of a DIAC.

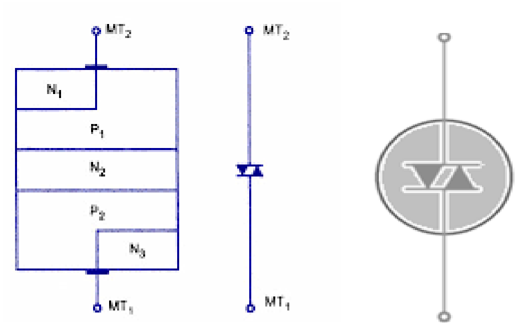


Fig 18. DIAC – Construction and Symbol

Operation

When a positive or negative voltage is applied across the terminals of a DIAC, only a small leakage current IBO will flow through the device. As the applied voltage is increased, the leakage current will continue to flow until the voltage reaches the break over voltage VBO. At this point, avalanche breakdown of the reverse-biased junction occurs and the device exhibits negative resistance i.e. current through the device increases with the decreasing values of applied voltage. The voltage across the device then drops to break back voltage V. Fig 19 shows the V-I characteristics of a DIAC. If positive voltage applied is less than + VBO and negative voltage less than – VBO a small leakage current (± IBO) flows through the device. Under such conditions, the DIAC blocks the flow of current and effectively behaves as an open circuit. The voltages + VBO and − VBO are the breakdown voltages and usually have a range of 30 to 50 volts.

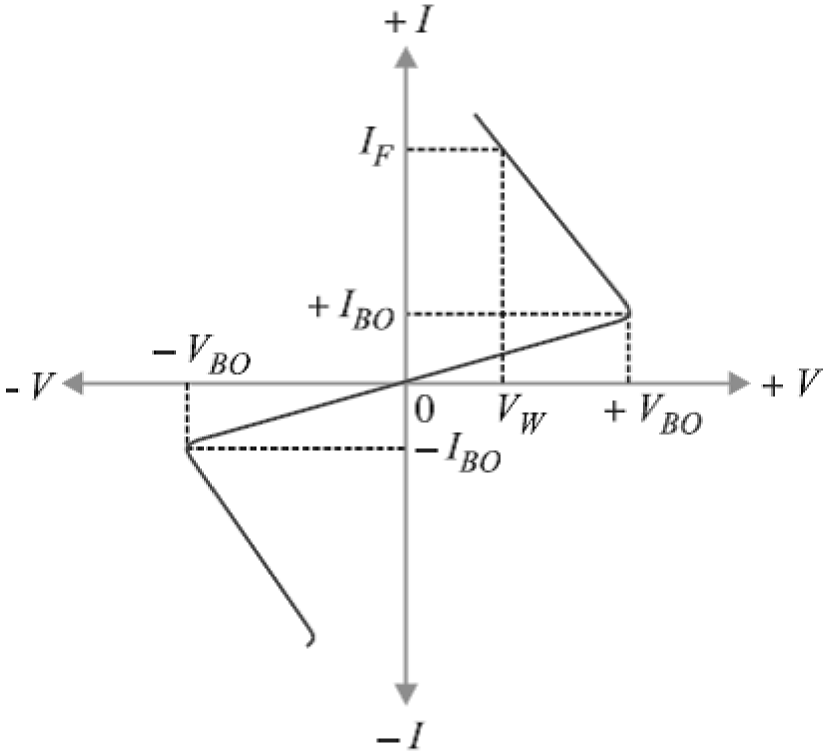


Fig. 19. V-I Characteristics of a DIAC

When the positive or negative applied voltage is equal to or greater than the breakdown voltage, DIAC begins to conduct and the voltage drop across it becomes a few volts. Conduction then continues until the device current drops below its holding current. Note that the break over voltage and holding current values are identical for the forward and reverse regions of operation. The DIAC can be used in many applications such as motor speed controls and light dimmers circuit.

Applications of DIAC

The DIAC s, because of their symmetrical bidirectional switching characteristics, are widely used as triggering devices in TRIAC phase control circuits employed for lamp dimmer, heat control, universal motor speed control etc. Although a TRIAC may be fired into the conducting state by a simple resistive triggering circuit, but triggering devices are typically placed in series with the gates of SCRs and TRIACs as they give reliable and fast triggering. DIAC is the most popular triggering device for the TRIAC. This is illustrated in the following applications.

1. TRIAC Lamp Dimmer Circuit.

The circuit for a TRIAC controlled by an R-C phase-shift network and a DIAC is given in figure. This circuit is an example of a simple lamp dimmer. The TRIAC conduction angle is adjusted by adjusting the potentiometer R. The longer the TRIAC conducts, the brighter the lamp will be. The DIAC acts like an open-circuit until the voltage across the capacitor exceeds its break over or switching voltage (and the TRIAC‘s required gate trigger voltage).

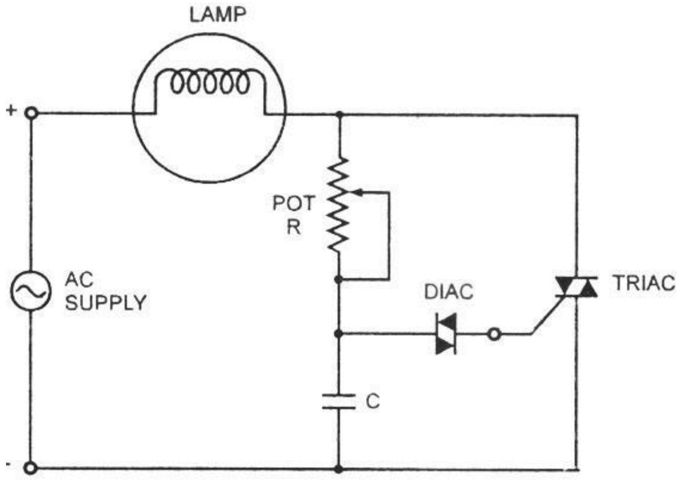


Fig.20. Lamp dimmer circuit

2. Heat Control Circuit.

A typical DIAC-TRIAC circuit used for smooth control of ac power to a heater is shown in figure. The capacitor C1 in series with choke L across the TRIAC slows-up the voltage rise across the device during off-state. The resistor R4 across the DIAC ensures smooth control at all positions of potentiometer R2. The TRIAC conduction angle is adjusted by adjusting the potentiometer R2. The longer the TRIAC conducts, the larger the output will be from the heater. Thus a smooth control of the heat output from the heater is obtained.

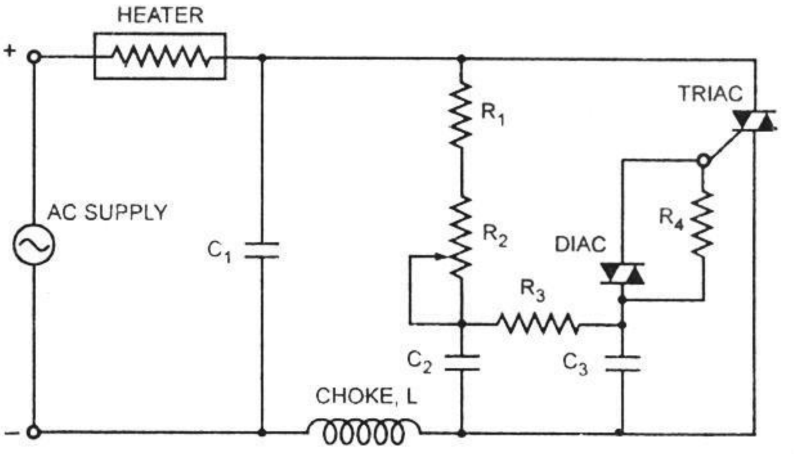


Fig. 21. Heat Control Circuit

10. TRIAC

Operation, construction of TRIAC and V-I characteristics curve

The TRIAC is a member of the thyristor family. But unlike a thyristor which conducts only in one direction (from anode to cathode) a TRIAC can conduct in both directions. Thus a TRIAC is similar to two back to back (anti parallel) connected thyristosr but with only three terminals. Construction and operating principle Fig. 5 (a) and (b) show the circuit symbol and schematic cross section of a TRIAC respective. As the TRIAC can conduct in both the directions the terms ―anode‖ and ―cathode‖ are not used for TRIACs. The three terminals are marked as MT1 (Main Terminal 1), MT2 (Main Terminal 2) and the gate by G. As shown in Fig 5 (b) the gate terminal is near MT1 and is connected to both N3 and P2 regions by metallic contact. Similarly MT1 is connected to N2 and P2 regions while MT2 is connected to N4 and P1 regions.

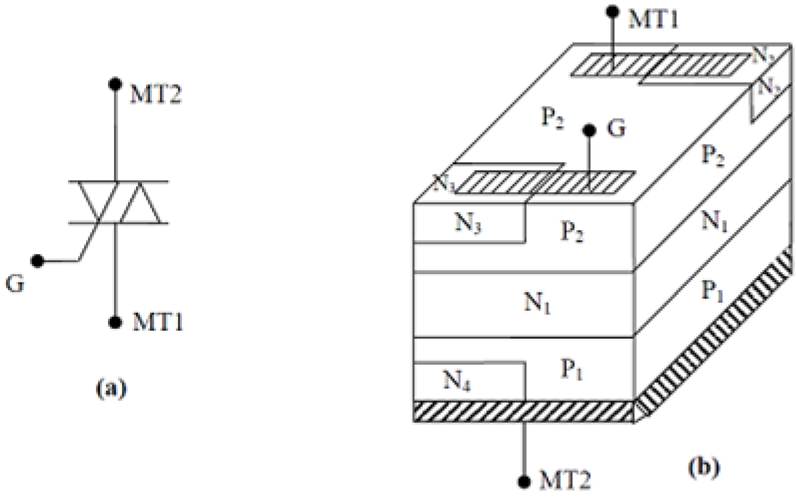


Fig.22 Circuit symbol and schematic construction of a Triac
(a) Circuit symbol (b) Schematic construction.

V-I characteristics

From a functional point of view a TRIAC is similar to two thyristors connected in anti parallel. Therefore, it is expected that the V-I characteristics of TRIAC in the 1st and 3rd quadrant of the V-I plane will be similar to the forward characteristics of a thyristors. As shown in Fig. 22, with no signal to the gate the TRIAC will block both half cycle of the applied ac voltage provided its peak value is lower than the break over voltage (VBO) of the device. However, the turning on of the TRIAC can be controlled by applying the gate trigger pulse at the desired instance. Mode-1 triggering is used in the first quadrant where as Mode-3 triggering is used in the third quadrant.

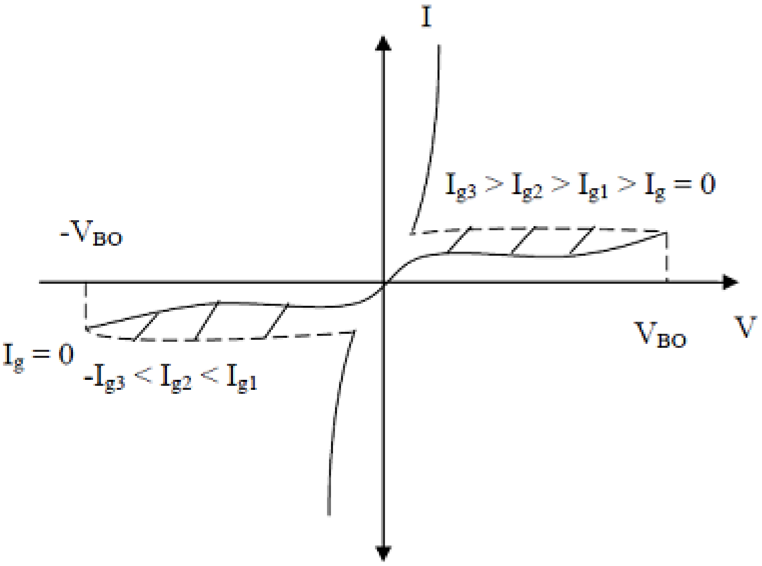


Fig.23. V-I characteristics of TRIAC

As such, most of the thyristor characteristics apply to the TRIAC (ie, latching and holding current). However, in a TRIAC the two conducting paths (from MT1 to MT2 or from MT1 to MT1) interact with each other in the structure of the TRIAC. Therefore, the voltage, current and frequency ratings of TRIAC s are considerably lower than thyristors. At present TRIAC s with voltage and current ratings of 1200V and 300A (rms) are available. TRIACs also have a larger on state voltage drop compared to a thyristor. Fig 24 Modes of operation of TRIAC and mentioned the preferred modes. Since a TRIAC is a bidirectional device and can have its terminals at various combinations of positive and negative voltages, there are four possible electrode potential combinations as given below

1. MT2 positive with respect to MT1, G positive with respect to MT1
2. MT2 positive with respect to MT1, G negative with respect to MT1
3. MT2 negative with respect to MT1, G negative with respect to MT1
4. MT2 negative with respect to MT1, G positive with respect to MT1

The triggering sensitivity is highest with the combinations 1 and 3 and is generally used. However, for bidirectional control and uniforms gate trigger mode sometimes trigger modes 2 and 3 are used. Trigger mode 4 is usually avoided. Fig 7 (a) and (b) explain the conduction mechanism of a TRIAC in trigger modes 1 & 3 respectively.

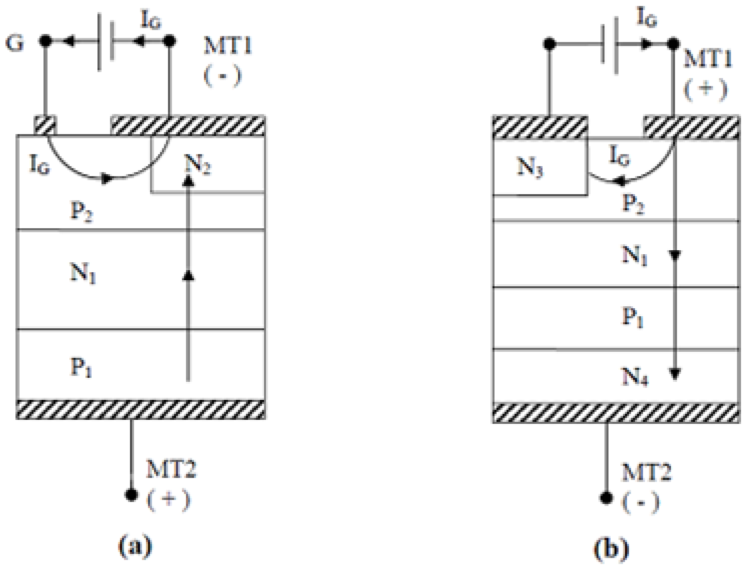


Fig. 24 Conduction mechanism of a triac in trigger modes 1 and 3
(a) Mode – 1 , (b) Mode – 3 .

In trigger mode-1 the gate current flows mainly through the P2 N2 junction like an ordinary thyristor. When the gate current has injected sufficient charge into P2 layer the TRIAC starts conducting through the P1 N1 P2 N2 layers like an ordinary thyristor. In the trigger mode-3 the gate current Ig forward biases the P2 P3 junction and a large number of electrons are introduced in the P2 region by N3. Finally the structure P2 N1 P1 N4 turns on completely.

Applications of TRIAC: (Phase control using TRIAC) A TRIAC is functionally equivalent to two anti parallel connected thyristors. It can block voltages in both directions and conduct current in both directions. A TRIAC has three terminals like a thyristor. It can be turned on in either half cycle by either a positive on a negative current pulse at the gate terminal. TRIACs are extensively used at power frequency ac load (eg heater, light, motors) control applications.

11. SILICON CONTROLLED RECTIFIER – SCR

Thyristor is a four layer three junction pnpn semiconductor switching device. It has 3 terminals these are anode, cathode and gate. SCRs are solid state device, so they are compact, possess high reliability and have low loss.

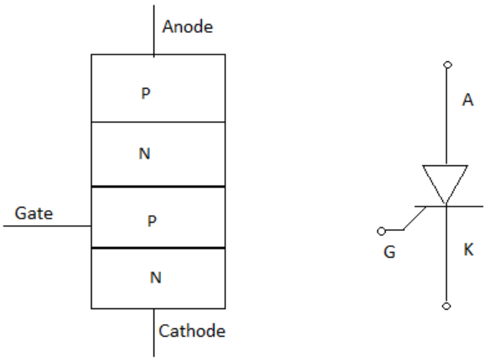


Fig 25.a) Schematic diagram of SCR, b) Symbol

SCR is made up of silicon, it act as a rectifier; it has very low resistance in the forward direction and high resistance in the reverse direction. It is a unidirectional device.

Static V-I characteristics of a Thyristor

The circuit diagram for obtaining static V-I characteristics is as shown

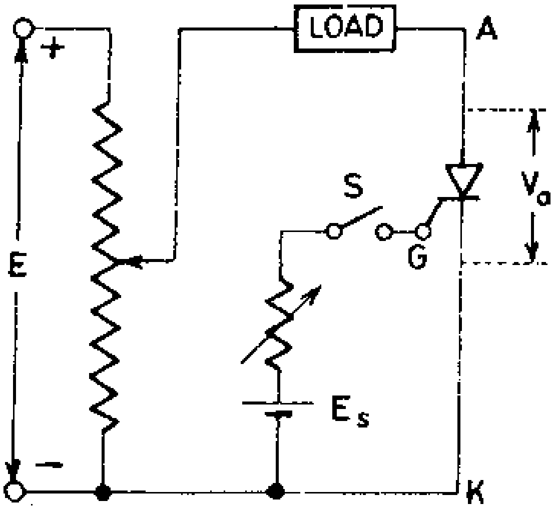


Fig. 26. Circuit diagram for obtaining thyristor V-I characteristics

Anode and cathode are connected to main source voltage through the load. The gate and cathode are fed from source *Es*.

A typical SCR V-I characteristic is as shown below:

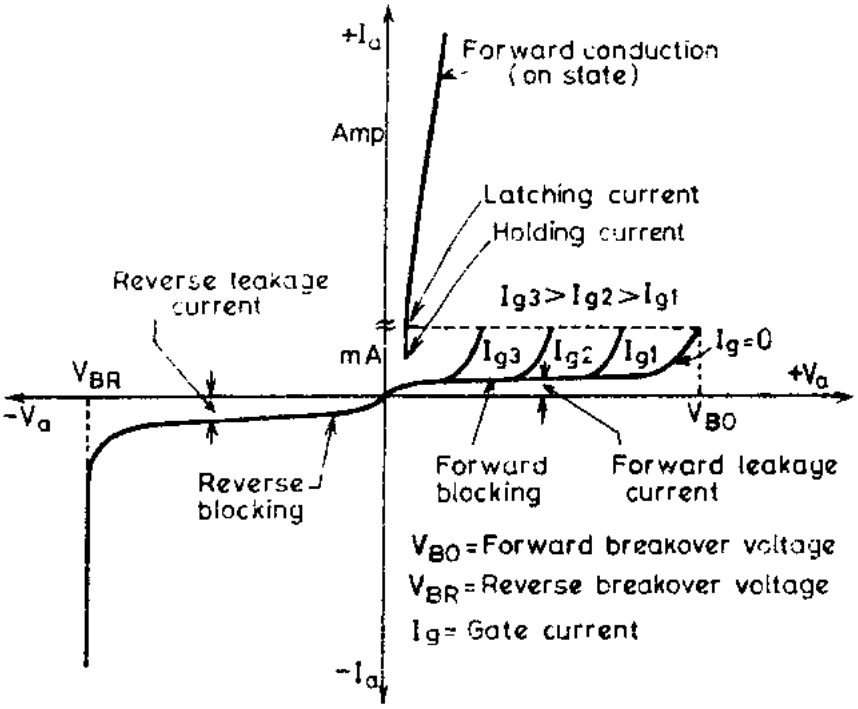


Fig.27. Static V-I Characteristics of a thyristor

VBO=Forward break over voltage

VBR=Reverse break over voltage

Ig=Gate current

Va=Anode voltage across the thyristor terminal A,K.

Ia=Anode current

It can be inferred from the static V-I characteristic of SCR. SCR have 3 modes of operation:

1. Reverse blocking mode
2. Forward blocking mode (off state)
3. Forward conduction mode (on state)

1. Reverse Blocking Mode

When cathode of the thyristor is made positive with respect to anode with switch open thyristor is reverse biased. Junctions $J1$ and $J2$ are reverse biased where junction $J2$ is forward biased. The device behaves as if two diodes are connected in series with reverse voltage applied across them.

- A small leakage current of the order of few mA only flows. As the thyristor is reverse biased and in blocking mode. It is called as acting in reverse blocking mode of operation.
- Now if the reverse voltage is increased, at a critical breakdown level called reverse breakdown voltage VBR,an avalanche occurs at $J1$ and $J3$ and the reverse current increases rapidly. As a large current associated with VBR and hence more losses to the SCR.

This results in Thyristor damage as junction temperature may exceed its maximum temperature rise.

2. Forward Blocking Mode

When anode is positive with respect to cathode, with gate circuit open, thyristor is said to be forward biased. Thus junction $J1$ and $J3$ are forward biased and $J2$ is reverse biased. As the forward voltage is increases junction $J2$ will have an avalanche breakdown at a voltage called forward breakover voltageVBO. When forward voltage is less then VBOthyristor offers high impedance. Thus a thyristor acts as an open switch in forward blocking mode.

3. Forward Conduction Mode

Here thyristor conducts current from anode to cathode with a very small voltage drop across it. So a thyristor can be brought from forward blocking mode to forward conducting mode:

1. By exceeding the forward break over voltage.
2. By applying a gate pulse between gate and cathode.

During forward conduction mode of operation thyristor is in on state and behave like a close switch. Voltage drop is of the order of 1 to 2mV. This small voltage drop is due to ohmic drop across the four layers of the device.

Different turn ON methods for SCR

1. Forward voltage triggering
2. Gate triggering
3. dv/dt triggering
4. Light triggering
5. Temperature triggering

1. Forward voltage triggering

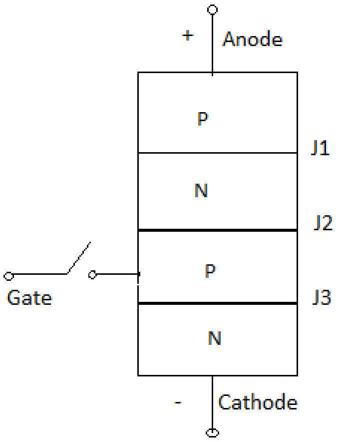


Fig.28. J_2 reverse biased and J_1, J_3 forward biased

A forward voltage is applied between anode and cathode with gate circuit open.

- Junction $J1$ and $J3$ is forward biased.
- Junction $J2$ is reverse biased.

- As the anode to cathode voltage is increased breakdown of the reverse biased junction $J2$ occurs. This is known as avalanche breakdown and the voltage at which this phenomena occurs is called forward break over voltage.
- The conduction of current continues even if the anode cathode voltage reduces below VBO till Ia will not go belowIh. Where Ih is the holding current for the thyristor.

2. Gate triggering

This is the simplest, reliable and efficient method of firing the forward biased SCRs. First SCR is forward biased. Then a positive gate voltage is applied between gate and cathode. In practice the transition from OFF state to ON state by exceeding VBO is never employed as it may destroy the device. The magnitude of VBO, so forward breakover voltage is taken as final voltage rating of the device during the design of SCR application.

First step is to choose a thyristor with forward break over voltage (say 800V) higher than the normal working voltage. The benefit is that the thyristor will be in blocking state with normal working voltage applied across the anode and cathode with gate open. When we require the turning ON of a SCR a positive gate voltage between gate and cathode is applied.

The point to be noted that cathode n- layer is heavily doped as compared to gate p-layer. So when gate supply is given between gate and cathode gate p-layer is flooded with electron from cathode n-layer. Now the thyristor is forward biased, so some of these electron reach junction $J2$ .As a result width of $J2$ breaks down or conduction at $J2$ occur at a voltage less than VBO.As Ig increases VBO reduces which decreases then turn ON time. Another important point is duration for which the gate current is applied should be more then turn ON time. This means that if the gate current is reduced to zero before the anode current reaches a minimum value known as holding current, SCR can’t turn ON. In this process power loss is less and also low applied voltage is required for triggering.

3. dv/dt triggering

This is a turning ON method but it may lead to destruction of SCR and so it must be avoided. When SCR is forward biased, junction $J1$ and $J3$ are forward biased and junction $J2$ is reversed biased so it behaves as if an insulator is place between two conducting plate. Here $J1$ and $J3$ acts as a conducting plate and $J2$ acts as an insulator. $J2$ is known as junction capacitor. So if we increase the rate of change of forward voltage instead of increasing the magnitude of voltage. Junction $J2$ breaks and starts conducting. A high value of changing current may damage the SCR. So SCR may be protected from highdv/dt.

$$q = cv$$

$$Ia = cdv/dt$$

$$Ia \alpha dv/dt$$

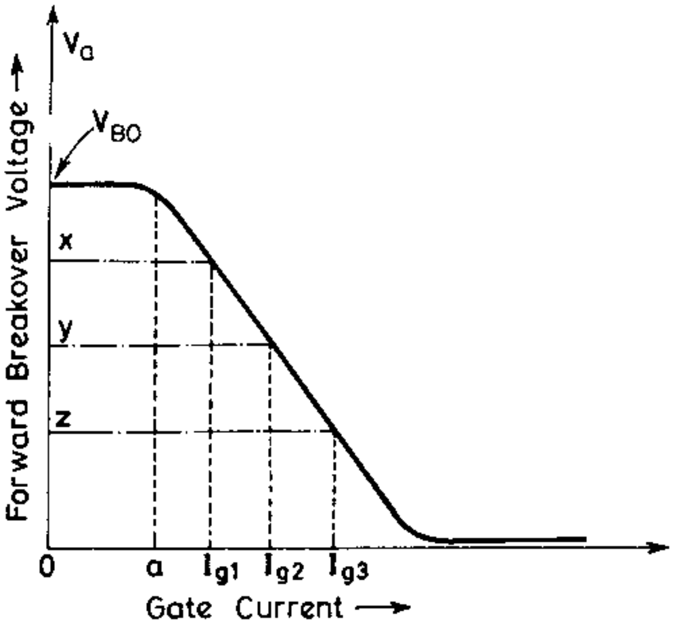


Fig 29. Variation of forward break over voltage with gate current

4. Temperature triggering

During forward biased, $J2$ is reverse biased so a leakage forward current always associated with SCR. Now as we know the leakage current is temperature dependant, so if we increase the temperature the leakage current will also increase and heat dissipitation of junction $J2$occurs. When this heat reaches a sufficient value $J2$ will break and conduction starts.

Disadvantages

- This type of triggering causes local hot spot and may cause thermal run away of the device.
- This triggering cannot be controlled easily.
- It is very costly as protection is costly.

5. Light triggering

First a new recess niche is made in the inner p-layer. When this recess is irradiated, then free charge carriers (electron and hole) are generated. Now if the intensity is increased above a certain value then it leads to turn ON of SCR. Such SCR are known as Light activated SCR (LASCR).

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**.**

2. AC Gate Triggering:-

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

(i) Resistance triggering:

The following circuit shows the resistance triggering.

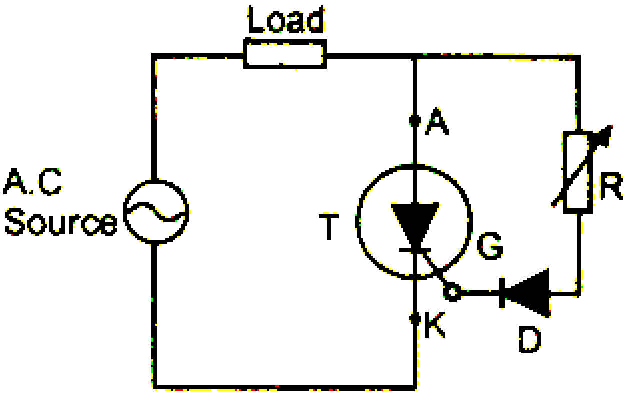


Fig. 30. Resistance triggering circuit of SCR

- 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.

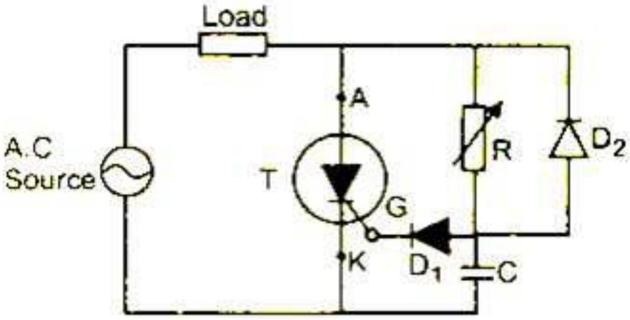


Fig. 30. Resistance Capacitance triggering circuit of SCR

- 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.

3. Pulse Gate Triggering:-

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

Advantages of pulse train triggering

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

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.

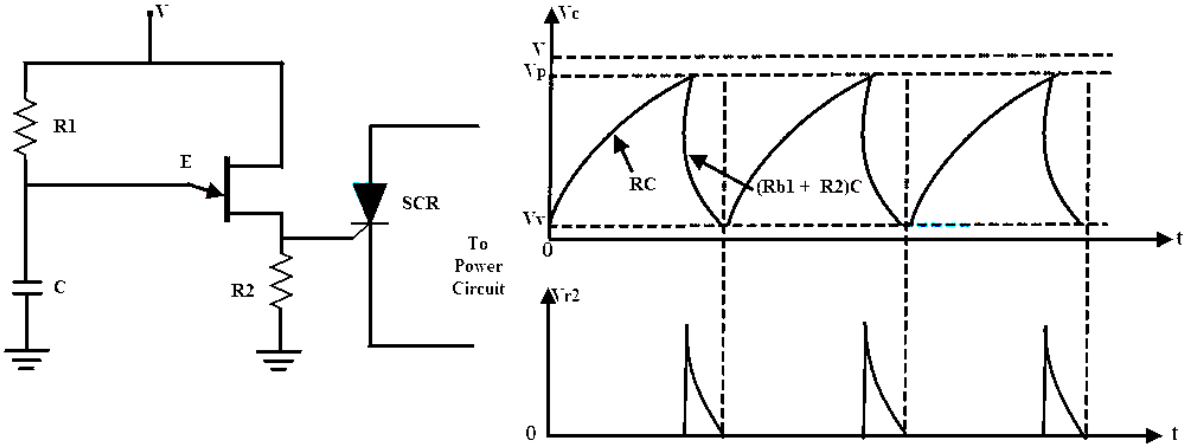


Fig. 31. UJT Firing circuit for SCR and corresponding waveforms

- 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

SOME DEFINITIONS

Latching current

The latching current may be defined as the minimum value of anode current which at must attain during turn ON process to maintain conduction even if gate signal is removed.

Holding current

It is the minimum value of anode current below which if it falls, the SCR will turn OFF.

SWITCHING CHARACTERISTICS OF THYRISTORS

The time variation of voltage across the thyristor and current through it during turn on and turn off process gives the dynamic or switching characteristic of SCR.

Switching characteristic during turn on

Turn on time

It is the time during which it changes from forward blocking state to ON state. Total turn on time is divided into 3 intervals:

1. Delay time
2. Rise time
3. Spread time

Delay time

Ig and Ia represent the final value of gate current and anode current. Then the delay time can be explained as time during which the gate current attains 0.9 Ig to the instant anode current reaches

0.1 Ig or the anode current rises from forward leakage current to 0.1 Ia.

1. Gate current 0.9 Ig to 0.1 Ia.
2. Anode voltage falls from Va to 0.9Va.
3. Anode current rises from forward leakage current to 0.1 Ia.

Rise time (tr)

Time during which

1. Anode current rises from 0.1 Ia to 0.9 Ia
2. Forward blocking voltage falls from 0.9Va to 0.1Va. Va is the initial forward blocking voltage.

Spread time (tp)

1. Time taken by the anode current to rise from 0.9Ia toIa.
2. Time for the forward voltage to fall from 0.1Vo to on state voltage drop of 1 to 1.5V.

During turn on, SCR is considered to be a charge controlled device. A certain amount of charge is injected in the gate region to begin conduction. So higher the magnitude of gate current it requires less time to inject the charges. Thus turn on time is reduced by using large magnitude of gate current.

How the distribution of charge occurs?

As the gate current begins to flow from gate to cathode with the application of gate signal. Gate current has a non uniform distribution of current density over the cathode surface. Distribution of current density is much higher near the gate. The density decrease as the distance from the gate increases. So anode current flows in a narrow region near gate where gate current densities are highest. From the beginning of rise time the anode current starts spreading itself.

The anode current spread at a rate of 0.1mm/sec. The spreading anode current requires some time if the rise time is not sufficient then the anode current cannot spread over the entire region of cathode. Now a large anode current is applied and also a large anode current flowing through the SCR. As a result turn on losses is high. As these losses occur over a small conducting region so local hot spots may form and it may damage the device.

Switching Characteristics during Turn Off

Thyristor turn off means it changed from ON to OFF state. Once thyristor is oON there is no role of gate. As we know thyristor can be made turn OFF by reducing the anode current below the latching current. Here we assume the latching current to be zero ampere. If a forward voltage is applied across the SCR at the moment it reaches zero then SCR will not be able to block this forward voltage. Because the charges trapped in the 4-layer are still favourable for conduction and it may turn on the device. So to avoid such a case, SCR is reverse biased for some time even if the anode current has reached to zero.

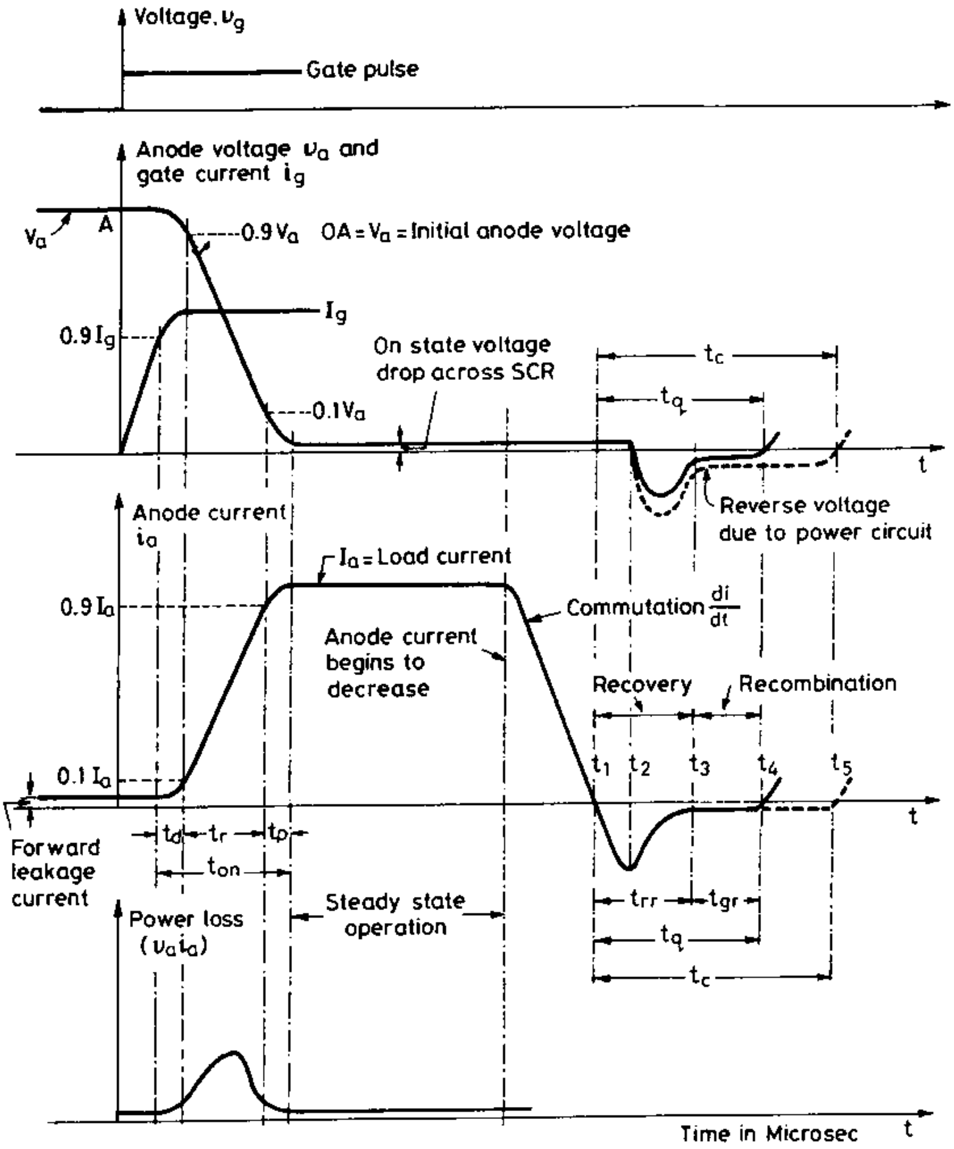


Fig.32. Thyristor voltage and current waveforms during turn on and turn off processes

So now the turn off time can be different as the instant anode current becomes zero to the instant when SCR regains its forward blocking capability.

$$t_q = t_{rr} + t_{qr}$$

Where,

tq is the turn off time, is the reverse recovery time, tqr is the gate recovery time. At $t1$ anode current is zero. Now anode current builds up in reverse direction with same $dvdt$ slope. This is due to the presence of charge carriers in the four layers. The reverse recovery current removes the excess carriers from $J1$ and $J3$ between the instants $t1$ and $t3$.

At instant $t3$ the end junction $J1$ and $J3$ is recovered. But $J2$ still has trapped charges which decay due to recombination only so the reverse voltage has to be maintained for some more time. The time taken for the recombination of charges between $t3$ and $t4$ is called gate recovery time tqr. Junction $J2$ recovered and now a forward voltage can be applied across SCR.

The turn off time is affected by:

1. Junction temperature
2. Magnitude of forward current di/dt during commutation.

Turn off time decreases with the increase of magnitude of reverse applied voltage.

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 (VPIV)

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

On State Voltage:

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

Finger Voltage:

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

Rate of Rise of Voltage (dV/dt)

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

Voltage Safety Factor:

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

Vf = Peak inverse voltage / (2 x RMS value of input voltage)
Normaly Vf 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 (Imac):

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: (Imrc)

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 (Imsc)

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

Latching Current (II)

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 (IH)

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:

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

Gate Power Loss:

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

Turn ON time:

This is 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.

THYRISTOR PROTECTION

OVER VOLTAGE PROTECTION

Over voltage occurring during the switching operation (transients) is the main cause of the failure of SCR.

INTERNAL OVERVOLTAGE

It is due to the operating condition of SCR. Large voltages may be generated internally during the commutation of SCR. When the anode current decays to zero, anode current reverses due to stored charges. First the reverse current rises to peak value, then reverse current reduces abruptly with large di/dt. Because of the series inductance L of the SCR circuit, large transient voltage i.e Ldi/dt is generated.

EXTERNAL OVER VOLTAGE

This is due to external supply and load condition. This is because of

1. The interruption of current flow in an inductive circuit.
2. Lightening strokes on the lines feeding the thyristor systems.

Suppose a SCR converter is fed from a transformer, voltage transient occurs when transformer primary will energised or de-energised. This over voltages may cause random turn ON of a SCR.

The effect of overvoltage is minimized using

1. RC circuits
2. Non linear resistor called voltage clamping device.

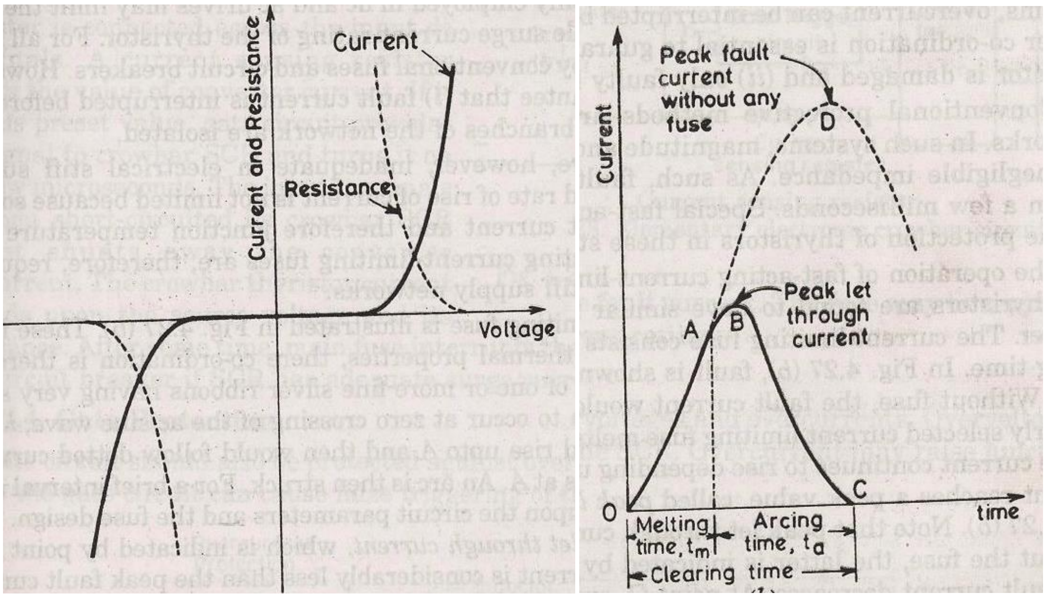


Fig 33. a) Volt-ampere characteristics of voltage clamping device. b) Action of current-limiting fuse in an ac circuit

Voltage clamping device is a non linear resistor. It is connected between cathode and anode of SCR. The resistance of voltage clamping device decreases with increasing voltages. During normal working condition Voltage clamping (V.C) device has high resistance, drawing only leakage current. When voltage surge appears voltage clamping device offers a low resistance and it create a virtual short circuit across the SCR. Hence voltage across SCR is clamped to a safe value. When surge condition over voltage clamping device returns to high resistance state. e.g. of voltage clamping device

1. Selenium thyractor diodes
2. Metal Oxide varistors
3. Avalanche diode suppressors

OVER CURRENT PROTECTION

Long duration operation of SCR, during over current causes the Junction temperature of SCR to rise above the rated value, causing permanent damage to device.

SCR is protected from over current by using

1. Circuit breakers
2. Fast acting fuses

Proper co-ordination is essential because

1. Fault current has to be interrupted before SCR gets damaged.
2. Only faulty branches of the network have to be replaced.

In weak or stiff supply network, fault current is limited by the source impedance. So in such system the magnitude and rate of rise of current is not limited. Fault current hence junction temperature raises in a few milli seconds.

1. Proper coordination between fast acting fuse and thyristor is essential.

2. The fuse is always rated to carry marginal overload current over definite period.

3. The peak let through current through SCR must be less than sub cycle rating of the SCR.

4. The voltage across the fuse during arcing time is called arcing or recovery voltage and is equal to sum of the source voltage and emf induced in the circuit inductance during arcing time.

5. On abrupt interruption of fuse current, induce emf would be high, which results in high arcing voltage.

Circuit Breaker (C.B)

C.B. has long tripping time. So it is used for protecting the device against continuous overload current or against the surge current for long duration. In order that fuse protects the thyristor realiably the $I2t$ rating of fuse current must be less than that of SCR.

ELECTRONIC CROWBAR PROTECTION

For over current protection of power converter using SCR, electronic crowbar are used. It provides rapid isolation of power converter before any damage occurs.

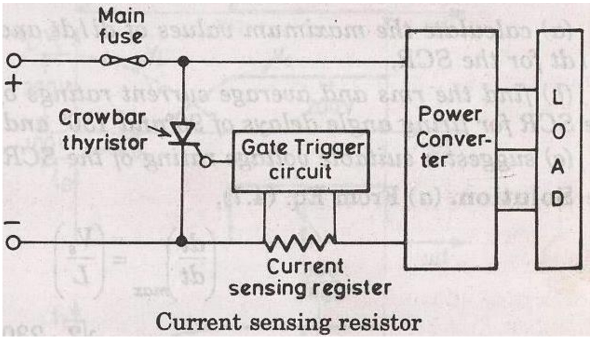


Fig.34. Electronic crowbar circuit

HEAT PROTECTION

To protect the SCR

1. from the local spots
2. Temp rise

SCRs are mounted over heat sinks.

GATE PROTECTION

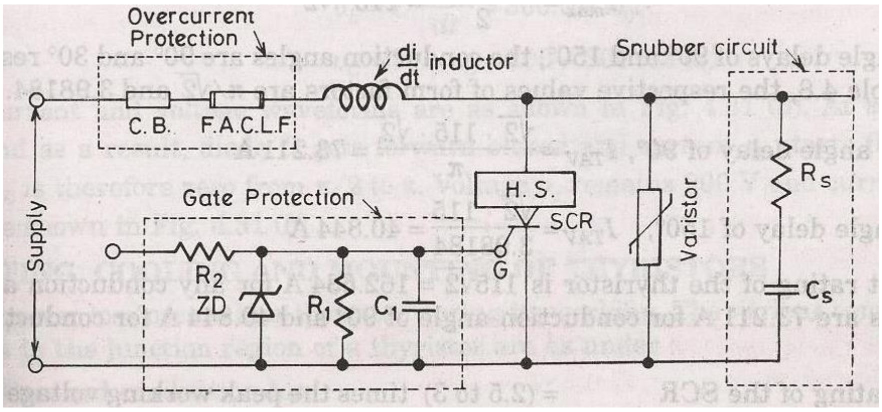


Fig.35. Circuit components showing the thyristor protection.

Gate circuit should also be protected from

1. Overvoltage
2. over current

Overvoltage across the gate circuit causes the false triggering of SCR

Over current raise the junction temperature. Overvoltage protection is by zener diode across the gate circuit.

Multiple Choice Questions

1 A power transistor is a _________ device.

a) Two terminal, bipolar, voltage controlled

b) Two terminal, unipolar, current controlled

c) Three terminal, unipolar, voltage controlled

d) Three terminal, bipolar, current controlled

Answer : d

2 Which of the following terminals does not belong to the MOSFET?

a) Drain

b) Gate

c) Base

d) Source

Answer: c

3 The controlling parameter in IGBT is the

a) IG

b) VGE

c) IC

d) VCE

Answer: b

4 The latching current of an SCR is __________ than the holding current

a) Lower

b) Higher

c) Same as

d) Negative of

Answer: b

5 The effect of over-voltages on SCR are minimized by using

a) RL circuits

b) Circuit breakers

c) Varistors

d) di/dt inductor

Answer: c

6 Over-current protection in SCRs is achieved through the use of

a) Varistors

b) Snubber Circuits

c) F.A.C.L.F & C.B.

d) Zener diodes

Answer: c

7 When SCR starts conducting, then …………… loses all control

a) Gate

b) Cathode

c) Anode

d) None of the above

Answer: a

8 Among the following, the most suitable method to turn on the SCR device is the

a) Gate triggering method

b) dv/dt triggering method

c) Forward voltage triggering method

d) Temperature triggering method

Answer: a

9 An SCR is turned off by …………….

a) Reducing anode voltage to zero

b) Reducing gate voltage to zero

c) Reverse biasing the gate

d) None of the above

Answer : a

10 IGBT possess

a) Low input impedance

b) High input impedance

c) High on-state resistance

d) Second breakdown problems

Answer: b

ASSIGNMENT

1. Explain the working of IGBT with neat diagram. Also, discuss in detail the static and switching characteristics of IGBT.
2. Explain the construction, working and switching characteristics of MOSFET

UNIT II CONVERTERS

Operation of 1ϕ half wave rectifiers with R, RL & RLE load.- 1ϕ Full wave rectifier with R, RL, & RLE load (fully controlled and half controlled) - Effect of source inductance & load inductance – Introduction to Cyclo Converters - Single phase mid - point cyclo-converters with Resistive and inductive load – Bridge configuration of single phase cyclo-converter – Waveforms. AC voltage controllers – Integral Cycle Control – Single Phase Voltage controller with R, RL load.

PHASE CONTROLLED CONVERTERS

INTRODUCTION

Unlike diode rectifiers, phase controlled rectifiers has an advantage of controlling the output voltage. The diode rectifiers are called uncontrolled rectifiers. When these diodes are replaced with thyristors, then in becomes phase controlled rectifiers. The output voltage can be controlled by varying the firing angle of the thyristors. These phase controlled rectifiers has its main application in speed control of DC motors.

1. Phase Controlled Rectifier

The 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 output voltage, the thyristors can be used to control 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 or natural commutation. In case of heavy inductive load, it is deactivated by firing another thyristor of the rectifier during the negative half cycle of input voltage.

Types of Phase Controlled Rectifier

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

i) Single-phase Controlled Rectifier

ii) Three-phase Controlled Rectifier

2. Single-phase Controlled Rectifier

This type of rectifier which works from single phase AC input 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 output control only in one half cycle of input AC supply, and it offers low DC output.

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

- Full wave controlled rectifier with a center tapped transformer requires two thyristors.

- Full wave bridge controlled rectifiers do not need a center tapped transformer

3. **Three-phase Controlled Rectifier**

   This type of rectifier operates from three phase AC input power supply

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

4. **APPLICATIONS**
   - Steel rolling mills, paper mills, textile mills where speed control of DC motors are necessary.
   - Electric traction.
   - High voltage DC transmission
   - Electromagnet power supplies
5. **Operation of Phase Controlled Rectifier**

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

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

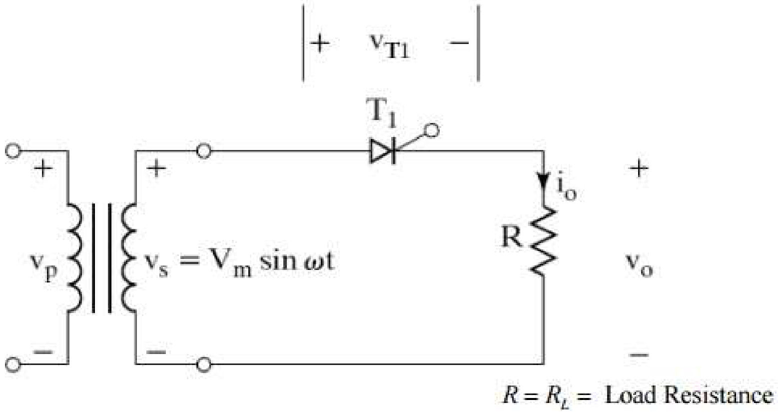


Fig. 1. Single phase half wave rectifier circuit

During the positive half cycle of input supply when the upper end of the transformer secondary winding is at a positive potential with respect to the lower end, the Thyristor is in a forward biased state.

The thyristor is activated at a delay angle of ωt =α, by applying an appropriate gate trigger pulse to the gate terminal of thyristor. When the thyristor is activated at a delay angle of ωt =α, the thyristor behaviors and assuming a perfect thyristor. The thyristor acts as a closed switch and the input supply voltage acts across the load when it conducts from ωt =α to π radians For a purely resistive load, the load current io that flows when the thyristor T1 is on, is given by the expression. Io= Vo/ RL, for α≤ ωt ≤ π

6. Single Phase Half Wave Controlled Rectifier

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.

- The circuit consist of a thyristor T, a voltage source Vs and a resistive load R.
- During the positive half cycle of the input voltage, the thyristor T is forward biased but it does not conduct until a gate signal is applied to it.
- When a gate pulse is given to the thyristor T at ωt = α, it gets turned ON and begins to conduct.
- When the thyristor is ON, the input voltage is applied to the load.
- During the negative half cycle, the thyristor T gets reverse biased and gets tuned OFF.
- So the load receives voltage only during the positive half cycle only.
- The average value of output voltage can be varied by varying the firing angle α.
- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.

The load current i0 flows through „R" the waveforms for voltage & current are as shown below. As load is resistive, Output current is given as,

$$I_0 = \frac{V_0}{R}$$

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 fripple=50 Hz (supply frequency)

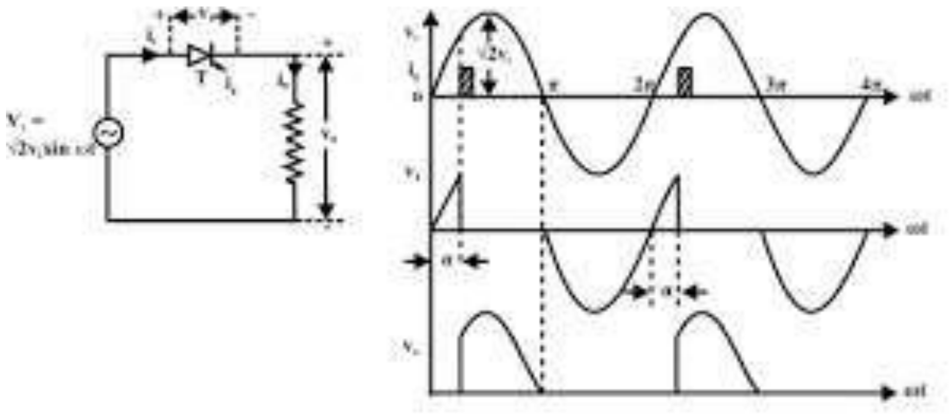


Fig 2. Single phase half wave controlled rectifier

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.

Single Phase Half Wave Controlled Rectifier with RL Load

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.

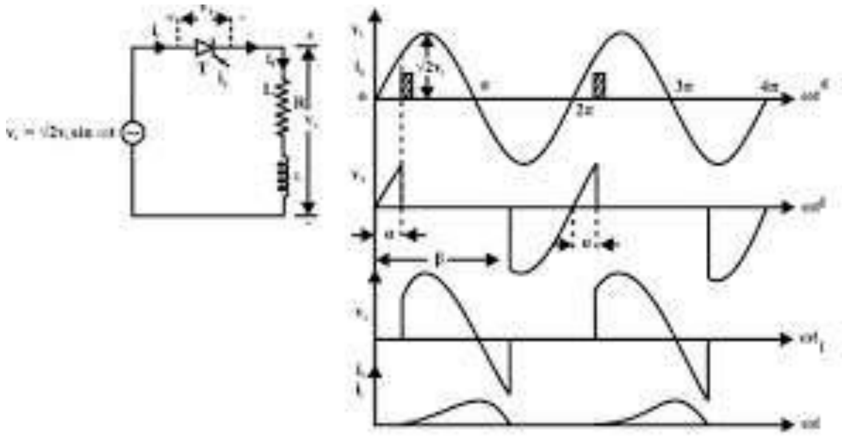


Fig. 3. Single phase half wave rectifier with RL load with waveforms

- 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 io=is.
- 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 “io‟ becomes zero & “T1‟ turns off.
- “io‟ becomes zero from “β‟ to “2π+α‟ hence it is discontinuous conduction.

The average output voltage

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

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

RMS load voltage

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

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

Single phase half controlled converter with RLE load

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

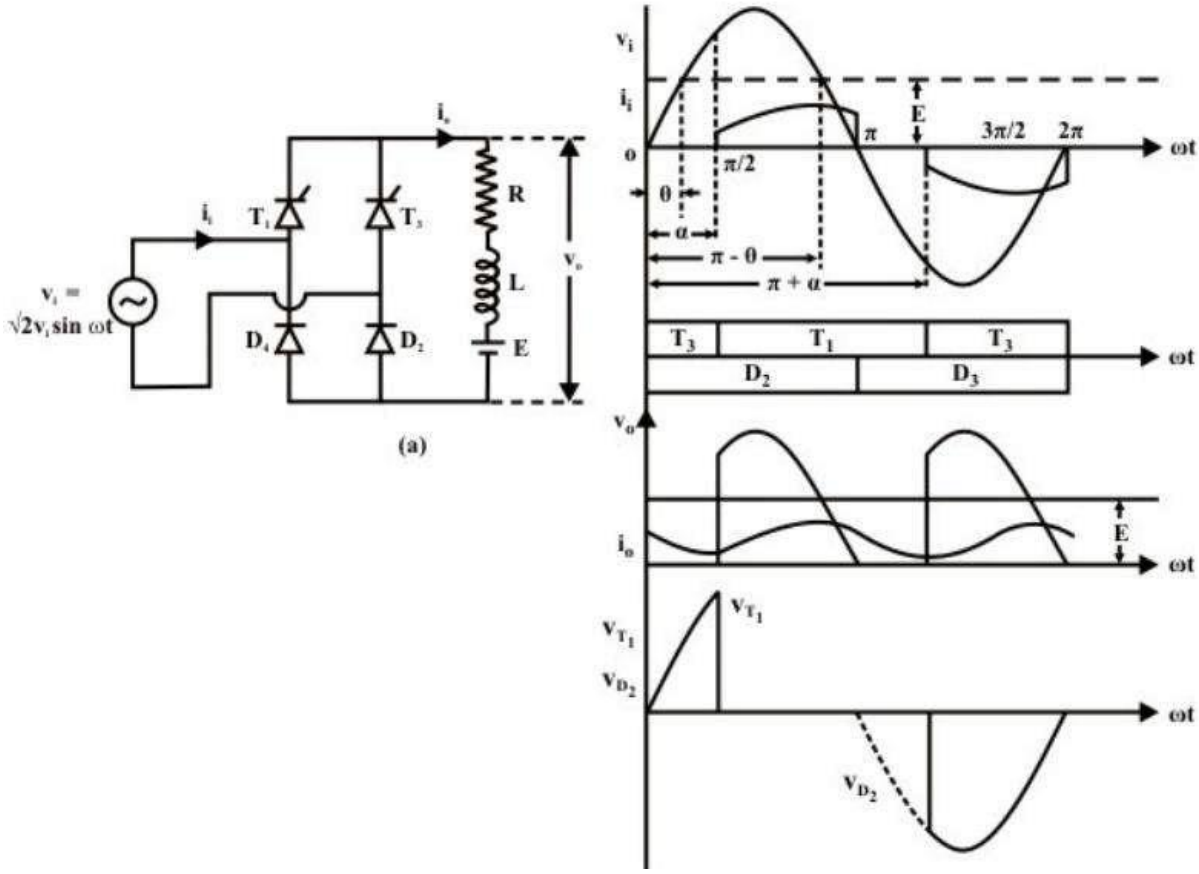


Fig. 4. Single phase half controlled converter with RLE load

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

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

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

Single phase half controlled converter with RLE load and freewheeling diode

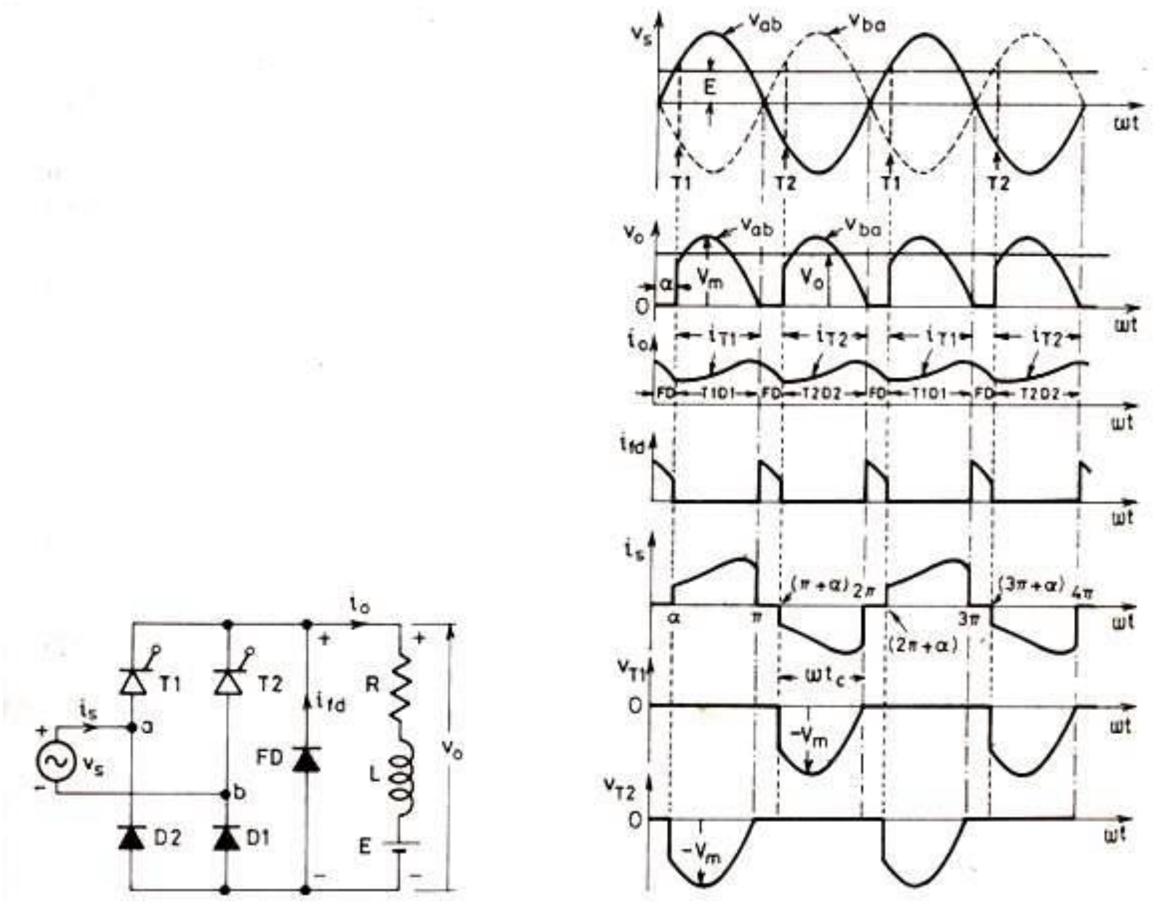


Fig. 5. Single phase half controlled converter with RLE load and freewheeling diode

7. Single phase full wave controlled rectifier

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

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

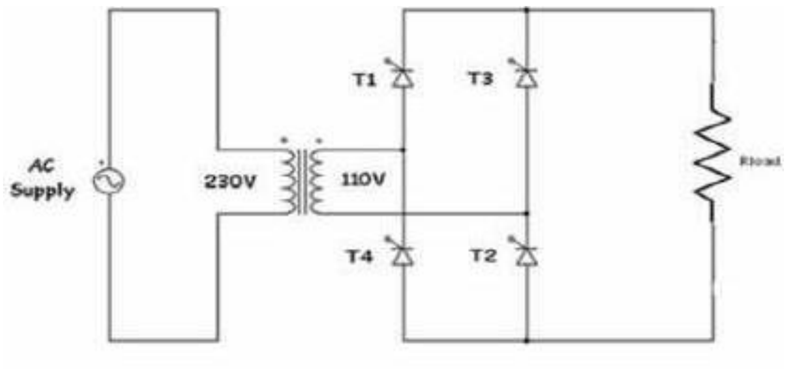


Fig. 6. Single phase full converter circuit with R load

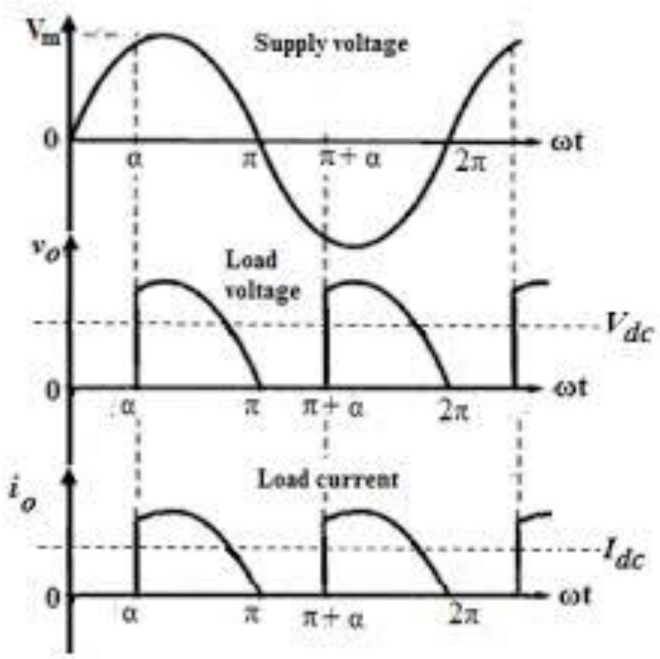


Fig. 7. Input and output waveforms of single phase full converter circuit with R load

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

I_O=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.

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

Single Phase Full Wave Controlled Rectifier with ‘RL’ load

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

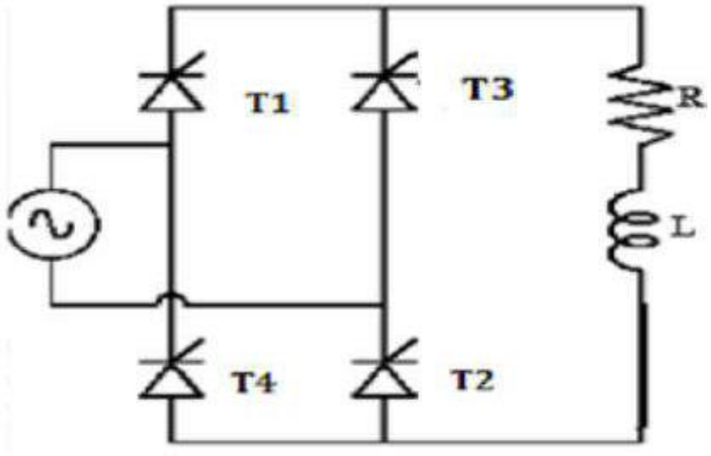


Fig. 8 Single phase full converter circuit with RL load

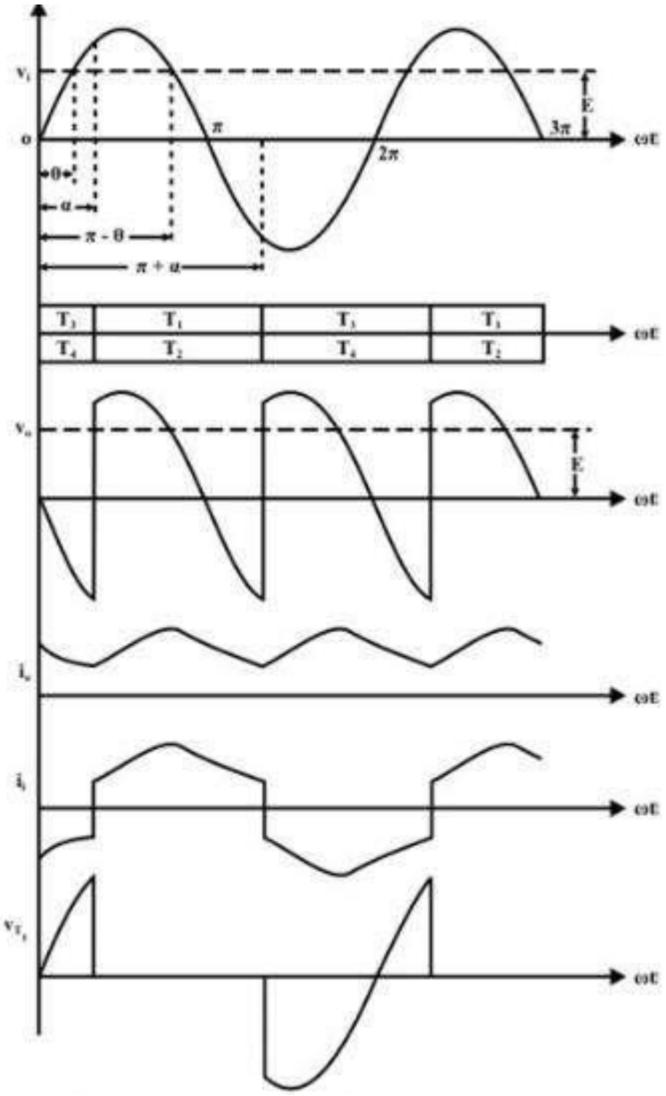


Fig. 9.Single phase full converter circuit with RL load input and output waveforms

Operation of this mode can be divided between four modes

Mode 1 (α toπ)

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

Mode 2 (π toπ+α)

- At wt=π, input supply is equal to zero & after π it becomes negative. But inductance opposes any change through it.
- In order to maintain a constant load current & also in same direction. A self induced emf appears across „L‟ as shown.
- Due to this induced voltage, SCR‟s T1 & T2 are forward 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.

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

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.

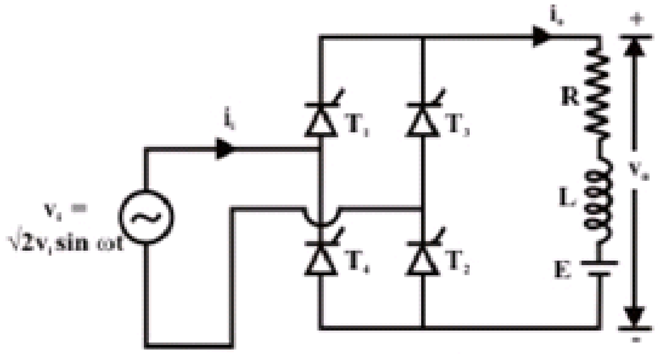


Fig. 10 Single phase full converter circuit with RLE load

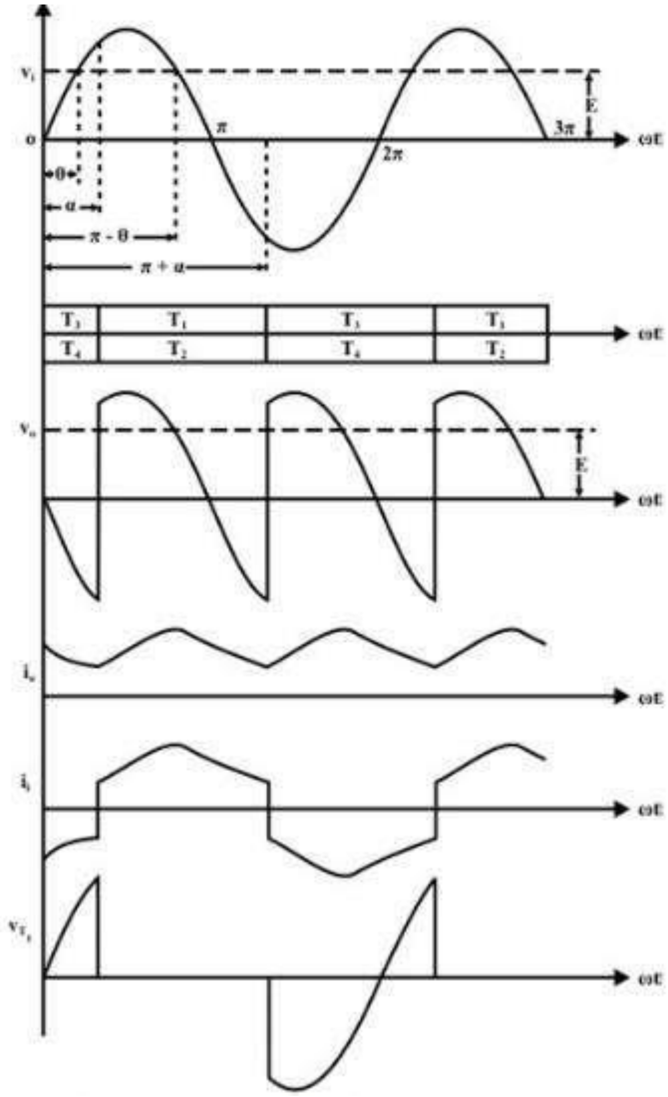


Fig. 11 Waveforms of Single phase full converter circuit with RLE load

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

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

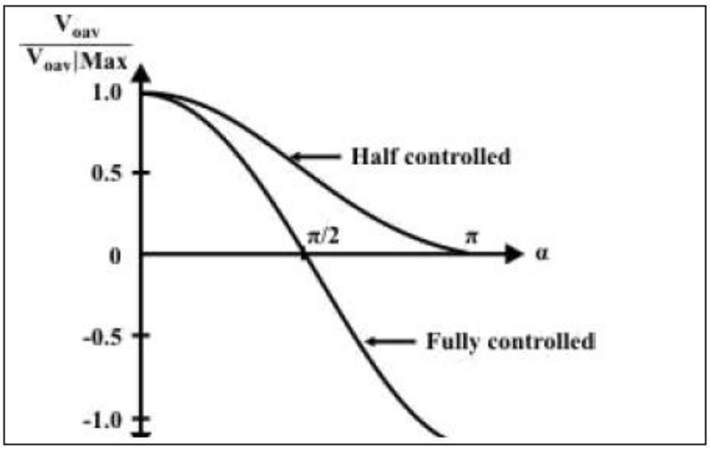


Fig. 12. Comparison of Single phase half and full converter circuit

8. 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 ωt = α. 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.14. This interval is called “overlap” interval.

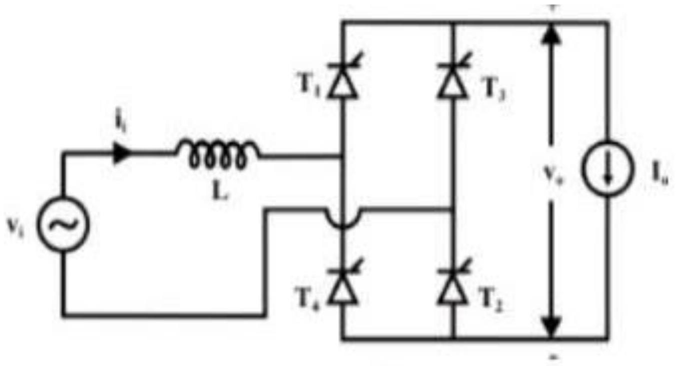


Fig.13. Single phase full converter circuit with source inductance

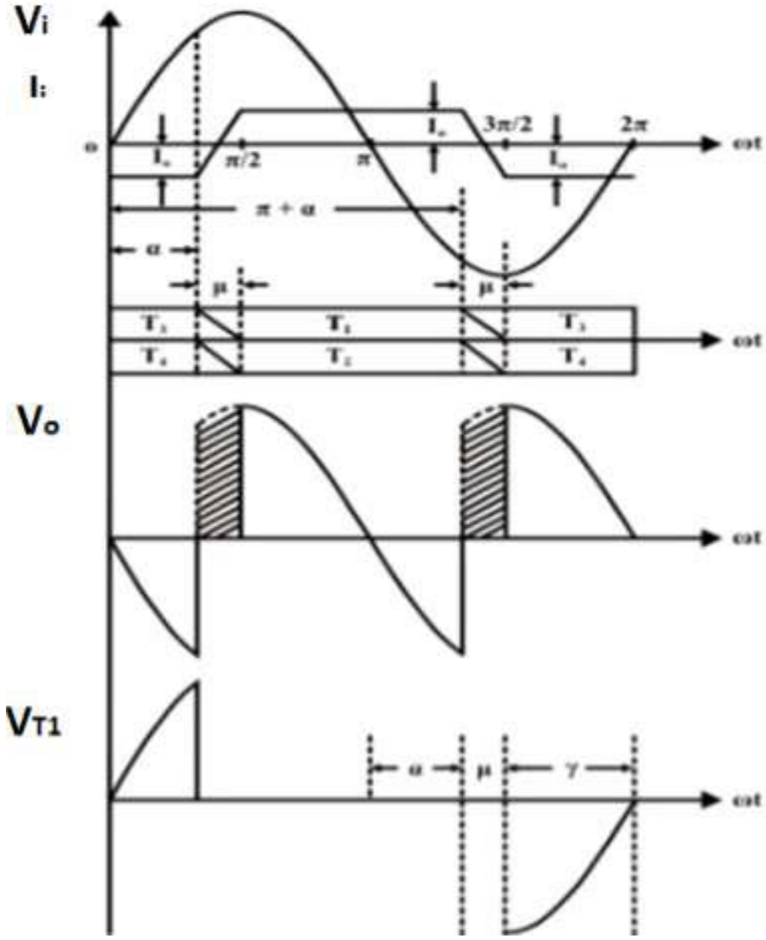


Fig. 14. Single phase full converter output waveforms with source inductance

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 ωt = π + α. From Fig. 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

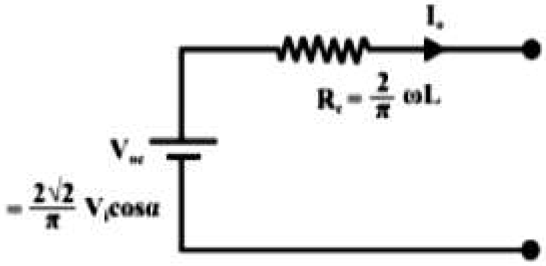


Fig. 15. Equivalent circuit of the given equation

Equivalent circuit representation of the single phase fully controlled rectifier with source inductance. The simple equivalent circuit of Fig. 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. 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.

9. CYCLO CONVERTERS

INTRODUCTION

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

The Cycloconverter has four thyristors divided into a positive and negative bank of two thyristors each. When positive current flows in the load, the output voltage is controlled by phase control of the two positive bank thyristors whilst the negative bank thyristors are kept off and vice versa when negative current flows in the load. An idealized output waveform for a sinusoidal load current and a 45 degrees load phase angle is shown in Figure 17. It is important to keep the non conducting thyristor bank off at all times, otherwise the mains could be shorted via the two thyristor banks, resulting in waveform distortion and possible device failure from the shorting current.

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

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

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

Operation Principles

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

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

To understand the operation principles of Cycloconverters, the single-phase to single-phase Cycloconverter (Fig. 16) should be studied first. This converter consists of back-to-back connection of two full-wave rectifier circuits. Fig 17 shows the operating waveforms for this converter with a resistive load.

Zero Firing angle, i.e. thyristors act like diodes. Note that the firing angles are named as αP for the positive converter and αN for the negative converter. The input voltage, vs is an ac voltage at a frequency, fi as shown in Fig. 17. For easy understanding assume that all the thyristors are fired at α=0°

Consider the operation of the Cycloconverter to get one-fourth of the input frequency at the output. For the first two cycles of vs, the positive converter operates supplying current to the load. It rectifies the input voltage; therefore, the load sees 4 positive half cycles as seen in Fig.17. In the next two cycles, the negative converter operates supplying current to the load in the reverse direction.

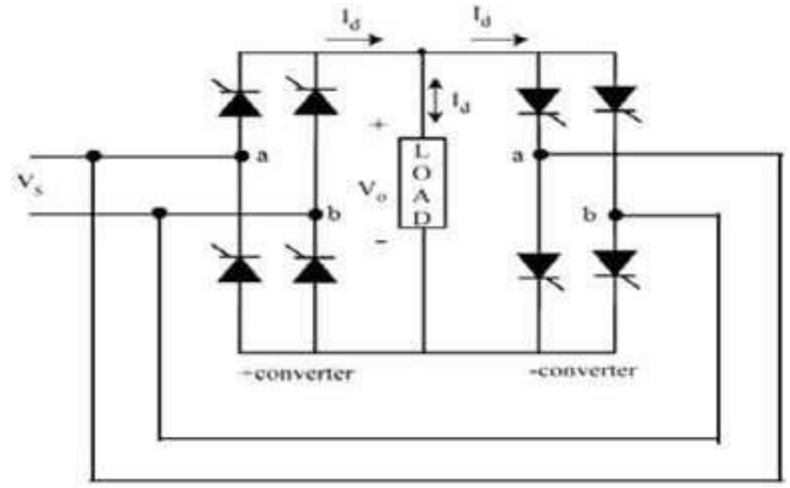


Fig.16. Circuit diagram of cycloconverter

The current waveforms are not shown in the figures because the resistive load current will have the same waveform as the voltage but only scaled by the resistance. Note that when one of the converters operates the other one is disabled, so that there is no current circulating between the two rectifiers.

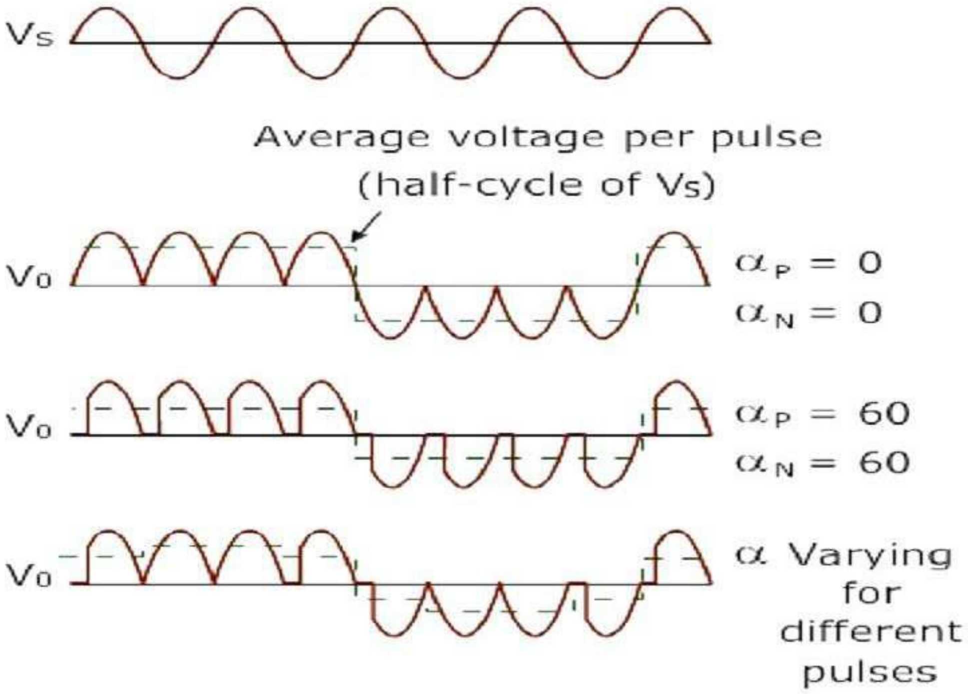


Fig. 17 Input and output waveforms of cycloconverter

Single phase midpoint Cyclo converters

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

Step-down cyclo-converter

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

Step-up cyclo-converter

It provides the output frequency more than that of input, fo > fi.

In case of step-down cyclo-converter, the output frequency is limited to a fraction of input frequency, typically it is below 20Hz in case 50Hz supply frequency. In this case, no separate commutation circuits are needed as SCRs are line commutated devices.

But in case of step-up cyclo-converter, forced commutation circuits are needed to turn OFF SCRs at desired frequency. Such circuits are relatively very complex. Therefore, majority of cyclo-converters are of step-down type that lowers the frequency than input frequency.

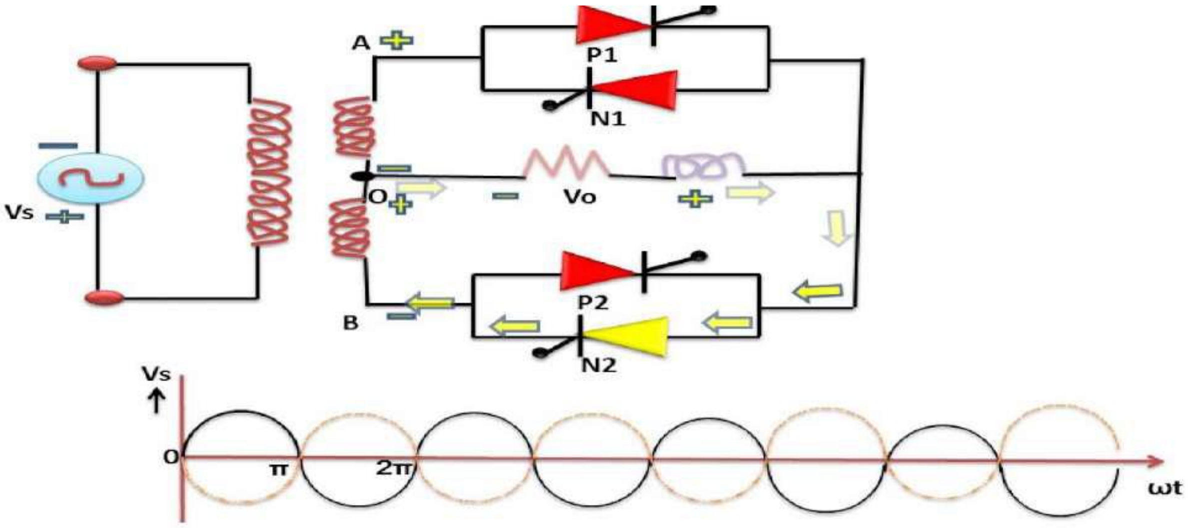


Fig. 18. Circuit diagram of midpoint cycloconverter

It consists of single phase transformer with mid tap on the secondary winding and four thyristors. Two of these thyristors P1, P2 are for positive group and the other two N1, N2 are for the negative group. Load is connected between secondary winding midpoint 0 and the load terminal. Positive directions for output voltage and output current are marked in fig.19

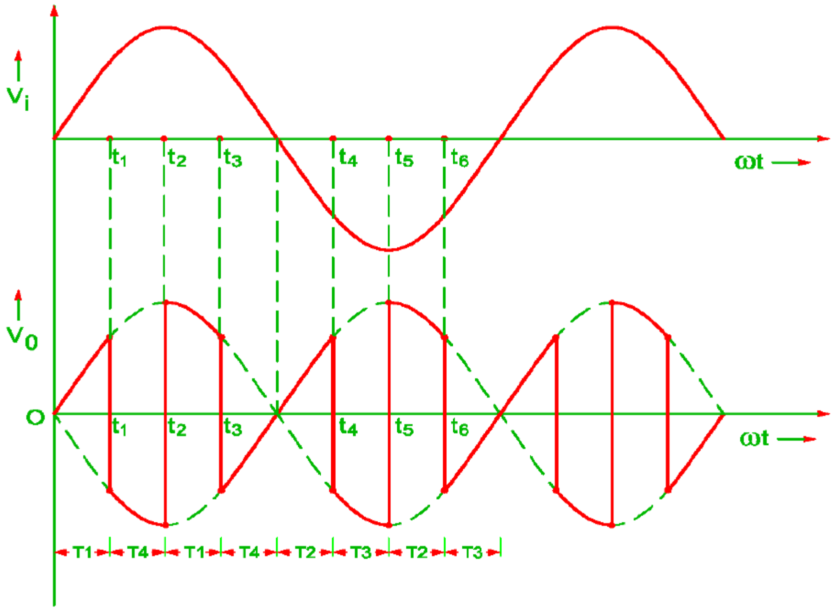


Fig. 19. Input and output waveforms of midpoint cycloconverter

In fig 18 during the positive half cycle of supply voltage terminal ‘a’ is positive with respect to terminal b. therefore in this positive half cycle, both p1 and N2 are forward biased from wt= 0 to Π. As such SCR P1 is turned on at wt = 0 so that load voltage is positive with terminal A and 0 negative. Now the load voltage is positive. At instant t1 P1 is force commutated and forward biased thyristor N2 is turned on so that load voltage is negative with terminal 0 and ‘A’ negative. Now the load voltage is negative. Now N2 is force commutated and P1 is turned on the load voltage is positive this is a continuous process and will get step up cyclo converter output

Bridge configuration of single phase Cyclo converter

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

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

If the firing angles of individual converters are modulated continuously, each converter produces same sinusoidal voltages at its output terminals. So the voltages produced by these two converters have same phase, voltage and frequency. The average power produced by the cyclo-converter can flow either to or from the output terminals as the load current can flow freely to and from the load through the positive and negative converters.

Therefore, it is possible to operate the loads of any phase angle (or power factor), inductive or capacitive through the cyclo-converter circuit. Due to the unidirectional property of load current for each converter, it is obvious that positive converter carries positive half-cycle of load current with negative converter remaining in idle during this period.

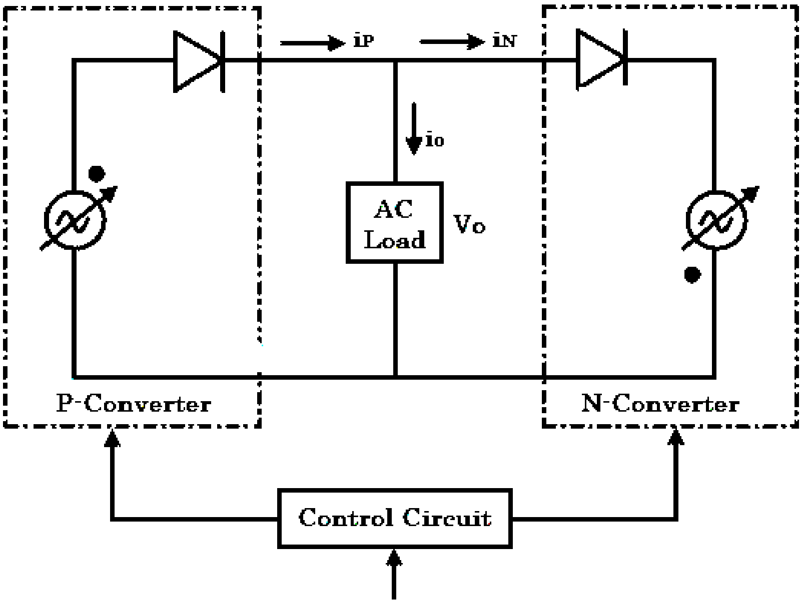


Fig 20 Block diagram of bridge type cycloconverter

Similarly, negative converter carries negative half cycle of the load current with positive converter remaining in idle during this period, regardless of the phase of current with respect to voltage. This means that each converter operates both in rectifying and inverting regions during the period of its associated half cycles.

The figure below shows ideal output current and voltage waveforms of a cyclo-converter for lagging and leading power factor loads. The conduction periods of positive and negative converters are also illustrated in the figure.

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

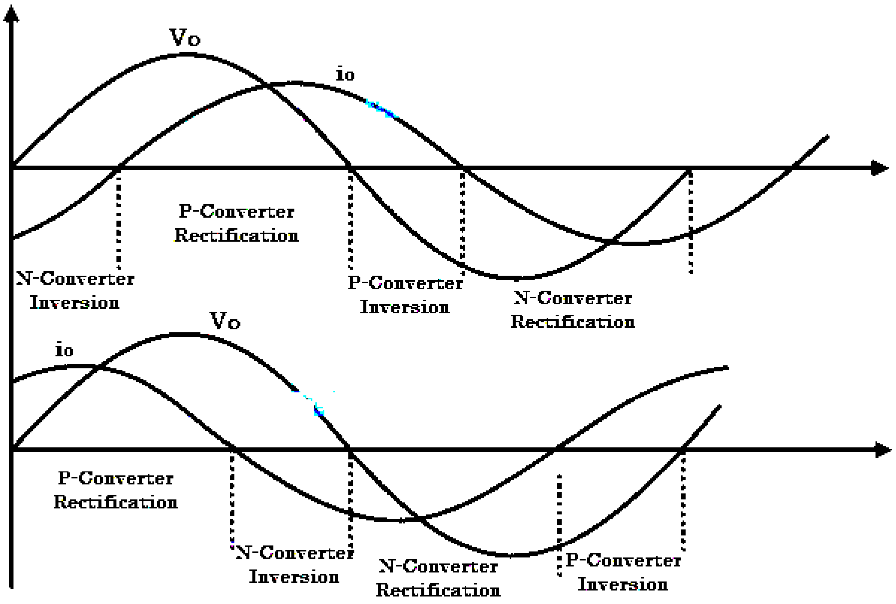


Fig. 21 Cyclo converter waveforms

10. Introduction to AC voltage controllers

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

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

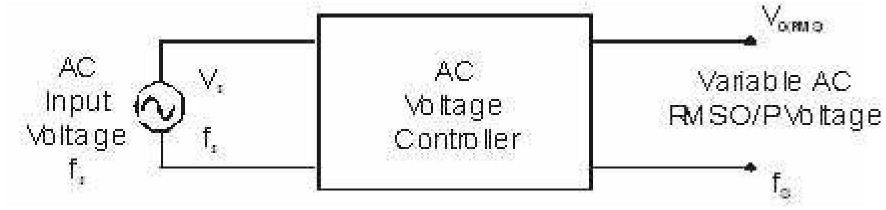


Fig. 22. Block diagram of AC voltage controller

Control strategies:

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

1. On-Off control
2. Phase control

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

Phase control

In phase control the Thyristors are used as switches to connect the load circuit to the input ac supply, for a part of every input cycle. That is the ac supply voltage is chopped using Thyristors during a part of each input cycle.

The thyristor switch is turned on for a part of every half cycle, so that input supply voltage appears across the load and then turned off during the remaining part of input half cycle to disconnect the ac supply from the load.

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

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

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

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

Type of ac voltage controllers

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

- Single Phase AC Controllers
- Three Phase AC Controllers

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

Performance parameters of ac voltage controllers

- RMS Output (Load) Voltage

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

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

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

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

- Duty Cycle

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

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

- RMS Load Current

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

- Output AC (Load) Power

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

- Input Power Factor

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

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

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

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

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

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

Applications of ac voltage controllers

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

Single phase AC voltage controller with R load

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

Fig. 23 illustrates the operation of the PAC converter with a resistive load. The device(s) is triggered at a phase-angle 'α' in each cycle. The current follows the voltage wave shape in each half and extinguishes itself at the zero crossings of the supply voltage. In the two-SCR topology, one SCR is positively biased in each half of the supply voltage. There is no scope for conduction overlap of the devices. A single pulse is sufficient to trigger the controlled devices with a resistive load. In the diode-SCR topology, two diodes are forward biased in each half. The SCR always receives a DC voltage and does not distinguish the polarity of the supply.

The rms voltage Vrms decides the power supplied to the load. It can be computed as

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

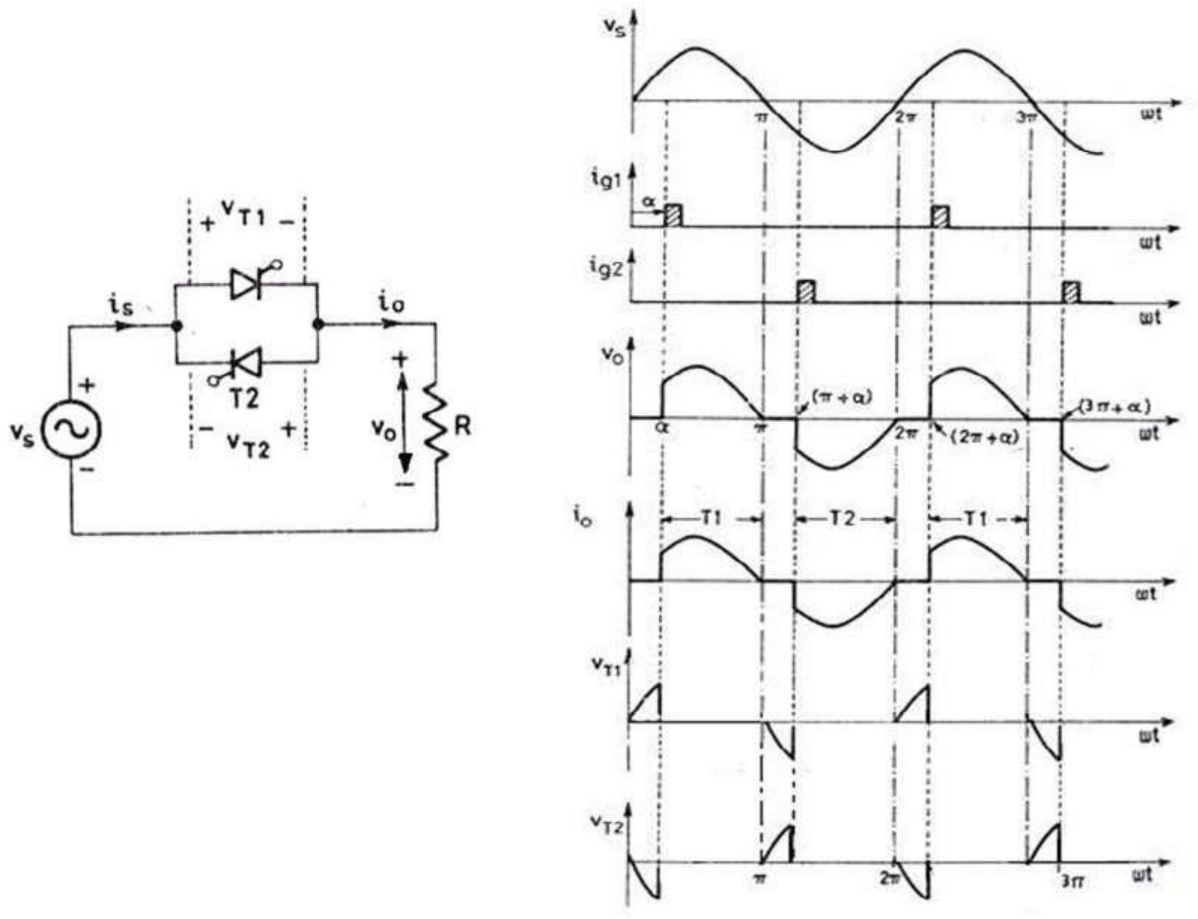


Fig. 23 Circuit diagram and output waveforms of AC voltage controller with R load

Power Factor

The power factor of a nonlinear deserves a special discussion. Fig. 23 shows the supply voltage and the non-sinusoidal load current. The fundamental load/supply current lags the supply voltage by the φ1, 'Fundamental Power Factor' angle. Cosφ1 is also called the 'Displacement Factor'. However this does not account for the total reactive power drawn by the system. This power factor is inspite of the actual load being resistive! The reactive power is drawn also y the trigger-angle dependent harmonics.

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

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

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

The Average Power, P drawn by the resistive load is

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

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

Single phase AC voltage controller with RL load

With inductive loads the operation of the PAC is illustrated in Fig 24. The current builds up from zero in each cycle. It quenches not at the zero crossing of the applied voltage as with the resistive load but after that instant. The supply voltage thus continues to be impressed on the load till the load current returns to zero. A single-pulse trigger for the TRIAC) or the anti parallel SCR has no effect on the devices if it (or the anti-parallel device) is already in conduction in the reverse direction. The devices would fail to conduct when they are intended to, as they do not have the supply voltage forward biasing them when the trigger pulse arrives. A single pulse trigger will work till the trigger angle α > φ, where φ is the power factor angle of the inductive load. A train of pulses is required here. The output voltage is controllable only between triggering angles φ and 180o. The load current waveform is further explained in Fig. 24.

The current is composed of two components. The first is the steady state component of the load current, iss and the second, itr is the transient component. With an inductance in the load the distinguishing feature of the load current is that it must always start from zero. However, if the switch could have permanently kept the load connected to the supply the current would have become a sinusoidal one phase shifted from the voltage by the phase angle of the load, φ. This current restricted to the half periods of conduction is called the 'steady-state component' of load current iss.

The 'transient component' of load current itr, again in each half cycle, must add up to zero with this iss to start from zero. This condition sets the initial value of the transient component to that of the steady state at the instant that the SCR/TRIAC is triggered.

Fig. 24 illustrates these relations. When a device is in conduction, the load current is governed by the equation

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

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

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

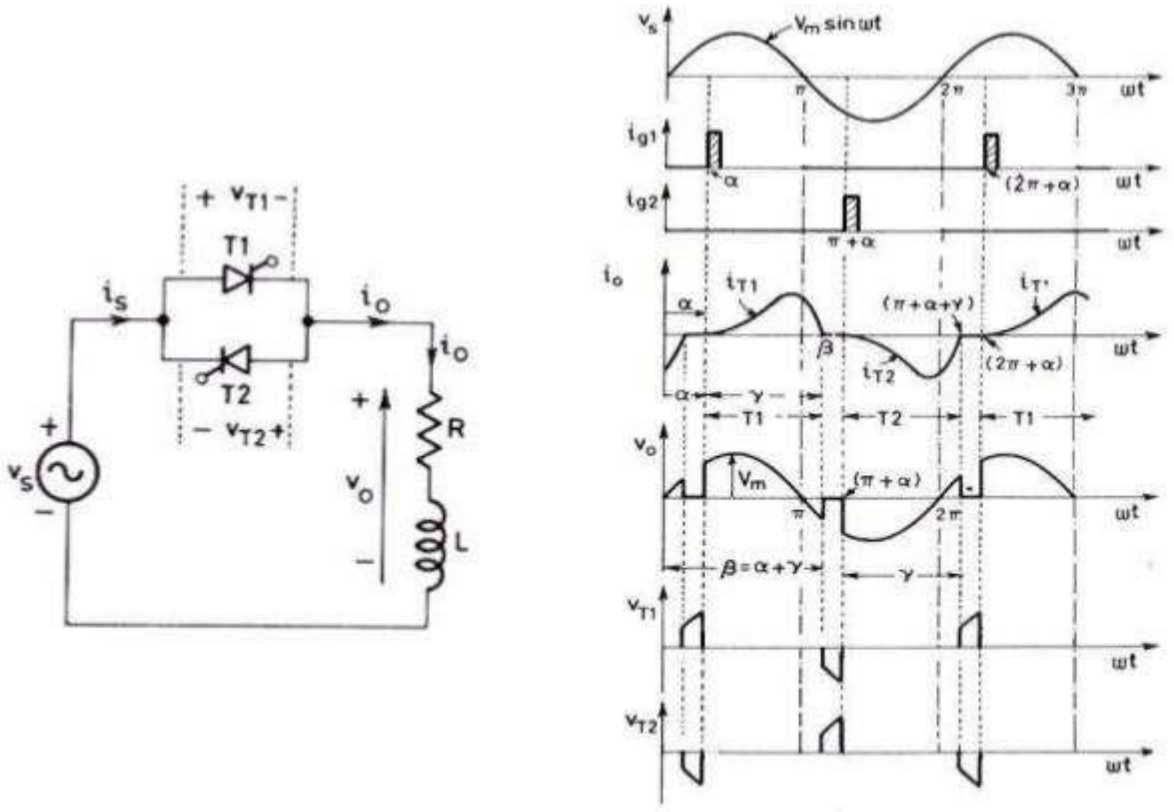


Fig. 24. Circuit diagram and output waveforms of AC voltage controller with RL load

Multiple Choice Questions

1 A single-phase symmetrical semi-converter employs

a) One SCR and one diode in each leg

b) Two SCRs and two diodes in each leg

c) Two SCRs in each leg

d) Two diodes in each leg

Answer: a

2 A dual converters has

a) Two full converters in series

b) Two half converters in series

c) Two full converters in anti-parallel

d) Two half converters in anti-parallel

Answer: c

3 The single phase bridge type cycloconverter uses __________ number of SCRs.

a) 4

b) 8

c) 6

d) None of the mentioned

Answer: b

4 AC voltage controllers convert

a) Fixed ac to fixed dc

b) Variable ac to variable dc

c) Fixed ac to variable ac

d) Variable ac to fixed ac

Answer: c

5. In the method of phase control, the phase relationship between ___ & ___ is controlled by varying the firing angle

a) Supply current, supply voltage

b) End of the load current, end of the load voltage

c) Start of the load current, start of the load voltage

d) Load current, load voltage

Answer: c

6. In a semi-converter with RLE load during the freewheeling period, the energy is

a) Fed back to the source

b) Fed to the inductor (L) and absorbed by E

c) Absorbed by the L & E and dissipated at R

d) Fed to the L & E and dissipated at R

Answer: d.

7. A single-phase symmetrical semi-converter employs

a) One SCR and one diode in each leg

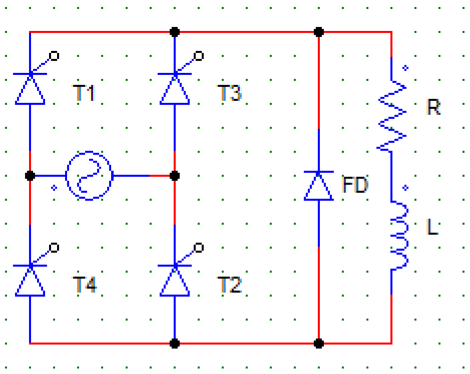
b) Two SCRs and two diodes in each leg

c) Two SCRs in each leg

d) Two diodes in each leg

Answer: a

8. For the below given circuit,



a) T2 and T3 are gated together

b) T1 and T4 are gated together

c) T1 and T3 are gated together

d) T1 and T2 are gated together

Answer: d

9. A single full converter alone can given a

a) Four quadrant operation

b) Three quadrant operation

c) Two quadrant operation

d) None of the mentioned

Answer: c

10. A cycloconverter is a __________

a) One stage power converter

b) One stage voltage converter

c) One stage frequency converter

d) None of the mentioned

Answer: c

11. In AC voltage controllers the

a) Variable ac with fixed frequency is obtained

b) Variable ac with variable frequency is obtained

c) Variable dc with fixed frequency is obtained

d) Variable dc with variable frequency is obtained

Answer: a

12. The AC voltage controllers are used in ___________ applications.

    a) Power generation

    b) Electric heating

    c) Conveyor belt motion

    d) Power transmission

    Answer: b

13. In the principle of phase control

    a) The load is on for some cycles and off for some cycles

    b) Control is achieved by adjusting the firing angle of the devices

    c) Control is achieved by adjusting the number of on off cycles

    d) Control cannot be achieved

    Answer: b

14. The major advantage of using dual converters is that

    a) It is cheaply available

    b) It has better pf

    c) No mechanical switch is required to change the mode of operation

    d) Its operating frequency is very high

    Answer: c

15. Applications of cycloconverters include

    a) Speed control of ac drives

    b) Induction heating

    c) Static VAR compensation

    d) All of the mentioned

    Answer: d

ASSIGNMENT

1. Examine the circuit and output wave form and explain the working of single phase full convertor bridge with RLE load.
2. Discuss the operation of three phase to single phase cyclo converter with neat diagram and wave forms.

UNIT III

UNIT III - INVERTERS & CHOPPERS

Voltage source inverters – series, parallel & bridge inverters – Current source inverters – PWM inverters. Commutation – Choppers – Control strategies – DC chopper – AC Chopper – Applications.

1. DC to AC Converter (Inverter)

DEFINITION: As we have already aware from the term Inverter which is an Electrical Setup used for daily purposes. In Inverter, input DC is converted to AC power by switching the DC input voltage in a sequence so as to generate AC output. The Inverter is the power electronic circuit, which converts the DC voltage into AC voltage. The DC source is normally a battery or output of the controlled rectifier.

Inverters can be broadly classified in to two types:

i. Voltage source inverters
ii. Current source inverters

A voltage source inverter is one in which the dc source has small or negligible impedance.
A current source inverter is fed with adjustable current from a dc source of high impedance.

2. Types of Voltage source inverters

i) Series Inverters
ii) Parallel Inverters
iii) Bridge Inverters

3. SERIES INVERTER

- Inverters in which commutating components are permanently connected in series with the load are called series inverters.
- The circuit diagram for a basic series inverter is shown in Fig.1.
- It consists of load resistance R in series with commutating components L and C. The L and C are so chosen that the series RLC circuit forms an under damped circuit.
- Two thyristors T1 and T2 are turned on appropriately so that output voltage of desired frequency can be obtained.
- When thyristor T1 is on, with T2 is off, current I start building up in the RLC circuit.

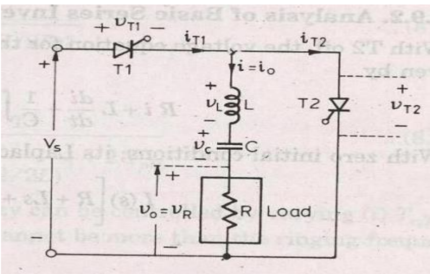


Fig 1. Series VSI

- As the circuit is under damped; the load current, after reaching some peak value, decays to zero at a point a, Fig 2
- At a point a, as the load current tends to reverse, SCR T1 is turned off. After instant a, some minimum time $t_{q.min}$ must elapse for T1 to regain its forward blocking capability.
- The minimum time is given by $t_{q.min} = \frac{\pi}{\omega} - \frac{\pi}{\omega_r} = \frac{1}{2}\left[\frac{1}{f} - \frac{1}{f_r}\right]$
- Where ω = output frequency in rad/sec
- And ω_r = circuit ringing frequency in rad/sec.

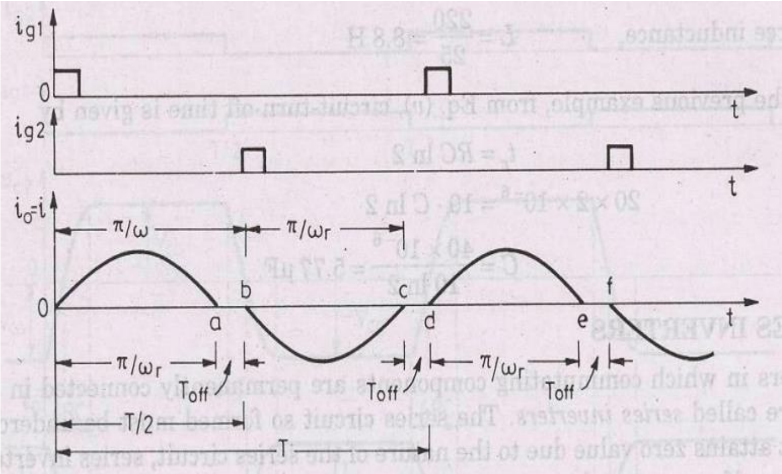


Fig 2. Load current waveform for series inverter

- In Fig.2. time interval between the instant T1 is turned off and the instant T2 is turned on is indicated by T_{off} = ab.
- After T1 has commutated, upper plate of capacitor attains positive polarity.
- Now when T2 is turned on at instant b, capacitor begin to discharge and load current in reverse direction builds up to some peak negative value and then decays to zero at instant c.
- In this manner dc is converted to ac with the help of series inverter.

4. SINGLE-PHASE PARALLEL INVERTER

- The basic inverter circuit for a single-phase parallel inverter, utilizing capacitor for its commutation is shown in figure below

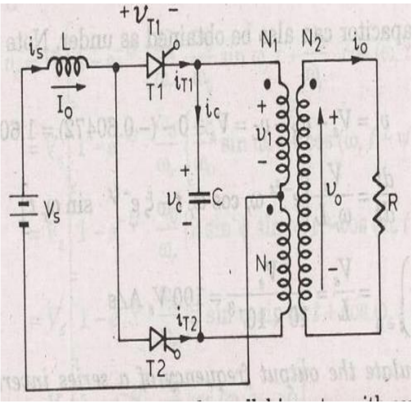


Fig.3. Parallel Inverter

- It consists of two thyristors T1 and T2 an inductor L, an output transformer and a commutating capacitor C.
- The transformer turns ratio from each primary half to secondary winding is assumed unity.
- The operation of this inverter can be explained in some well-defined modes as under:

MODE 1:

- In this mode, thyristor T1 is conducting and current flows in the upper half of primary winding. This current establishes magnetic flux that links both the halves of primary winding.
- As a result, an emf V_S is induced across upper as well as lower half of the primary winding.
- This voltage charges the commutating capacitor C to a voltage of $2V_S$ with upper plate positive as shown in Fig.4. (a).

MODE 2:

- At time t=0, thyristor T2 is turned on by applying the triggering pulse to its gate.
- At this time t=0, capacitor voltage $2V_S$ appears as a reverse bias across T1, therefore turned off.
- A current I_O begins to flow through T2, lower half primary winding V_S and L as shown in Fig.4. (b).

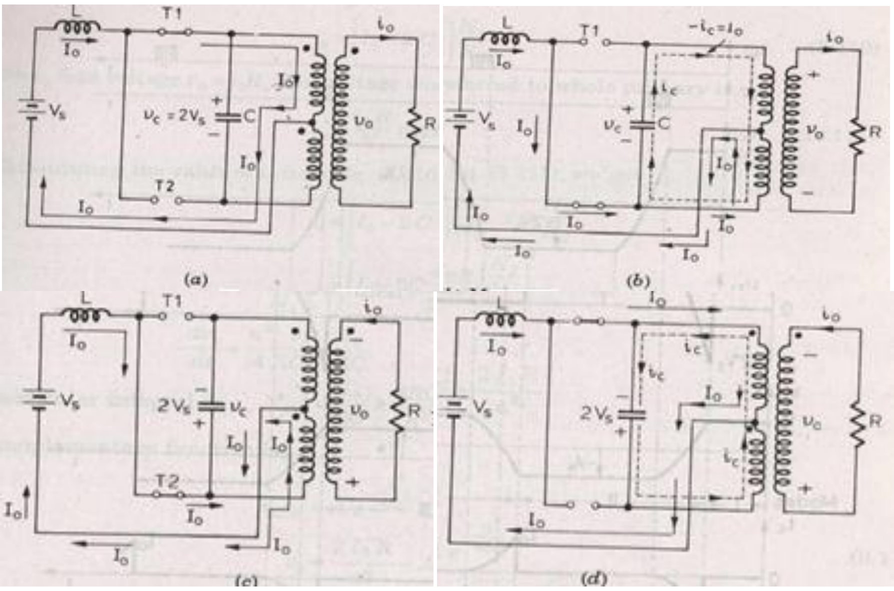


Fig.4. a) Mode I, $t<0$: (b) Mode II, $t=0+$ (c) Mode II, $t1 \leq t < T/2$ (d) Mode III just after $t = T/2$

MODE 3:

- When capacitor has charged to $-2V_S$ with upper plate negative and lower plate positive, SCR T1 may be turned on any time.
- In 4. (d), T1 is triggered at $t=T/2$. Capacitor voltage $2V_S$ applies a reverse bias across T2, it is therefore turned off.

5. SINGLE PHASE BRIDGE INVERTER

Single phase bridge inverters are of two types.

- Single-phase half bridge inverter
- Single-phase full bridge inverter
- Power circuit diagrams of the two configurations of single-phase bridge inverters are shown in Fig.5 (a) and 6 (a)
- The gating signals for the thyristors and resulting output voltage waveforms are shown in Fig.5 (b) and 6(b) for half-bridge and full-bridge respectively.
- These voltage waveforms are drawn on the assumptions that each thyristor conducts for the duration its gate pulse is present and is commutated as soon as pulse is removed.
- In Fig 5(b) and 6(b), ig1 to ig4 are gate signals applied respectively to thyristors T1 to T4.

SINGLE PHASE HALF-BRIDGE INVERTER:

- Single-phase half bridge inverter consists of two SCRs, two diodes and three wire supply.
- It is seen from Fig 5(b), for $0 < t < T/2$, thyristor T1 conducts and the load is subjected to a voltage $V_S/2$.
- At, $t = T/2$, Thyristor T1 is commutated and T2 is gate on.

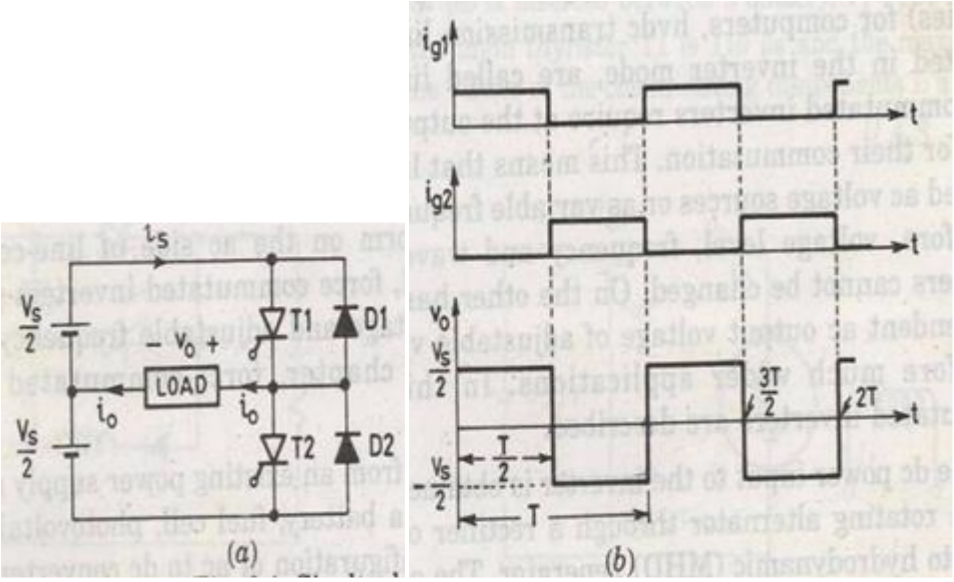


Fig 5.Single phase half bridge inverter a) circuit b) waveforms

- During the period $T/2 < t < T$, thyristor T2 conducts and the load is subjected to voltage $(-V_S/2)$.
- The load voltage is an alternating voltage waveform of amplitude $V_S/2$ and of frequency 1/T Hz.
- The main drawback of half-wave bridge inverter is that it requires 3-wire dc supply. This can be overcome by full-bridge inverter.

SINGLE-PHASE FULL BRIDGE INVERTER:

- For, full bridge inverter, when T1, T2 conduct, load voltage is V_S and when T3, T4 conduct load voltage is $-V_S$ as shown in Fig.6 (b)
- Frequency of output voltage can be controlled by varying the periodic time T.

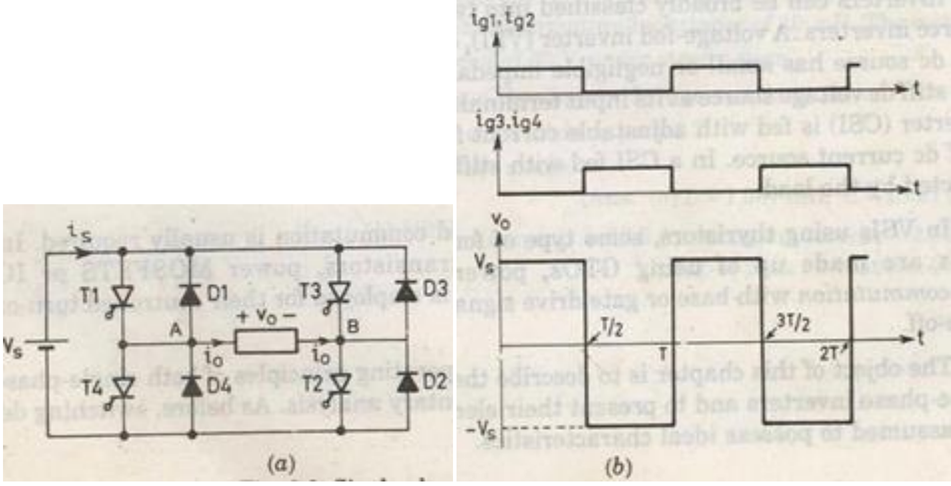


Fig 6.Single phase full bridge inverter

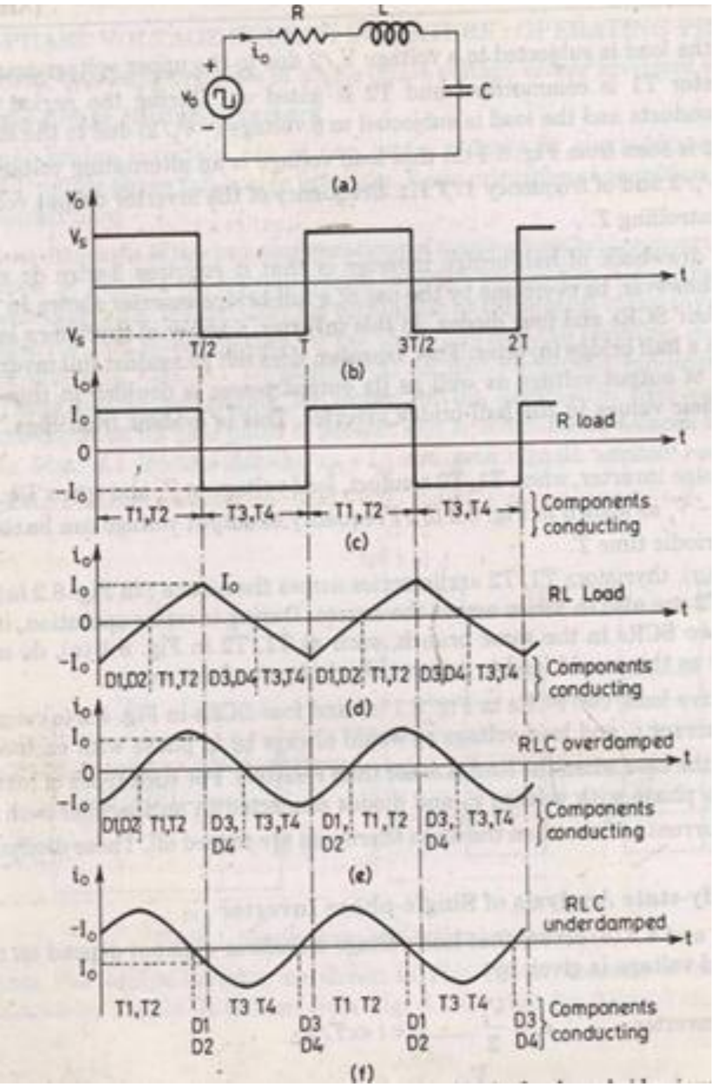


Fig.7. Load voltage and current waveforms for Single phase bridge inverter

The load voltage is given by,

For half-bridge inverter $V_0 = V_S / 2$ ….. $0< t <<T/2$
$V_0 = -V_S / 2$ …. $T/2< t <T$
Foe Full-bridge inverter $V_0 = V_S$ ….. $0< t <<T/2$
$V_0 = V_S$ ….. $T/2< t <T$

The load current is depends on nature of load.

Let the load consists of RLC in series shown in Fig.7 (a)

It is seen from Waveform that load current will be

$I_o = -I_o$ …..At t = 0, T, 2T, 3T,

$I_o = I_o$ …..At t = T/2, 3T/2, 5T/2,

The voltage equation for the circuit model of Fig 7(a) for half bridge inverter for

1.) 0< t < T/2 is given by

$$\frac{V_S}{2} = Ri_0 + L\frac{di_0}{dt} + \frac{1}{C}\int i_0 dt + V_{c1}$$

For full-bridge inverter, replace $V_S/2$ by V_S in the above equation.

2.) T/2 <t<T is given by

$$-\frac{V_S}{2} = Ri_0 + L\frac{di_0}{dt} + \frac{1}{C}\int i_0 dt + V_{c1}$$

For full-bridge inverter, replace $(-V_S/2)$ by $(-V_S)$

6. CURRENT SOURCE INVERTERS

- In the current source inverters (CSI), input current is constant but adjustable.
- The amplitude of output current from CSI is independent of Load. However, the magnitude of output voltage and its waveform output from CSI is dependent upon the nature of load impedance.
- A CSI converts the input dc current to an ac current at its output terminals.
- The output frequency of ac current depends upon the rate of triggering the SCRs. The amplitude of ac current can be adjusted by controlling the magnitude of the dc input current.
- A CSI does not require any feedback diodes, where these are required in a VSI.

SINGLE PHASE CSI WITH IDEAL SWITCHES

- A single-phase CSI with ideal thyristors is shown in Fig.8.(a).
- Here a thyristor is assumed an ideal switch with zero commutation time. Positive directions

for load voltage V_O and load current I_O are indicated in Fig.8. (a)

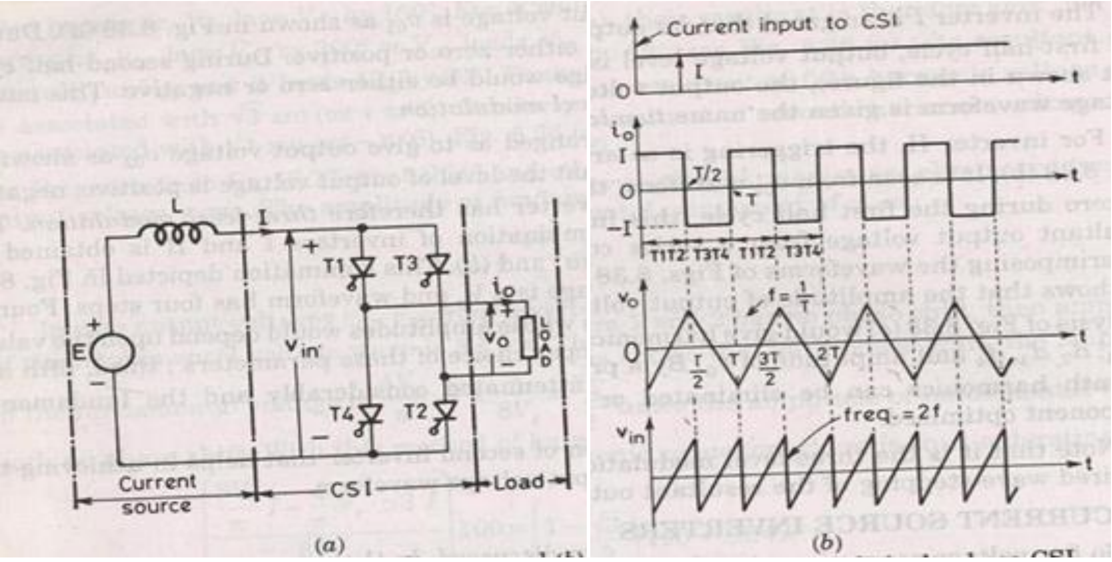


Fig.8. a) Power circuit diagram and b) waveforms for an ideal single phase CSI

In Fig.8. (a)

- When T1 and T2 are on, load current I_O positive and equal to I.
- When T3 and T4 are on, load current I_O is negative and equals to –I as shown in Fig.8 (b).
- The output frequency of I_O can be varied by controlling the frequency of triggering the Thyristor pairs T1, T2 and T3, T4.
- It is seen from the Fig.8. (b) that output current I_O is a square wave of amplitude equal to the dc input current I.
- Assume that load consists of a capacitor C. It is known for a capacitor that $I_O = C\frac{dv_0}{dt}$
- As I_O is constant, slope $\frac{dv_0}{dt}$ must be constant over every half cycle.
- This slope is positive from zero to T/2 and negative from T/2 to T.

SINGLE PHASE CAPACITOR COMMUTATED CSI WITH R LOAD

- Power circuit diagram for single-phase CSI with resistive load R is shown in Fig.9 (a).
- The source for this inverter is a constant but adjustable dc current source. Capacitor C in parallel with the load is used for storing the charge for force commutating SCRs.
- The thyristors T1 to T4 are four power switches.
- These SCRs are gated in pairs; T1, T2 together by gating signals i_{g1}, i_{g2} and T3,T4 by i_{g3}, i_{g4} as shown in figure.

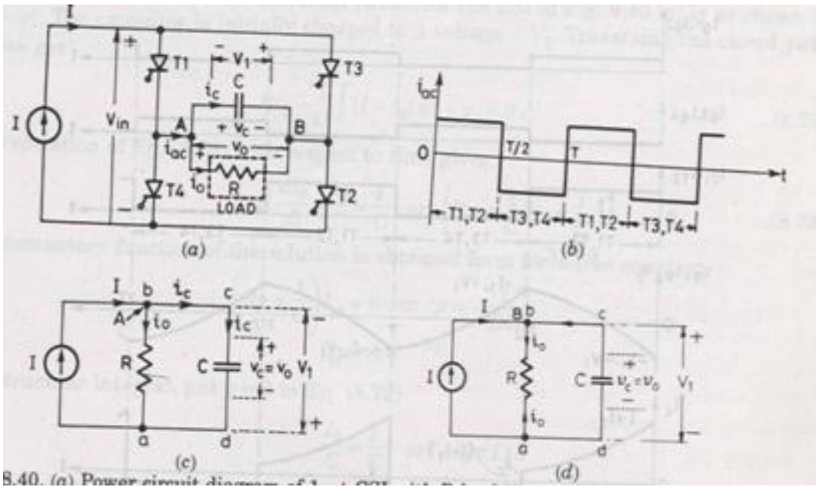


Fig 9. a) Power circuit diagram for 1- Φ CSI with R load
b) AC output current waveform
c) Equivalent circuit of fig a for 0 < t < T/2
d) Equivalent circuit of fig a for T/2 < t < T

Parameters of the Current Source Inverter with R-Load

If we trigger T_1 and T_2 from 0 to T/2 then the output current and the output voltage is expressed as

$$I_0=I_S>0$$
$$V_0=I_0R$$

If we trigger T_3 and T_4 from T/2 to T then the output current and the output voltage is expressed as

$$I_0=-I_S>0$$
$$V_0=I_0R<0$$

In the case of resistive load, forced commutation is required. From 0 to T/2, T_1 and T_2 are conducting and from T/2 to T, T_3 & T_4 are conducting. So, the conduction angle of each switch will be equal to π and the conduction time of each switch will be equal to T/2.

The input voltage of the resistive load is expressed as

$$V_{in} = V_0 \text{ (from 0 to T/2)}$$

$$V_{in} = -V_0 \text{ (from T/2 to T)}$$

The RMS output current and the RMS output voltage of the CSI resistive load is expressed as

$$I_{0(RMS)} = I_S$$

$$V_{0(RMS)} = I_{0(RMS)}R$$

The average and RMS thyristor current of the CSI with resistive load is

$$I_{T(avg)}=I_S/2$$

$$I_{T(RMS)}=I_S/\sqrt{2}$$

The Fourier series of output current and the output voltage of the CSI with resistive load is

$$I_0(t) = \sum_{n=1,3,5}^{\infty} \frac{4I_S}{n\pi} sin n\omega_0 t$$

$$V_0(t) = \sum_{n=1,3,5}^{\infty} \frac{4I_S R}{n\pi} sin n\omega_0 t$$

The fundamental component of the RMS output current is

$$I_{01(RMS)}=2\sqrt{2}/\pi * I_S$$

The distortion factor of the current source inverter with R-load is

$$g=2\sqrt{2}/\pi$$

The total harmonic distortion is expressed as

$$THD=48.43\%$$

The fundamental component of average and RMS thyristor current is

$$I_{T01(avg)}= I_{01(max)}/ \pi$$

$$I_{T01(RMS)}=I_{01(max)}/ 2$$

The fundamental power across the load is expressed as

$$V_{01(RMS)}*I_{01(RMS)}*\cos\phi_1$$

The total power across the load is expressed as

$$I_{0(RMS)}^2 R= V_{0(RMS)}^2/ R$$

The input voltage V_{in} is always positive because the power is always delivered from source to load. The output waveform of the current source inverter with R-load is shown in the below figure.

Applications of CSI:

- Speed control of ac motors.
- Induction heating.
- Lagging VAr compensation.
- Synchronous motor starting.

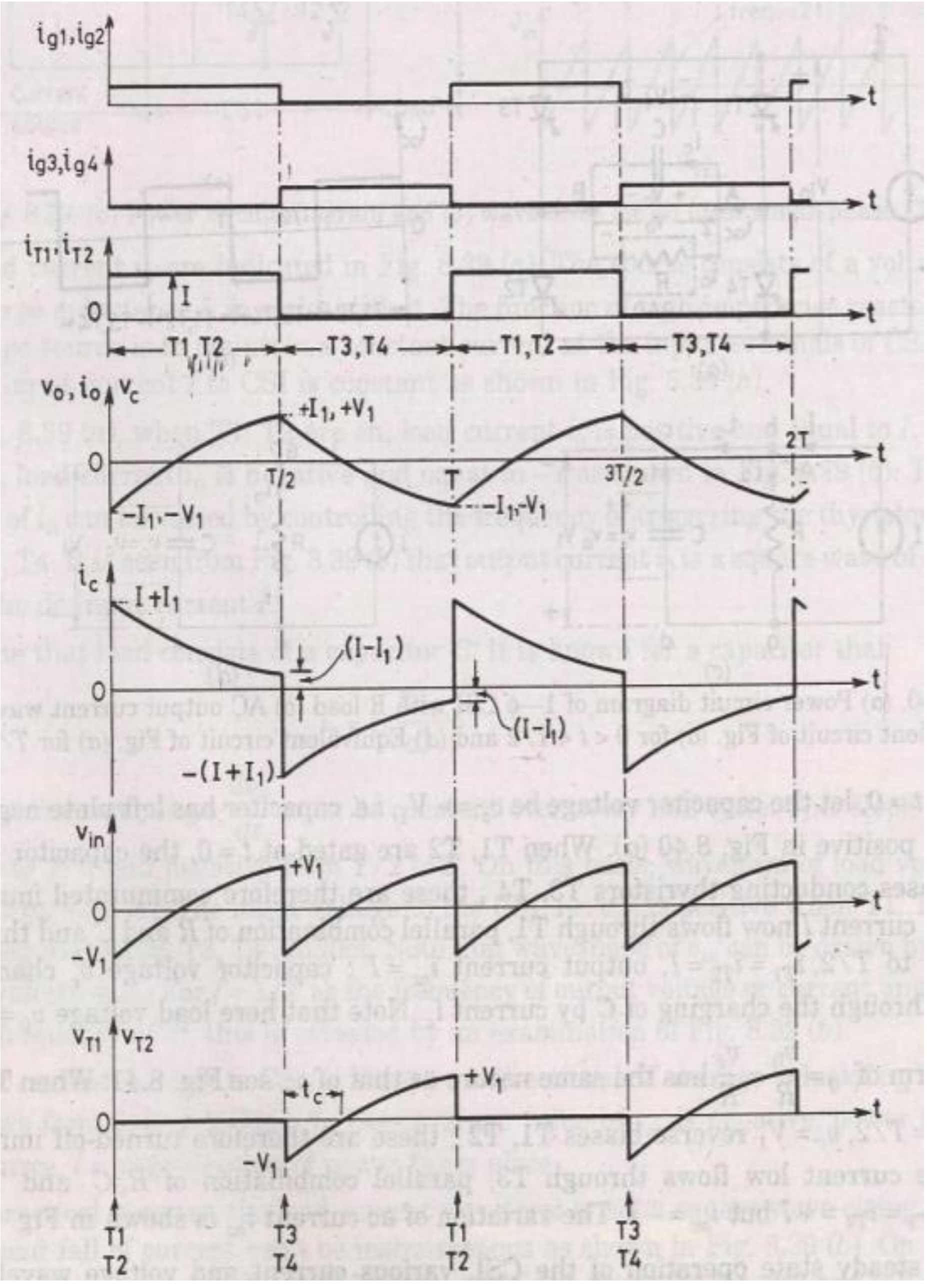


Fig. 10. Current and voltage waveforms for Single phase CSI with R load

7. PULSE WIDTH MODULATED INVERTERS (PWM INVERTERS)

Pulse-width modulation is the process of modifying the width of the pulses in a pulse train in direct proportion to small control signal. Greater the control voltage, the wider the resulting pulses become.

- PWM inverters are gradually taking over the other types of inverters in industrial applications.
- PWM techniques are characterized by constant amplitude pulses.
- The width of the pulses is, however, modulated to obtain inverter output voltage control and to reduce its harmonic content.

- Different PWM techniques are as under:
    i. Single-pulse modulation
    ii. Multiple-pulse modulation
    iii. Sinusoidal-pulse modulation
- The three PWM techniques mentioned above differ from each other in the harmonic content in their respective output voltages.
- Choice of a particular PWM technique depends upon the permissible harmonic content in the inverter output voltage.

Single Pulse Width Modulation (SPWM)

- The output voltage from-single phase full-bridge inverter is shown in Fig.11 (a).
- When this wave form is modulated, the output voltage will be as shown in Fig.11 (b).
- It consists of a pulse of width 2d located symmetrically about π/2 and another pulse located symmetrically about 3π/2.
- The range of pulse width 2d varies from 0 to π.
- The output voltage is controlled by varying pulse-width 2d.
- This shape of output voltage wave is shown in Fig.11 (b) is called **quasi-square** wave.

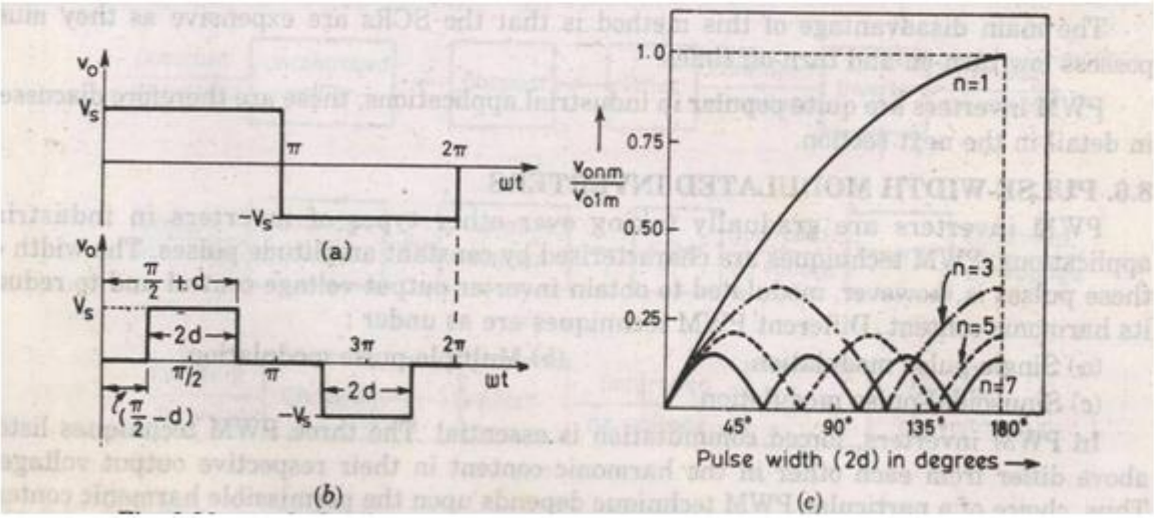


Fig.11. a),b) Single-pulse modulation, c) Harmonic content in SPM

- Fourier analysis of Fig.11 (b) is as under:

$$A_n = \frac{2}{\pi}\int_{\frac{\pi}{2}-d}^{\frac{\pi}{2}+d} V_s \sin n\omega t . d(\omega t) = \frac{4V_s}{n\pi}\left[\sin\frac{n\pi}{2}\sin nd\right] \quad \text{……… (1)}$$

- Positive and negative half cycles of V_o in Fig.11 (b) are symmetrical about π/2 and 3π/2 respectively. In addition, these half cycles are also identical.
- As a result Waveform of Fig.11 (b) can be described by Fourier series as

$$V_o = \sum_{n=1,3,5}^{\infty} \frac{4V_s}{n\pi}\sin\frac{n\pi}{2}\sin nd \sin n\omega d \qquad \text{… (2)}$$

- When pulse width 2d is equal to maximum value π radians, the fundamental component of output voltage has a peak value of

$$V_{o1m} = \frac{4V_s}{\pi} \ \dots (3)$$

- Peak value of nth harmonic is

$$V_{onm} = \frac{4V_s}{n\pi} \dots (4)$$

- From Equations (3) and (4),

$$\frac{V_{o1m}}{V_{onm}} = \frac{\sin nd}{n} \dots\dots\dots (5)$$

- The ratio given by Equation (5) is plotted in Fig 11 (c).
- It is seen from these curves that the fundamental component is reduced to 0.5 for 2d = 60 degrees.
- The R.M.S value of output voltage is $v_{or} = v_s \left[\frac{2d}{\pi}\right]^{\frac{1}{2}}$ …(6)

Multiple Pulse Width Modulation (MPWM)

- This method of pulse modulation is an extension of single pulse-modulation. In multiple pulse modulations (MPM), several equidistant pulses per half cycle are used.
- For simplicity, the effect of using two symmetrically spaced pulses per half cycle Fig.12 (a) is investigated here.

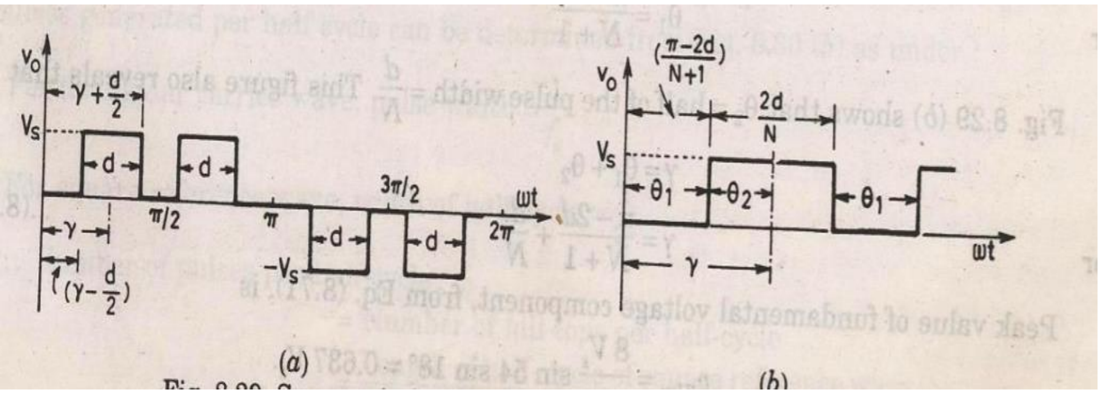


Fig.12. Symmetrical two pulse modulation pertaining to MPM

- In this Figure, pulse width is taken half of that of in fig.12(b) but their amplitudes are same.
- This means that R.M.S values of pulses in Fig 12(b) and 12 (a) are equal to that given in Equation 6
- Fourier constants are as under

$$A_n = \frac{2}{\pi}\int_0^{\pi} v_0 \sin n\omega t . d(\omega t)$$

$$A_n = \frac{2}{\pi}\int_{\gamma-\frac{\pi}{2}}^{\gamma+\frac{d}{2}} V_s \sin n\omega t . d(\omega t). 2$$

- The use of factor 2 in the above expression accounts for the two pulses from 0 to π in Fig.12(a).
- Waveform of Fig.12 (a) can be described by Fourier series as

$$V_o = \sum_{n=1,3,5}^{\infty} \frac{8V_s}{n\pi} \sin n\gamma \sin \frac{nd}{2} \sin n\omega t$$

- The amplitude of nth harmonic of the two-pulse waveform of Fig.12 (a) is

$$V_n = \frac{8V_s}{n\pi} \sin n\gamma \sin \frac{nd}{2}$$

- In MPM lower order harmonics can be eliminated by proper choice of 2d and ϒ.
- The R.M.S value of output voltage is $v_{or} = v_s \left[\frac{2d}{\pi}\right]^{\frac{1}{2}}$

Sinusoidal-pulse Modulation (sin M)

- In this method of modulation, several pulses per half cycle are used as in the case of multiple-pulse modulation (MPM). In MPM, the pulse width is equal for all the pulses. But in sin M, the pulse width is s sinusoidal function of the angular position of the pulse in a cycle as shown in Fig. 13
- The intersection of V_C and V_R waves determines the switching instants and communication of the modulated pulse.
- V_C is the peak value of triangular carrier wave and V_R that of reference or modulating signal
- The carrier and reference waves are mixed in a comparator.
- When sinusoidal wave has magnitude higher than the triangular wave, the comparator output is HIGH, otherwise it is LOW.
- The comparator output is processed in a trigger pulse generator in such a manner that the output voltage wave of the inverter has a pulse width in agreement with the comparator output pulse width.
- The ratio of $\frac{V_C}{V_R}$ is called the modulation index (MI) and it controls the harmonic content of the output voltage form.

Applications

- Most commonly PWM inverters are utilized in the speed AC drives where the speed of the drive is dependent on the variation in the frequency of the applied voltage.
- Majorly the circuits in power electronics can be controlled by using PWM signals.

- To generate the signals in analog form from digital devices like microcontrollers, the PWM technique is beneficial.
- Further, there are various applications where PWM technology is used in different circuits.

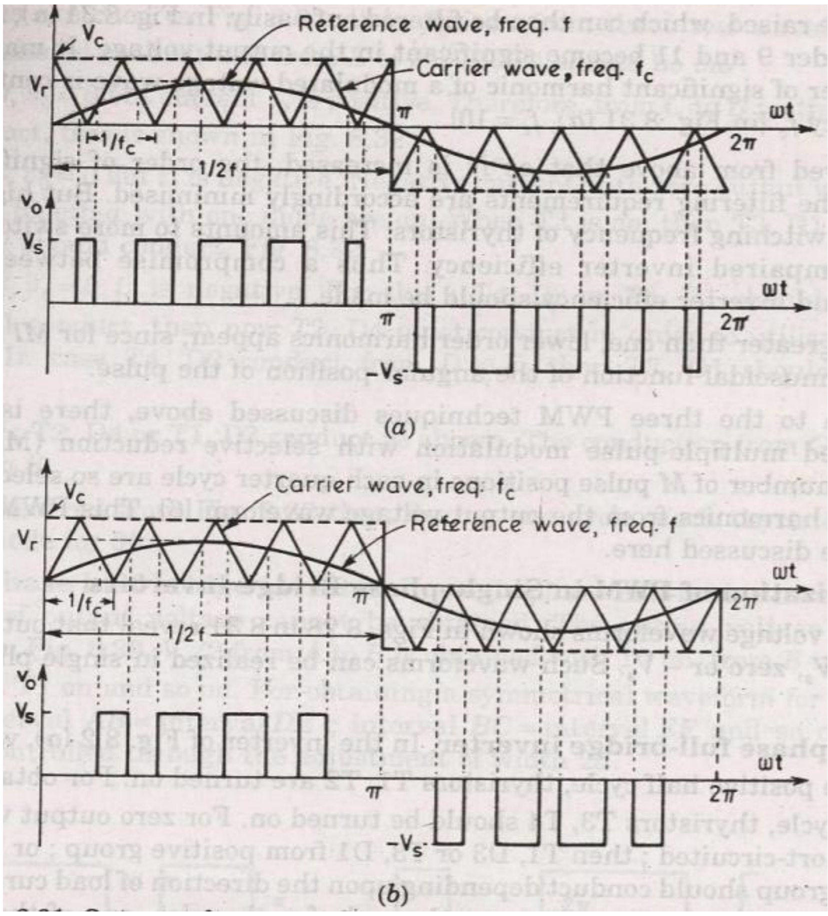


Fig.13. Output voltage waveforms with sinusoidal pulse modulation

8. COMMUTATION

SCR Commutation

Commutation is nothing but the turn OFF method of an SCR. It is the method used to bring an SCR or thyristor from ON state to OFF state.

A thyristor can be turned on by triggering a gate terminal with a low voltage short duration pulse. But after turning on, it will conduct continuous until the thyristor is reverse biased or the load current falls to zero. This continuous conduction of thyristors causes problems in some applications. The process used for turning off a thyristor is called commutation. By the commutation process, the thyristor operating mode is changed from forward conducting mode to forward blocking mode. The commutation techniques of thyristors are classified into two types:

Natural Commutation
Forced Commutation

Natural Commutation

Generally, if we consider AC supply, the current will flow through the zero crossing line while going from positive peak to negative peak. Thus, a reverse voltage will appear across the device simultaneously, which will turn off the thyristor immediately. This process is called natural commutation as the thyristor is turned off naturally without using any external components or circuit or supply for commutation purposes. Natural commutation can be observed in AC voltage controllers, phase-controlled rectifiers, and cyclo converters.

Forced Commutation

The thyristor can be turned off by reverse biasing the SCR or by using active or passive components. Thyristor current can be reduced to a value below the value of holding current. Since the thyristor is turned off forcibly it is termed as a forced commutation process. The electrical components such as inductance and capacitance are used as commutating elements for commutation. Forced commutation can be observed while using DC supply; hence it is also called DC commutation.

Classification of Forced Commutation Methods

The forced commutation can be classified into different methods as follows:

Class A: Self commutated by a resonating load
Class B: Self commutated by an LC circuit
Class C: Cor L-C switched by another load-carrying SCR
Class D: C or L-C switched by an auxiliary SCR
Class E: An external pulse source for commutation
Class F: AC line commutation

Class A: Self Commutated by a Resonating Load

In Class A, if thyristor is triggered or turned on, then anode current will flow by charging capacitor C with dot as positive. The second-order under-damped circuit is formed by the inductor or AC resistor, capacitor, and resistor. If the current builds up through SCR and completes the half-cycle, then the inductor current will flow through the SCR in the reverse direction which will turn off the thyristor.

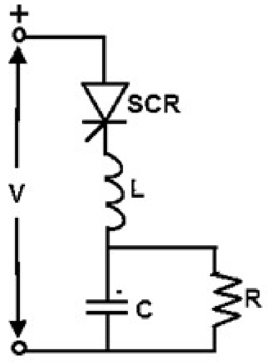


Fig 14.a) Class A

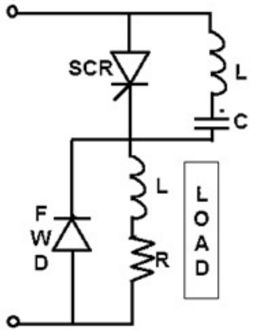


Fig 14.b) Class B

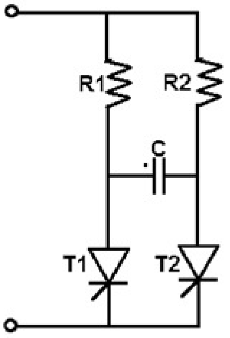


Fig14.c) Class C

After commutation, the capacitor will start discharging through the resistor in an exponential manner. The thyristor will be in reverse bias condition until the capacitor voltage returns to the supply voltage level.

Class B: Self Commutated by an L-C Circuit

The major difference between the class A and class B is that the LC is connected in parallel with thyristor in class B. Before triggering on the SCR, the capacitor is charged up. If the SCR is triggered then the resulting current has two components.

The constant load current flowing through the R-L load is ensured by the large reactance connected in series with the load which is clamped with a freewheeling diode. If sinusoidal current flows through the resonant L-C circuit, then the capacitor C is charged up with dot as negative at the end of the half-cycle. This current will then reverse and flow through the SCR in opposition to the load current for a small fraction of the negative swing till the total current through the SCR becomes zero. The SCR will turn off when the resonant–circuit (reverse) current is just greater than the load current.

Class C: C or L-C Switched by another Load Carrying SCR

In class C commutation, one SCR is considered as the main thyristor and the other as an auxiliary thyristor. If the thyristor T2 is triggered, then the capacitor will be charged up. If the thyristor T1 is triggered, then the capacitor will discharge and this discharge current of C will oppose the flow of load current in T2 as the capacitor is switched across T2 via T1.

Class D: L-C or C Switched by an Auxiliary SCR

The difference for class C and class D commutation is the load current. In class D, only one of the SCR’s will carry the load current while the other acts as an auxiliary thyristor whereas in class C both SCRs will carry load current. By triggering the Ta (auxiliary thyristor) the capacitor is charged up to supply voltage and then the Ta will turn OFF. The extra voltage if any, due to substantial inductance in the input lines will be discharged through the diode-inductor-load circuit.

If the Tm (main thyristor) is triggered, then the current will flow in two paths: commutating current will flow through the C-Tm-L-D path, and load current will flow through the load. If the charge on the capacitor is reversed and held at that level using the diode and if Ta is re-triggered, then the voltage across the capacitor will appear across the Tm via Ta. Thus, the main thyristor Tm will be turned off.

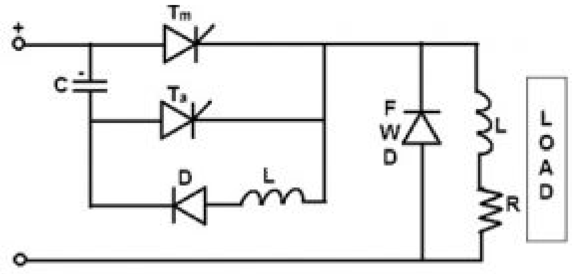


Fig.15. a) Class D

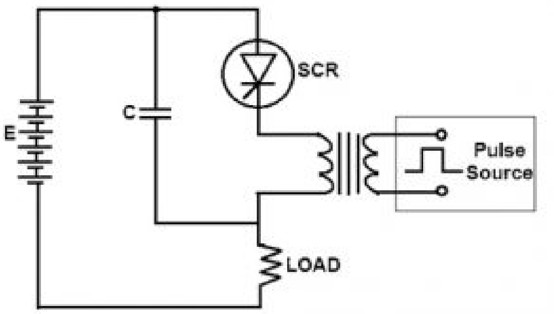


Fig 16.b) Class E

Class E: External Pulse Source for Commutation

In class E, if the thyristor T is triggered, then the current will flow through the load and pulse transformer. An external pulse generator is used to generate a positive pulse which is supplied to the cathode of the thyristor through a pulse transformer. The capacitor C is charged to around 1v and it is considered to have zero impedance for the turn-off pulse duration. The voltage across the thyristor is reversed by the pulse from the transformer which supplies the reverse recovery current, and for the required turn-off time it holds the negative voltage.

Class F: AC Line Commutation

In class F commutation, an alternating voltage is used for supply and, during the positive half cycle of this supply, the load current will flow.During the negative half-cycle as the load current becomes zero, then the thyristor will turn off.

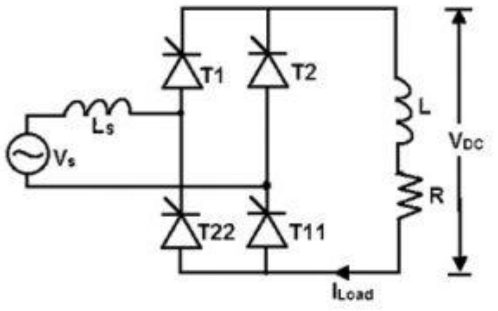


Fig. 17. Line commutation

Here, the duration of the half-cycle must be greater than the turn-off time of the thyristor. This commutation process is similar to the concept of a three-phase converter. Let us consider, primarily T1 and T11 are conducting with the triggering angle of the converter, which is equal to 60 degrees and is operating in continuous conduction mode with a highly inductive load. If the thyristors T2 and T22 are triggered, then instantaneously the current through the incoming devices will not rise to the load current level. If the current through the incoming thyristors reaches the load current level, then the commutation process of outgoing thyristors will be initiated. This reverse biasing voltage of the thyristor should be continued until the forward blocking state is reached.

9. CHOPPERS

A chopper converts a fixed DC input voltage into a variable DC output voltage. Choppers are now being used all over the world, for rapid transit systems. These are also used in trolley cars, marine hoists, trucks and mine haulers. The future electric automobiles are likely to use choppers for their speed control and braking. The power semi conductor devices used for a chopper circuit can be power BJT, power MOSFET, GTO or force-commutated thyristor. The power semiconductor devices have on stage voltage drops of 0.5V to 2.5V. A chopper is high speed on/off semiconductor switch. It connects source to load and disconnects the load from the source at a fast speed.

10. DC Chopper

A DC chopper is a static device that converts fixed dc input voltage to a variable dc output voltage directly. A chopper can be said as dc equivalent of an ac transformer as they behave in an identical manner. This kind of chopper is more efficient as they involve one stage conversion. Just like a transformer, a chopper can be used to step up or step down the fixed dc output voltage. Choppers are used in many applications all over the world inside various electronic equipments. A chopper system has a high efficiency, fast response and a smooth control.

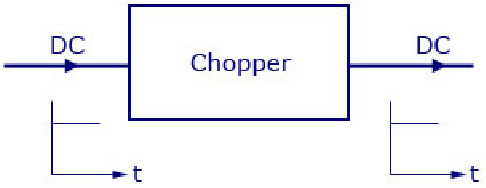


Fig.18. DC Chopper

11. AC link chopper

In the case of an ac link chopper, first dc is converted to ac with the help of an inverter. After that, AC is stepped-up or stepped-down by a transformer, which is then converted back to dc by a diode rectifier. Ac link chopper is costly, bulky and less efficient as the conversion is done in two stages.

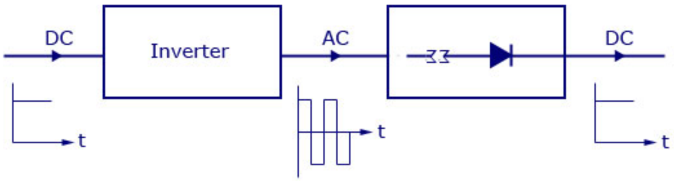


Fig .19.AC link chopper

12. APPLICATIONS OF CHOPPERS

Chopper circuits are used in multiple applications, including::

- Switched mode power supplies, including DC to DC converters.

- Speed controllers for DC motors.
- Driving brushless DC torque motors or stepper motors in actuators.
- Class D electronic amplifiers.
- Switched capacitor filters.
- Variable-frequency drives.
- DC voltage boosting.
- Battery-operated electric cars.
- Battery charges.
- Railway tractions.

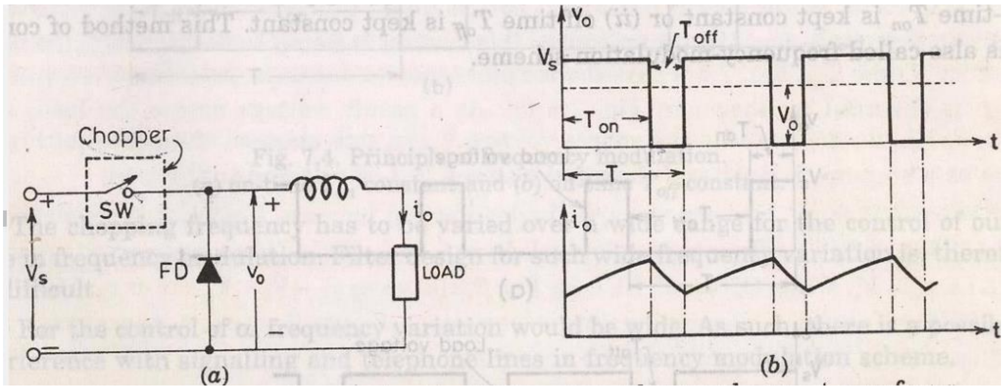


Fig.20. (a) Elementary Chopper circuit and (b) output voltage and current waveforms

- A chopped load voltage as shown is obtained from a constant DC supply of magnitude Vs.
- In the above figure chopper is represented by a switch SW inside a dotted rectangle, which may be turned ON or turned OFF as desired.
- Ton chopper is on and load voltage is equal to source voltage Vs. During the interval Toff chopper is off, load current flows through the Freewheeling diode FD.
- The load current as shown in figure is continuous.
- Average load voltage Vo is given by

$$Vo=[Ton/(Ton + Toff)]Vs$$

$$Vo= (Ton/T)\ Vs$$

$$Vo= \alpha\ Vs$$

Where, Ton = on- time, Toff= off-time

T= Ton + Toff = chopping period

α = Ton/T = duty cycle

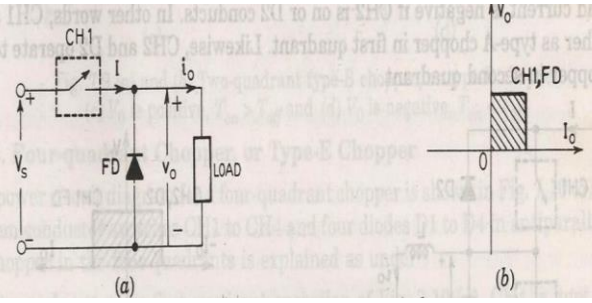
- Thus load voltage can be controlled by varying duty cycle α
- The above equation shows that load voltage is independent of load current.

$$\underline{Vo= f. Ton.Vs}$$

Where, f=1/T = chopping frequency

- Power semi conductor devices used in chopper circuits are unidirectional devices, polarities of output voltage Vo, and the direction of output current Io are therefore restricted.
- A chopper can however, operate in any of the four quadrants by an appropriate arrangement of semi conductor devices.
- This characteristic of their operation in any of the four quadrant forms the basis of their chopper classification as Type-A chopper, Type-B chopper etc....

13. FIRST QUADRANT, or Type – A chopper



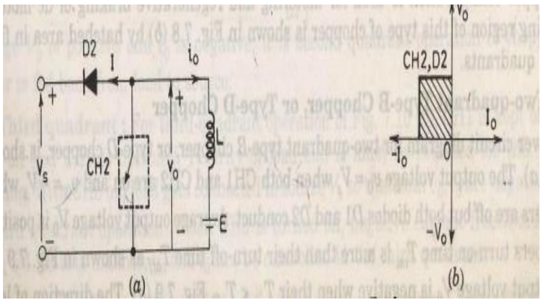


Fig 21.First quadrant / Type A Chopper

Fig 22.Second quadrant / Type B Chopper

- When chopper CH1 is on, Vo=Vs and current Io flows in the arrow direction shown. When CH1 is off, Vo=0 but Io in the load continuous flowing in the same direction through free wheeling diode FD.
- The power flow in type-A chopper is always from source to load. This chopper is also called step-down chopper as average output voltage Vo is always less than the input DC voltageVs

14. SECOND QUADRANT or Type-B chopper

- Power circuit for this of chopper is shown in fig.
- The load must contain a DC source E, like a battery (or a dc motor) in this chopper.
- When CH2 is on, Vo=0 but load voltage E drives current through L and CH2. Inductance L stores energy during Ton of CH2. When CG2 is off,
  Vo=[E+L di/dt] exceeds source voltage Vs.
- As a result, diode D2 is forward biased and begins conduction, thus allowing the power to the source.
- As load voltage Vo= [E+L di/dt] is more than source voltage Vs, type- B chopper is also called as step-up chopper.
- Both type-A and type-B chopper configurations have a common negative terminal between their input and output circuits.

15. TWO QUADRANT TYPE- A chopper or TYPE- C chopper

- This type of chopper is obtained by connecting type-A and type-B choppers in parallel as shown in fig.23.

- The output voltage Vo, is always positive because of the presence of freewheeling diode FD across the load.

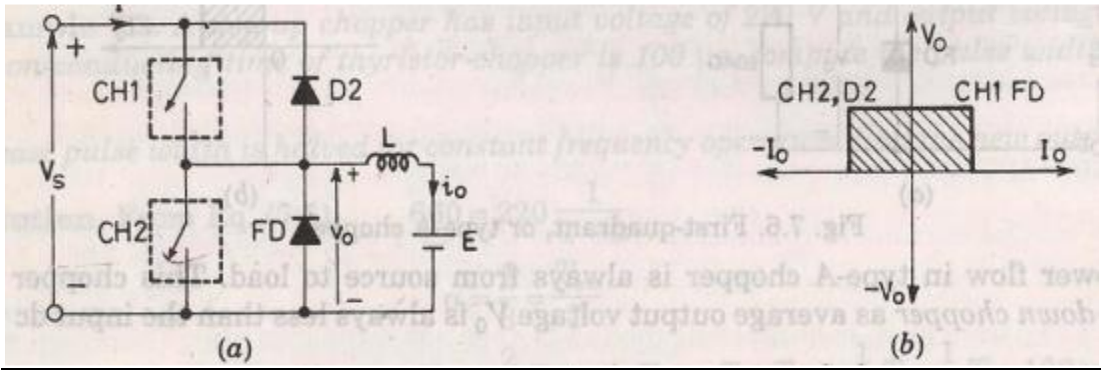


Fig.23. Two Quadrant TYPE- A chopper or TYPE- C chopper

- When chopper CH2 is on, or freewheeling diode FD conducts, output voltage Vo=0 and In case chopper CH1is on or diode D2 conducts, output voltage Vo=Vs

16. TWO QUADRANT TYPE-B CHOPPER or TYPE-D CHOPPER

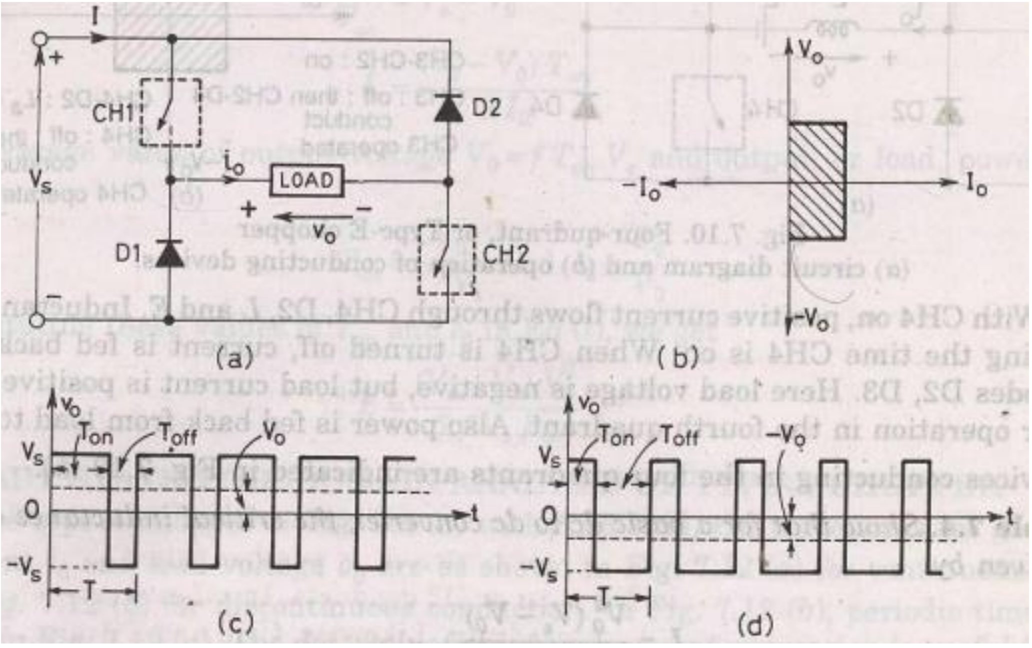


Fig .24.Two quadrant chopper

- CH1 and FD operate together as type-A chopper in first quadrant. Likewise,CH2 and D2 operate together as type-B chopper in the second quadrant
- The output voltage Vo=Vs when both CH1 and CH2 are on and Vo= - Vs when both choppers are off but both diodes D1 andD2 conduct.
- As Vo is reversible, power flow is reversible. The operation of this type of chopper is shown by the hatched area in the first and fourth quadrants.

17. FOUR QUADRANT CHOPPER or TYPE – E CHOPPER

- It consists of four semi conductor switches CH1 to CH4 and four diodes D1 to D4 in anti parallel

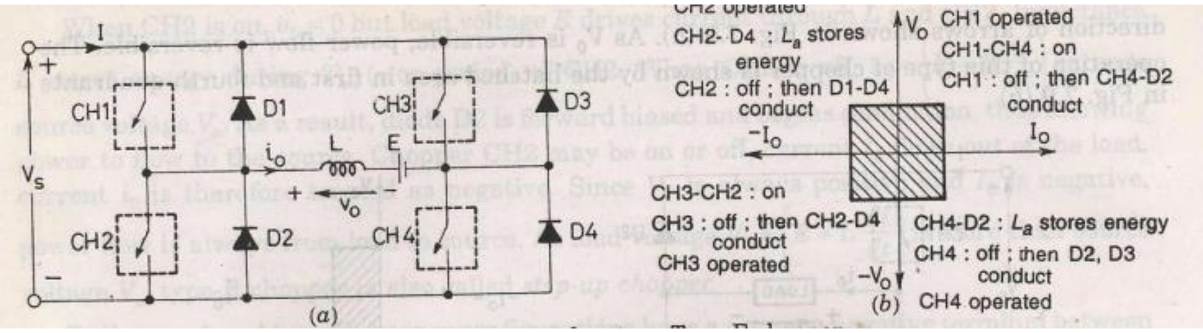


Fig.25. Four quadrant Chopper

FIRST QUADRANT

- For first quadrant CH4 is kept on, CH3 is kept off and CH1 is operated.
- With CH1, CH4 on, load voltage VO=Vs and the load current begins to flow. Here both Vo and Io are positive giving first quadrant operation, when CH1 is turned off, positive current freewheels through CH4 and D2.
- In this manner we can control both Vo and Io in the first quadrant.

SECOND QUADRANT

- Here CH2 is operated and CH1, CH3, CH4 are kept off. With CH2 on, reverse current flows through L, CH2, D4 and E.
- Inductance L stores energy during the time CH2 is on, when CH2 is turned off; current is fed back to source through diodes D1, D4.
- In this manner we can control both Vo and Io in the second quadrant.

THIRD QUADRANT

- For third quadrant operation, CH1 is kept off, CH2 is kept on and CH3 is operated.
- Polarity of the load Emf E must be reversed for this quadrant working.
- With CH3 on, load gets connected source so that both Vo, Io are negative leading to third quadrant operation.
- When CH3 is turned off, negative current freewheels through CH2,D4
- In this manner Vo, Io can be controlled in the third quadrant.

FOURTH QUADRANT

- Here CH4 is operated and other devices are kept off. Load Emf E must have its polarity reversed for operation in four quadrant

- With CH4 on, the positive current flows through CH4, D2, L and E. Inductance L stores energy during the time CH4 is on. When CH4 is turned off, current is fed back to source through diodes D2, D3.
- Here load voltage is negative, but load current is positive leading to the chopper operation in the fourth quadrant.
- Also power fed back from load to source.

18. CONTROL STRATEGIES

- The average value of output voltage Vo can be controlled through α by opening and closing the semiconductor switch periodically.
- The various control strategies for varying duty cycle "α" are
    1. Constant frequency system.
    2. Variable frequency system.

Constant frequency system

- In this scheme; on-time Ton is varied but chopping frequency "F "is kept constant.
- Variation of Ton means the adjustment of pulse width as such as this scheme is also called a pulse width modulation scheme.
- This scheme is also referred to as time ratio control**.**

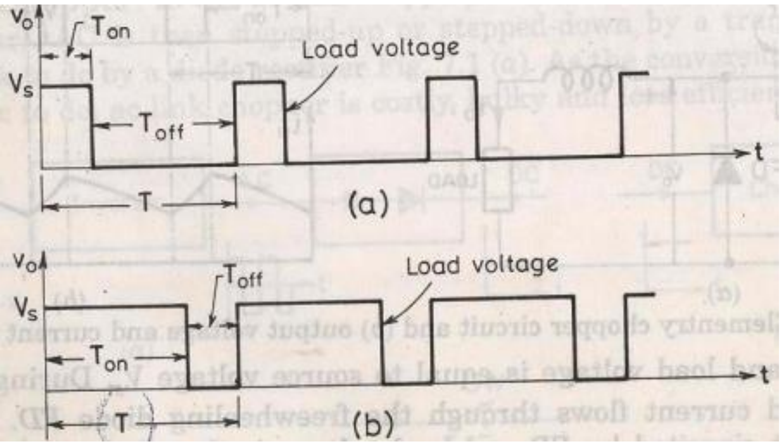


Fig.26. Pulse width modulated scheme

Here the chopping period "T" is constant.

T_{on} = ¼ T so that the value of α = 0. 25 or 25%

T_{on} = ¾ T so that the value of α = 0.75 or 75%.

Ideally, the value of α can be varied from zero to infinity. Therefore the output voltage Vo can be varied between zero and source voltage Vs.

Variable frequency system

In this scheme; the chopping frequency F varied and either on time Ton is kept constant or off time T_{off} is kept constant. The method of controlling "α "is called as frequency modulation scheme.

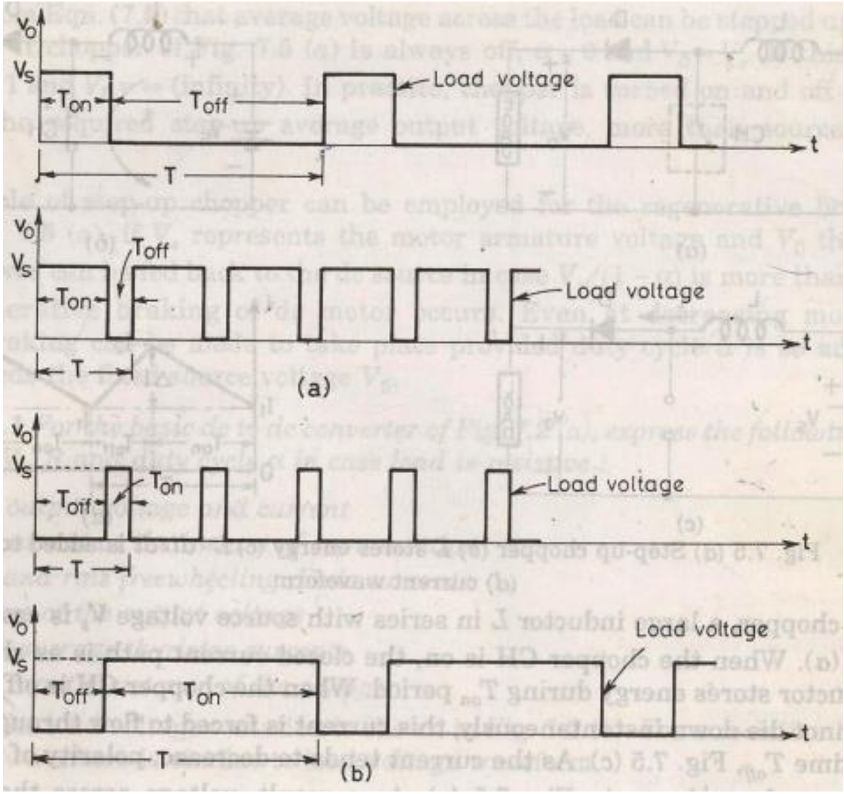


Fig.27. Principle of frequency modulation. (a) On time T_{on} constant and (b) off time T_{off} constant

- The diagram illustrates the principle of frequency modulation.
- T_{on} is kept constant but T is varied , $T_{on} = 1/4$ so that α= 0.25, if $T_{on} = 3/4$; α=0.75
- T_{off} is kept constant; T is varied Ton=1/4T; α=0.25; $T_{on} = 3/4T$ so that α=0.75.

It is seen from the above constant frequency scheme which is better than the variable frequency scheme. PWM technique has a limitation. In this technique Ton cannot be reduced near to zero for most of the Communication circuits used in choppers. However, this can be achieved by increasing the chopping period.

Multiple Choice Questions

1 Inverters converts
a) DC power to DC power
b) DC power to AC power
c) AC power to AC power

d) AC power to DC power

Answer: b

2 In a VSI (Voltage source inverter)
a) The internal impedance of the DC source is negligible
b) The internal impedance of the DC source is very high
c) The internal impedance of the AC source is negligible
d) The IGBTs are fired at 0 degrees.
Answer: a

3 The output current wave of a single-phase full bridge inverter on RL load is

a) A sine wave

b) A square wave

c) A triangular wave

d) Constant DC

Answer: c

4 Choppers converter is

a) AC to DC

b) DC to AC

c) DC to DC

d) AC to AC

Answer: c

5 What is the duty cycle of a chopper?

a) Ton/Toff

b) Ton/T

c) T/Ton

d) Toff x Ton

Answer b

6 In constant frequency TRC or pulse width modulation scheme, _________ is varied.

a) Vs

b) Ton

c) T

d) f

Answer: b

7 In current source inverters (CSIs), the output voltage’s

a) Amplitude depends upon the load impedance

b) Waveform depends upon the load impedance

c) Amplitude as well as the nature of the waveform depends on the load

d) Both amplitude and waveform are independent of the load impedance

Answer: c

8 In voltage source inverters (VSIs), the amplitude of the output voltage is

a) Independent of the load

b) Dependent on the load

c) Dependent only on L loads

d) None of the mentioned

Answer: a

9 In the ____________ type of chopper, two stage conversions take place.

a) AC-DC

b) AC link

c) DC link

d) None of the mentioned

Answer b

10 The values of duty cycle (α) lies between

a) $0 < \alpha < 1$

b) $0 > \alpha > -1$

c) $0 <= \alpha <= 1$

d) $1 < \alpha < 100$

Answer a

16. A chopper is a

a) Time ratio controller

b) AC to DC converter

c) DC transformer

d) High speed semiconductor switch

Answer: d

ASSIGNMENT

1. Enumerate the working principle of single pulse width modulation PWM inverter and multiple pulse width modulation PWM inverters with suitable diagrams.
2. Explain the four quadrant operation of using class-E chopper with aid of diagrams and waveforms.

DC DRIVES

UNIT IV - DC DRIVES

Advantages, types & selection of electrical drives, Methods of speed control of DC motors – Armature control & Field control – Ward Leonard drives –Converter fed & Chopper fed DC drives - Two quadrant & Four quadrant chopper drives.

1. DRIVE CHARACTERISTICS

Electrical Drives:

Motion control is required in large number of industrial and domestic applications like transportation systems, rolling mills, paper machines, textile mills, machine tools, fans, pumps, robots, washing machines etc.

Systems employed for motion control are called DRIVES, and may employ any of prime movers such as diesel or petrol engines, gas or steam turbines, steam engines, hydraulic motors and electric motors, for supplying mechanical energy for motion control. Drives employing electric motors are known as ELECTRICAL DRIVES.

An ELECTRIC DRIVE can be defined as an electromechanical device for converting electrical energy into mechanical energy to impart motion to different machines and mechanisms for various kinds of process control.

2. Classification of Electric Drives

According to Mode of Operation

- Continuous duty drives
- Short time duty drives
- Intermittent duty drives

According to Means of Control

- Manual
- Semi automatic
- Automatic

According to Number of machines

- Individual drive
- Group drive
- Multi-motor drive

According to Dynamics and Transients

- Uncontrolled transient period
- Controlled transient period

According to Methods of Speed Control

- Reversible and non-reversible uncontrolled constant speed.
- Reversible and non-reversible step speed control.
- Variable position control.
- Reversible and non-reversible smooth speed control.

3. Advantages of Electrical Drive

1. They have flexible control characteristics. The steady state and dynamic characteristics of electric drives can be shaped to satisfy the load requirements.
2. Drives can be provided with automatic fault detection systems. Programmable logic controller and computers can be employed to automatically control the drive operations in a desired sequence.
3. They are available in wide range of torque, speed and power.
4. They are adaptable to almost any operating conditions such as explosive and radioactive environments
5. It can operate in all the four quadrants of speed-torque plane
6. They can be started instantly and can immediately be fully loaded
7. Control gear requirement for speed control, starting and braking is usually simple and easy to operate.

4. Choice (or) Selection of Electrical Drives

Choice of an electric drive depends on a number of factors. Some of the important factors are.

1. Steady State Operating conditions requirements

   Nature of speed torque characteristics, speed regulation, speed range, efficiency, duty cycle, quadrants of operation, speed fluctuations if any, ratings etc

2. Transient operation requirements

   Values of acceleration and deceleration, starting, braking and reversing performance.

3. Requirements related to the source

   Types of source and its capacity, magnitude of voltage, voltage fluctuations, power factor, harmonics and their effect on other loads, ability to accept regenerative power

4. Capital and running cost, maintenance needs life.
5. Space and weight restriction if any.
6. Environment and location.
7. Reliability.

5. Group Electric Drive

This drive consists of a single motor, which drives one or more line shafts supported on bearings. The line shaft may be fitted with either pulleys and belts or gears, by means of which a group of machines or mechanisms may be operated. It is also some times called as SHAFT DRIVES.

Advantages

A single large motor can be used instead of number of small motors

Disadvantages

There is no flexibility. If the single motor used develops fault, the whole process will be stopped.

6. Individual Electric Drive

In this drive each individual machine is driven by a separate motor. This motor also imparts motion to various parts of the machine.

7. Multi Motor Electric Drive

In this drive system, there are several drives, each of which serves to actuate one of the working parts of the drive mechanisms.

E.g.: Complicated metal cutting machine tools

Paper making industries, Rolling machines etc.

8. General Electric Drive System

Block diagram of an electric drive system is shown in the figure below.

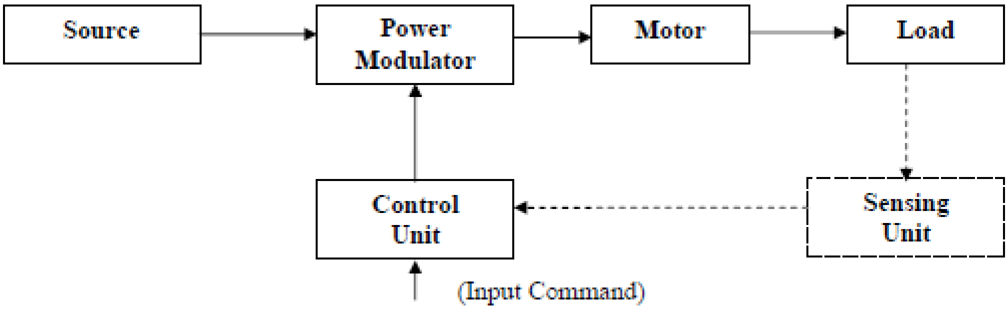


Fig.1. Block diagram of an electric drive system

A modern variable speed electrical drive system has the following components

Electrical machines and loads

Power Modulator

Sources

Control unit

Sensing unit

Electrical Machines

Most commonly used electrical machines for speed control applications are the following

DC Machines

Shunt, series, compound, separately excited DC motors and switched reluctance machines.

AC Machines

Induction, wound rotor, synchronous, PM synchronous and synchronous reluctance machines.

Special Machines

Brush less DC motors, stepper motors, switched reluctance motors are used.

Power Modulators

Functions:

- Modulates flow of power from the source to the motor in such a manner that motor is imparted speed-torque characteristics required by the load
- During transient operation, such as starting, braking and speed reversal, it restricts source and motor currents with in permissible limits.
- It converts electrical energy of the source in the form of suitable to the motor
- Selects the mode of operation of the motor (i.e.) Motoring and Braking.

Types of Power Modulators

In the electric drive system, the power modulators can be any one of the following

- Controlled rectifiers (ac to dc converters)
- Inverters (dc to ac converters)
- AC voltage controllers (AC to AC converters)
- DC choppers (DC to DC converters)
- Cyclo converters (Frequency conversion)

Electrical Sources

Very low power drives are generally fed from single phase sources. Rest of the drives is powered from a 3 phase source. Low and medium power motors are fed from a 400v supply. For higher ratings, motors may be rated at 3.3KV, 6.6KV and 11 KV. Some drives are powered from battery.

Sensing Unit (From Motor)

- Speed Sensing
- Torque Sensing
- Position Sensing
- Current sensing and Voltage Sensing from Lines or from motor terminals

From Load

- Torque sensing
- Temperature Sensing

Control Unit

Control unit for a power modulator are provided in the control unit. It matches the motor and power converter to meet the load requirements.

9. Classification of Electrical Drives

Another main classification of electric drive is

DC drive

AC drive

Comparison between DC and AC drives

DC DRIVES	AC DRIVES
The power circuit and control circuit is simple and inexpensive	The power circuit and control circuit are complex
It requires frequent maintenance	Less Maintenance
The commutator makes the motor bulky, costly and heavy	These problems are not there in these motors and are inexpensive, particularly squirrel cage induction motors
Fast response and wide speed range of control, can be achieved smoothly by conventional and solid state control	In solid state control the speed range is wide and conventional method is stepped and limited
Speed and design ratings are limited due to commutations	Speed and design ratings have upper limits

10. Applications

- Paper mills
- Cement Mills
- Textile mills
- Sugar Mills
- Steel Mills
- Electric Traction
- Petrochemical Industries
- Electrical Vehicles

11. Braking

Basically, there are three types of electrical braking done in a DC Motor:-

1. Regenerative Braking
2. Dynamic Braking
3. Plugging

1. Regenerative Braking

It is a form of braking in which the kinetic energy of the motor is returned to the power supply system. This type of braking is possible when the driven load forces the motor to run at a speed higher than its no-load speed with a constant excitation. The motor back emf Eb is greater than the supply voltage V, which reverses the direction of the motor armature current. The motor begins to operate as an electric generator. It is very interesting to note that regenerative braking cannot be used to stop a motor but to control its speed above the no-load speed of the motor driving the descending loads.

2. Dynamic Braking

It is also known as Rheostatic braking. In this type of braking, the DC motor is disconnected from the supply and a braking resistor Rb is immediately connected across the armature. The motor will now work as a generator, and produces the braking torque. During electric braking when the motor works as a generator, the kinetic energy stored in the rotating parts of the motor and a connected load is converted into electrical energy. It is dissipated as heat in the braking resistance Rband armature circuit resistance Ra. Dynamic Braking is an inefficient method of braking as all the generated energy is dissipated as heat in resistances.

3. Plugging

It is also known as reverse current braking. The armature terminals or supply polarity of a separately excited DC motor or shunt DC motor when running are reversed. Therefore, the supply voltage V and the induced voltage Eb i.e. back emf will act in the same direction. The effective voltage across the armature will be V + Eb which is almost twice the supply voltage. Thus, the armature current is reversed and a high braking torque is produced. Plugging is a highly inefficient method of braking because, in addition to the power supplied by the load, power supplied by the source is wasted in resistances. It is used in elevators, printing press etc. These were the main three types of braking techniques preferred to stop a DC motor and used widely in industrial applications.

12. SPEED CONTROL OF D.C. MOTORS:

In the case of speed control, armature voltage control and flux control methods are available. The voltage control can be from a variable voltage source like Ward Leonard arrangement or by the use of series armature resistance.

12.1. Speed control of shunt motor

We know that the speed of shunt motor is given by:

$$n = \frac{V_a - I_a r_a}{k\phi}$$

Where, Va is the voltage applied across the armature and ö is the flux per pole and is proportional to the field current If. As explained earlier, armature current Ia is decided by the mechanical load present on the shaft. Therefore, by varying Va and If we can vary n. For fixed supply voltage and the motor connected as shunt we can vary Va by controlling an external resistance connected in series with the armature. If of course can be varied by controlling external field resistance Rf connected with the field circuit. Thus for shunt motor we have essentially two methods for controlling speed, namely by:

1. Varying armature resistance.
2. Varying field resistance.

1. Speed control by varying armature resistance

The inherent armature resistance ra being small, speed n versus armature current Ia characteristic will be a straight line with a small negative slope as shown in figure. In the discussion to follow we shall not disturb the field current from its rated value. At no load (i.e., Ia = 0) speed is highest and

$$n_0 = \frac{V_a}{k\phi} = \frac{V}{k\phi}$$

Note that for shunt motor voltage applied to the field and armature circuit are same and equal to the supply voltage V. However, as the motor is loaded, IaRa drop increases making speed a little less than the no load speed n0. For a well-designed shunt motor this drop in speed is small and about 3 to 5% with respect to no load speed. This drop in speed from no load to full load condition expressed as a percentage of no load speed is called the inherent speed regulation of the motor.

$$\text{Inherent \% speed regulation} = \frac{n - n_0}{n_0} \times 100$$

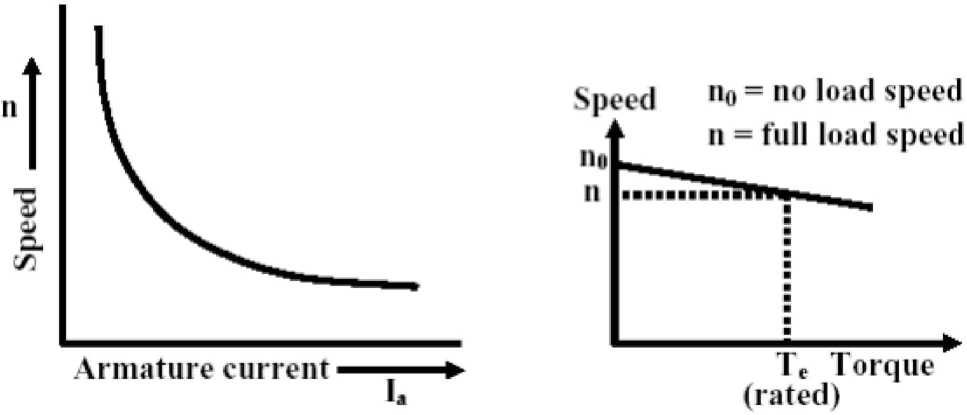


Fig 2.

Speed vs. armature current characteristic.

Speed vs. torque characteristic.

It is for this reason, a d.c shunt motor is said to be practically a constant speed motor (with no external armature resistance connected) since speed drops by a small amount from no load to full load condition.

Since $T_e = k\phi I_a$, for constant flux ϕ, operation, Te becomes simply proportional to Ia. Therefore, speed vs. torque characteristic is also similar to speed vs. armature current characteristic as shown in figure.

The slope of the n vs Ia or n vs Te characteristic can be modified by deliberately connecting external resistance r_{ext} in the armature circuit. One can get a family of speed vs. armature curves as shown in figures for various values of r_{ext}. From these characteristics it can be explained how speed control is achieved. Let us assume that the load torque TL is constant and field current is also kept constant. Therefore, since steady state operation demands Te = TL, Te = a k I ö too will remain constant; which means Ia will not change. Suppose $r_{ex}1 = 0$, then at rated load torque, operating point will be at C and motor speed will be n. If additional resistance r_{ext1} is introduced in the armature circuit, new steady state operating speed will be n1 corresponding to the operating point D. In this way one can get a speed of n2 corresponding to the operating point E, when r_{ext} 2 is introduced in the armature circuit. This same load torque is supplied at various speeds. Variation of the speed is smooth and speed will decrease smoothly if r_{ext} is increased.

Obviously, this method is suitable for controlling speed below the base speed and for supplying constant rated load torque which ensures rated armature current always. Although, this method provides smooth wide range speed control (from base speed down to zero speed), has a serious draw back since energy loss takes place in the external resistance r_{ext} reducing the efficiency of the motor.

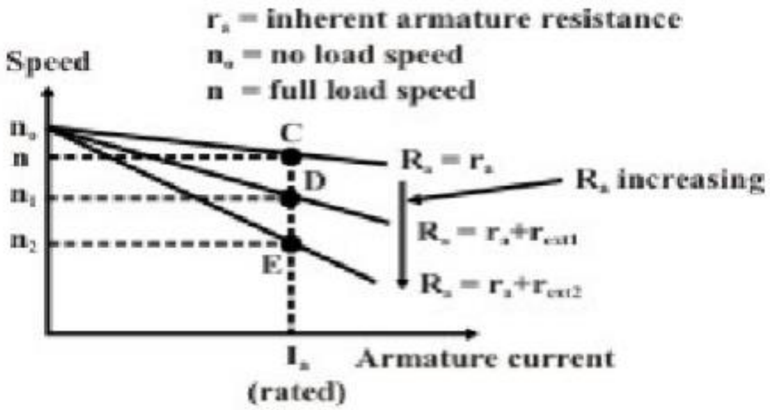


Fig. 3. Family of speed vs. armature current characteristic.

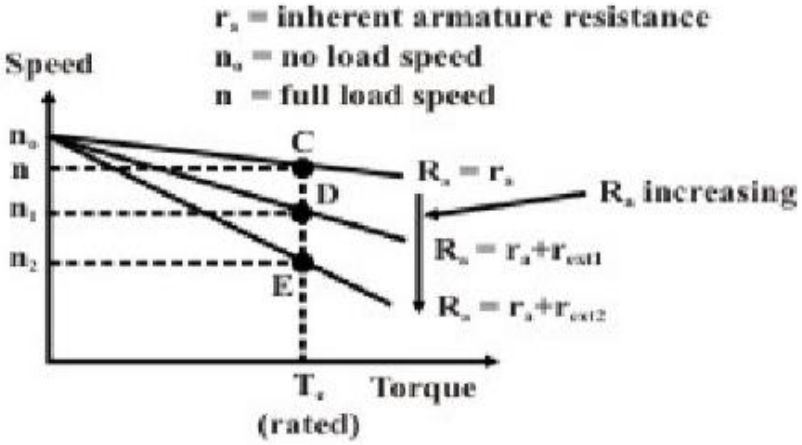


Fig 4. Family of speed vs. Torque current characteristic.

3. Speed control by varying field current

In this method field circuit resistance is varied to control the speed of a d.c shunt motor. Let us rewrite the basic equation to understand the method.

$$n = \frac{V - I_a r_a}{k\phi}$$

If we vary I_f, flux ϕ will change, hence speed will vary. To change If an external resistance is connected in series with the field windings. The field coil produces rated flux when no external resistance is connected and rated voltage is applied across field coil. It should be understood that we can only decrease flux from its rated value by adding external resistance. Thus the speed of the motor will rise as we decrease the field current and speed control above the base speed will be achieved.

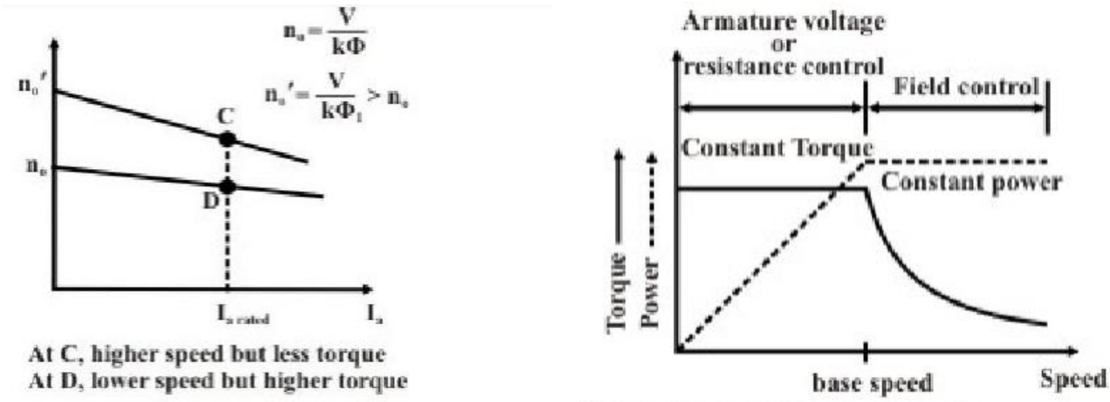
Speed versus armature current characteristic is shown in figure for two flux values ϕ and ϕ_1, Since $\phi_1 < \phi$, no load speed n'_o for flux value ϕ_1 is than the no load speed no corresponding to ϕ. However, this method will not be suitable for constant load torque. To make this point clear, let us assume that the load torque is constant at rated value. So from the initial steady condition, we have $T_{L\,rated} = T_{e1} = k\phi I_{a\,rated}$. If load torque remains constant and flux is reduced to ϕ_1, new armature current in the steady state is obtained from $k\phi_1 I_{a1} = T_{L\,rated}$.

Therefore new armature current is

$$I_{a1} = \frac{\phi}{\phi_1} I_{a\,rated}$$

But the fraction, $\frac{\phi}{\phi_1} > 1$; hence new armature current will be greater than the rated armature current and the motor will be overloaded. This method therefore, will be suitable for a load whose torque demand decreases with the rise in speed keeping the output power constant as shown in figure. Obviously this method is based on flux weakening of the main field.

Therefore at higher speed main flux may become so weakened, that armature reaction effect will be more pronounced causing problem in commutation.



Family of speed vs. armature current characteristic. Constant torque & power operation.

Fig.5. Characteristic curves

3. Speed control by armature voltage variation

In this method of speed control, armature is supplied from a separate variable d.c voltage source, while the field is separately excited with fixed rated voltage as shown in figure. Here the armature resistance and field current are not varied. Since the no load speed $n_0 = \frac{V_a}{k\phi}$, the speed versus Ia characteristic will shift parallel as shown in figure for different values of Va.

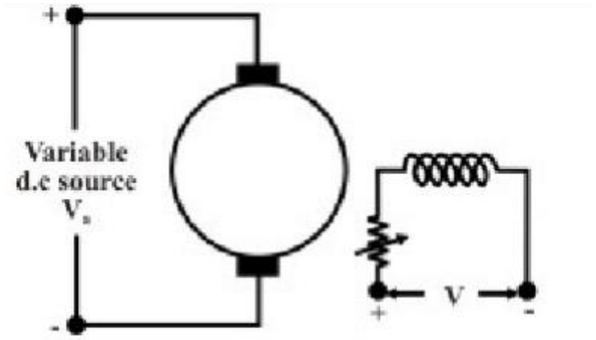


Fig.6. Speed control by controlling armature voltage.

As flux remains constant, this method is suitable for constant torque loads. In a way armature voltage control method is similar to that of armature resistance control method except that the former one is much superior as no extra power loss takes place in the armature circuit. Armature voltage control method is adopted for controlling speed from base speed down to very small speed, as one should not apply across the armature a voltage, which is higher than the rated voltage.

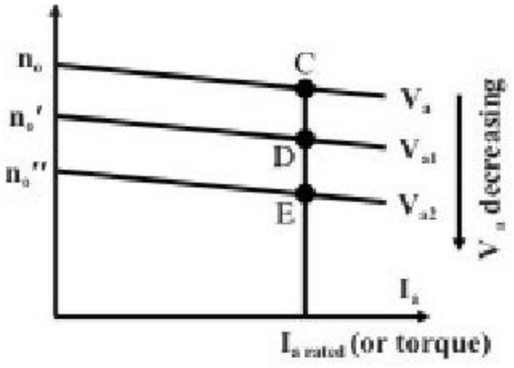


Fig.7. **Family of *n* VS. I_a characteristics.**

4. Ward Leonard method: combination of Va and If control

In this scheme, both field and armature control are integrated as shown in figure. Arrangement for field control is rather simple. One has to simply connect an appropriate rheostat in the field circuit for this purpose. However, in the pre power electronic era, obtaining a variable d.c supply was not easy and a separately excited d.c generator was used to supply the motor armature. Obviously to run this generator, a prime mover is required. A 3-phase induction motor is used as the prime mover which is supplied from a 3-phase supply. By controlling the field current of the generator, the generated emf,

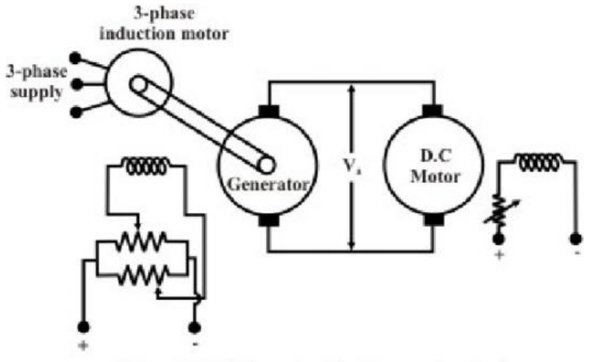
Ward Leonard control system is introduced by Henry Ward Leonard in 1891. Ward

Leonard method of speed control is used for controlling the basic armature control method. This control system is consisting of a dc motor M powered by a DC generator G. In this method the speed of the dc motor (M_1) is controlled by applying variable voltage across its armature. This variable voltage is obtained using a motor-generator set which consists of a motor M with the generator G. It is a very widely used method of speed of a DC motor

Principle of Ward Leonard Method

Basic connection diagram of the Ward Leonard speed control system is shown in the figure below.

The speed of motor M1 is to be controlled which is powered by the generator G. The shunt field of the motor M1 is connected across the DC supply lines. Now, generator G is driven by the motor M2. The speed of the motor M2 is constant. When the output voltage of the generator is fed to the motor M1 then the motor starts to rotate. When the output voltage of the generator varies then the speed of the motor also varies. Now controlling the output voltage of the generator the speed of motor can also be controlled. For this purpose of controlling the output voltage, a field regulator is connected across the generator with the dc supply lines to control the field excitation. The direction of rotation of the motor M1 can be reversed by excitation current of the generator and it can be done with the help of the reversing switch R.S. But the motor-generator set must run in the same direction.



Scheme for Ward Leonard method

Fig. 8. **Ward Leonard System**

Advantages of Ward Leonard System

1. It is a very smooth speed control system over a very wide range (from zero to normal speed of the motor).
2. The speed can be controlled in both the direction of rotation of the motor easily.
3. The motor can run with a uniform acceleration.
4. Speed regulation of DC motor in this ward Leonard system is very good.
5. It has inherent regenerative braking property.

Disadvantages of Ward Leonard System

1. The system is very costly because two extra machines (motor-generator set) are required.
2. Overall efficiency of the system is not sufficient especially if it is lightly loaded.
3. Larger size and weight.
4. Requires more floor area.
5. Frequent maintenance.
6. The drive produces more noise.

Application of Ward Leonard System

This Ward Leonard method of speed control system is used where a very wide and very sensitive speed control is of a DC motor in both the direction of rotation is required. This speed control system is mainly used in colliery winders, cranes, electric excavators, mine hoists, elevators, steel rolling mills, paper machines, diesel-locomotives, etc.

12.2. Speed Control of DC Series Motor

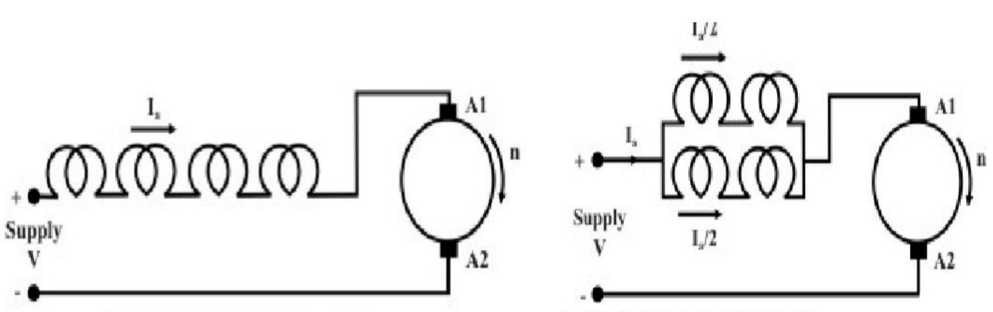
Speed control of DC series motor can be done either by armature control or by field control.

Armature Control of DC Series Motor

Speed adjustment of DC series motor by armature control may be done by any one of the methods that follow,

1. Armature resistance control method: This is the most common method employed. Here the controlling resistance is connected directly in series with the supply of the motor.

2. The power loss in the control resistance of DC series motor can be neglected because this control method is utilized for a large portion of time for reducing the speed under light load condition.



coils in series

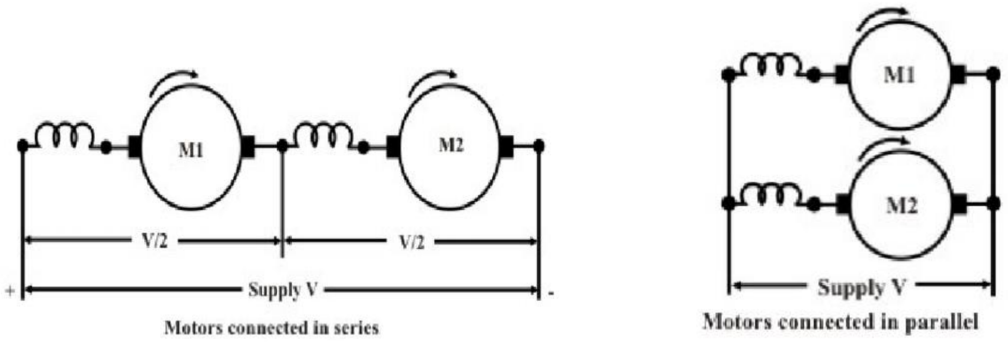
Series-parallel connection of coils.

Fig. 9.Coil arrangement with series motor

This method of speed control is most economical for constant torque. This method of speed control is employed for DC series motor driving cranes, hoists, trains etc.

3. Shunted armature control: The combination of a rheostat shunting the armature and a rheostat in series with the armature is involved in this method of speed control. The voltage applied to the armature is varies by varying series rheostat R 1. The exciting current can be varied by varying the armature shunting resistance R2. This method of speed control is not economical due to considerable power losses in speed controlling resistances. Here speed control is obtained over wide range but below normal speed.

4. Armature terminal voltage control: The speed control of DC series motor can be accomplished by supplying the power to the motor from a separate variable voltage supply. This method involves high cost so it rarely used.



Motors connected in series

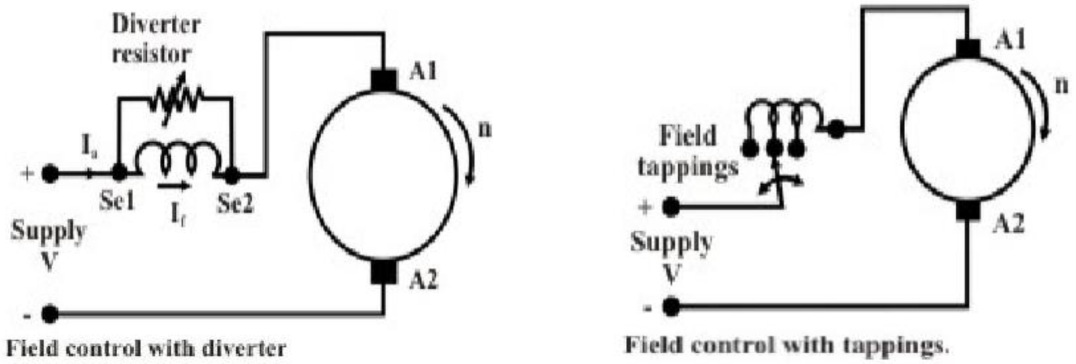
Motors connected in parallel

Fig. 10. Motors in series and parallel

Field Control of DC Series Motor

The speed of DC motor can be controlled by this method by any one of the following ways –

1. Field Diverter Method. This method uses a diverter. Here the field flux can be reduced by shunting a portion of motor current around the series field. Lesser the diverter resistance less is the field current, less flux therefore more speed. This method gives speed above normal and the method is used in electric drives in which speed should rise sharply as soon as load is decreased diagram



Field control with diverter

Field control with tappings.

Fig. 11. Field control of seies motor

2. Tapped Field Control. This is another method of increasing the speed by reducing the flux and it is done by lowering number of turns of field winding through which current flows. In this method a

number of tapping from field winding are brought outside. This method is employed in electric traction.

13. Single phase Controlled rectifier fed DC drives:

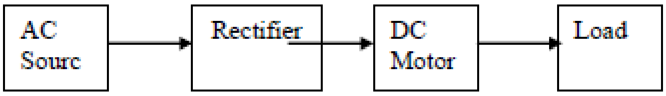


Fig 12. Rectifier /Converter fed DC drive

Half wave controlled rectifiers

- In the single phase half controlled rectifier, the load resister, RL is connected in series with anode A.
- A variable resistance r is inserted in the gate circuit for controlling gate current. During the negative half cycles of the input ac voltage .
- The SCR does not conduct regardless of the gate voltage, because anode is negative with respect to cathode K.
- The SCR will conduct during the positive half cycles provided appropriate gate current is made to flow .the gate current can be varied with the help of variable resistance r inserted in the gate circuit for this purpose .the greater the gate current, the lesser will be the supply voltage at which SCR will start conducting.

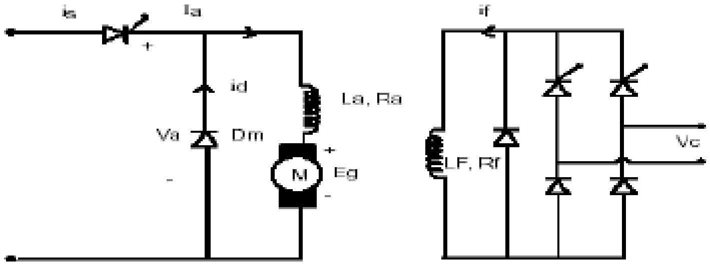


Fig. 13. Half wave controlled rectifiers fed DC drive

- Assume that the gate current is such that SCR starts conducting at a positive voltage V, being less than peak value of input ac voltage Vmax, it is clear that the SCR starts conducting, as soon as input ac voltage becomes equal to V volts in the positive half cycle, and will continue conducting till ac voltage becomes zero when it will turn-off, again in next positive half cycle, SCR will start conducting when input ac voltage becomes equal to V volts.
- The angle by which the SCR starts conducting is called as firing angle or delay angle the conduction will take place for(π - α) radians.
- The thyristor circuit uses phase commutation.
- The average output voltage (VL) from a half-wave controlled rectifier for the given input ac voltage V=Vmaxsin wt

$$V_L = \frac{V_{\max}}{\Pi} \cos^2 \frac{\alpha}{2}$$

Average output current

$$I_L = \frac{V_L}{R_L} = \frac{V_{\max}}{\Pi R_L} \cos^2 \frac{\alpha}{2}$$

Thus the desired value of load current IL can be obtained by varying firing angle α

$$I_L = \frac{V_{\max}}{\Pi R_L} when \alpha = 0$$

$$I_L = \frac{V_{\max}}{2\Pi R_L} when \alpha = \frac{\Pi}{2}$$

Hence, load current decreases with the increase in value of firing angle α. So the terminal voltage decreases the motor run slowly and vice versa.

With Freewheeling diode

- Let RL load is connected with the single-phase half controlled rectifier .Due to the inductive nature of the load, the load current lags by an angle ⍰ with respect to the voltage.
- During voltage reversal, the voltage reaches zero but due to the inductive nature of the load, the current still flow through the thyristor.
- It takes some time for the current to reach zero. so during that instant ,a negative voltage will be appearing across the inductive load and the freewheeling diode connected in parallel with the load is turned on, as the diode is turned on, the load voltage becomes the diode forward drop.
- It is otherwise called commutating diode. This diode is connected anti parallel with load .this diode comes into picture only when the load is inductive.
- In case of inductive load even though the input voltage reaches zero and becomes negative, the current is still flowing through the thyristor, so it remains on when the voltage across the load becomes negative.
- The freewheeling diode is turned on when the load voltage is negative.
- So, the voltage across the load becomes zero and it provides a path for the load current. During this interval, the energy stored in the inductor is dissipated through this diode
- This freewheeling diode prevents the negative the negative reversal of voltage across the load.
- It improves the input power factor.
- It improves the load current wave from thereby it improves the performance parameters.

Full controlled rectifier

- The full wave half controlled rectifier circuit consists of two thyristors and two diodes.
- The gates of both thyristors are supplied from two gate control supply circuits.
- One thyristors (or SCR) conducts during the positive half cycles and the other during the negative half cycles and thus unidirectional current flows through the load circuit.

Now, if the supply voltage v =Vmaxsin □ t and firing angle is □ ,then average output voltage is given by

$$\mathrm{V}_L = \frac{1}{\Pi}\int_{\alpha}^{\Pi} V_{\max}\sin\omega t\, d(\omega t)$$

$$V_L = \frac{V_{\max}}{\Pi}(1+\cos\alpha)$$

$$= \frac{2V_{\max}}{\Pi}\cos^2\frac{\alpha}{2}$$

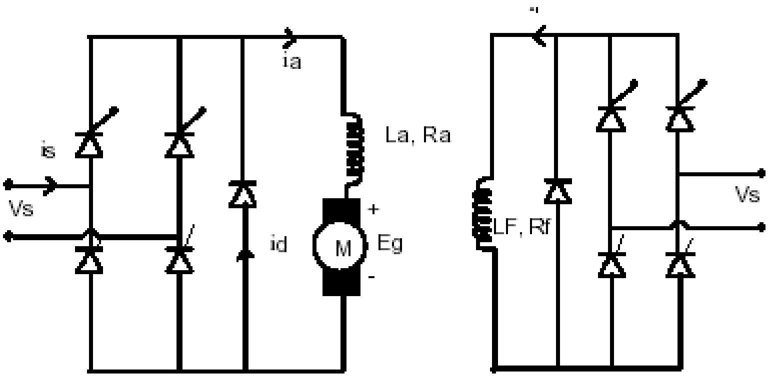


Fig. 14. Fully controlled rectifier fed DC drive

Average output current,

$$I_L = \frac{V_L}{R_L} = \frac{2V_{\max}}{\Pi R_L}\cos^2\frac{\alpha}{2}$$

Advantages:

- Basic operation is simple and reliable
- Time response is faster
- Small size
- Less weight

Disadvantages:

- Introduce current and voltage harmonics into supply systems
- The overload capacity is lower

- Due to switching of SCR distortion of the AC supply voltage and telephone interference may be produced.

14. DC Chopper fed DC Drives

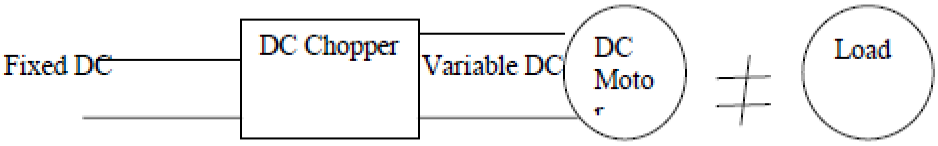


Fig. 15. Block diagram of Chopper fed DC drive

A Chopper converts fixed DC voltage into variable DC voltage. Chopper circuit can be interfaced between fixed DC voltage source and DC motor armature circuit. By varying the duty cycle (δ) of the DC chopper, variable voltage can be applied to the armature terminals of the DC motor to obtain the speed control below the speed. Chopper circuit is adoptable for regenerative braking of DC motor and kinetic energy can be returned to the DC source. Choppers can be used for dynamic braking also.

The following controlled modes are explained in detail.

1. Power control or motoring control.
2. Regenerative –braking control.

Chopper Controlled Separately Excited DC motor

If the source of supply is D.C. (for example in a battery vehicle or a rapid transit system) a chopper-type converter is usually employed. The chopper-fed motor is, if anything, rather better than the phase-controlled, because the armature current ripple can be less if a high chopping frequency is used.

Motoring Mode of Operation

The Fig shows the circuit for motoring control of Chopper fed DC motor which is the first quadrant operation. By modifying chopper circuit configuration all four quadrant operation of DC motor drive is possible. Chopper fed DC drives are widely employed in traction systems.

A transistor is used to chop the DC input voltage into pieces and chopped DC voltage is given to the motor as shown in the fig. Current limit control is used in chopper. In current limit control, the load current is allowed to vary between two given limits (i.e. Upper and lower limits). The ON and OFF times of the transistor is adjusted automatically, when the current increases beyond the upper limit the chopper is turned off, the load current free wheels and starts to decrease. When the current falls below the lower limit, the chopper is turned ON. The current starts increasing if the load. The load current and voltage waveforms are shown in the fig. By assuming proper limits of current, the amplitude of ripple can be controlled.

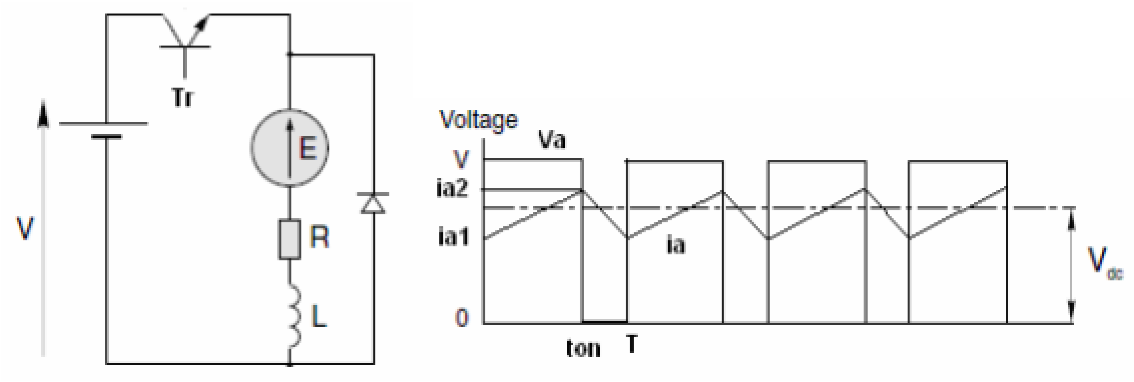


Fig. 16. Motoring control of Chopper fed DC motor

The lower the current ripple, the higher the chopper frequency. By this switching losses increase. Discontinuous conduction avoid in this case. The current limit control is superior one.

Duty Interval

During the ON period of the chopper (i.e) duty interval 0 <t<t_{ON}, motor terminal voltage Va is a source voltage V and armature current increases from ia1 to ia2. The operation is described by,

$$R_a I_a + L_a \frac{di_a}{dt} + E = V \quad 0 \leq t \leq t_{ON}$$

In this interval the armature current increases from Ia1 to Ia2 since the motor is connected to the source during this interval, it is called as duty cycle.

Free Wheeling Interval

Chopper Tr is turned off at t=t_{ON}. Motor current free wheels through the diode D and the motor terminal voltage is zero. During interval $t_{ON} \leq t \leq T$. Motor operation during this interval is known as free wheeling interval and is described by

$$R_a I_a + L_a \frac{di_a}{dt} + E = 0 \quad t_{ON} \leq t \leq T$$

During this interval current decreases from ia2 to ia1

Duty cycle (or) Duty Ratio:

Duty cycle is defined as the ratio of duty interval t_{ON} to chopper period T is called Duty cycle (or) Duty Ratio.

$$\delta = \frac{Duty\ Interval}{Chopper\ Period} = \frac{t_{ON}}{T}$$

Then the speed of the chopper drive can be obtained as

$$\omega_m = \frac{\delta V}{K} - \frac{R_a}{K^2\phi} \mathrm{T}$$

The torque speed characteristics of chopper fed separately excited DC motor is shown in the fig.17

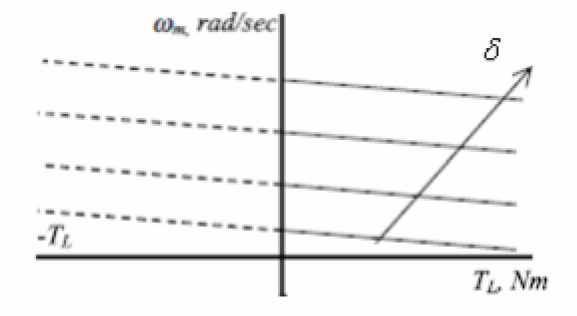


Fig. 17. Torque vs speed characteristics

Regenerative Braking Mode

Regenerative braking operation by chopper is shown in the fig. Regenerative braking of a separately excited motor is fairly simple and can be carried out down to very low speeds.

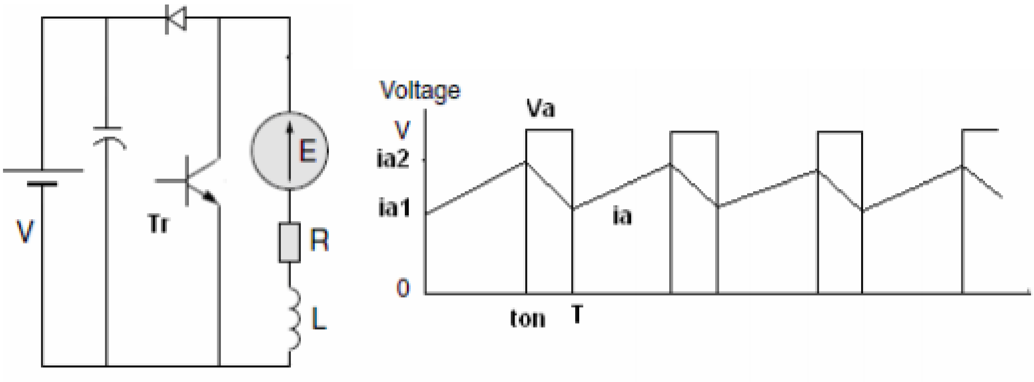


Fig. 18. Regenerative braking by chopper

Mechanical energy is converted into electrical energy by the motor and motor now working as a generator, increases the stored magnetic energy in the armature circuit. When chopper is switched off, a large voltage appears across the motor terminals this voltage is more than that of the supply voltage V and the energy stored in the inductance and energy supplied by the machine is fed back to the supply system. When the voltage of the motor fall to V, the diodes in the line blocks the current flow preventing any short circuit of the load can be supplied to the source. Very effective braking of motor is possible up to extreme small speeds.

Four Quadrant operation of DC Drive (or)

TYPE – E Four Quadrant chopper Fed Drive:

Operation

The armature current Ia is either positive or negative (flow in to or away from armature) the armature voltage Va is also either positive or negative. This is known as four quadrant chopper drive. Two type – C choppers can be combined to form a class – E chopper as shown in fig.

First Quadrant – Forward motoring mode

For first quadrant operation, thyristor S4 is kept on, thyristor S3 is kept off and thyristor switch S1 is operated. With S1, S4 ON, armature voltage Va = Vs and armature control Ia begins flow. Here both Va and Ia are positive giving first quadrant operation, when S1 is turned off, positive current freewheels through S4, D2. In this manner, Va, Ia can be controlled in this first quadrant, and operation gives forward motoring mode.

Second Quadrant – Forward braking mode

Here thyristor S2 is operated and S1 , S3 and S4 are kept off. With S4 on, reverse or negative current flows through La, S2, D4 and Eb. During the operation time of S2, the armature inductance ‘La’ stores energy during the time S2 is on. When S2 is turned off, current is fed back to source through diodes D1 , D4 . Note that here (E+L(di/dt)) is more than the source voltage Vs .As the Vs is positive and Ia is negative, it is a second quadrant operation gives forward braking mode. In that power is fed back from armature to source.

Third Quadrant – Reverse motoring mode

For third quadrant operation, thyristor S1 is kept off, S2 is kept on and S3 is operated, polarity of armature back emf Eb must be reversed for this quadrant operation. With thyristor S3 is on, armature gets connected to source V. so that both Va , Ia are negative, leading to third quadrant operation. When S3 is turned off, negative current free wheels through S2,D4. In this manner only Va and Ia can be controlled in the third quadrant.

Fourth Quadrant – Reverse Braking mode

Here thyristor S4 is operated and other devices kept off, back emf Eb must have its polarity reversed as in third quadrant operation. With S4 on, positive current flows through S4, D2, La and Eb (armature). Armature inductance La stores energy during the time S4 is on. When S4 is turned off, current is fed back to source through diodes D2, D3.Here armature voltage Va is negative, but Ia is positive, leading to the chopper drive operation in the fourth quadrant. Also power is fed back from armature to source. These four quadrant operations are clearly depicted in fig

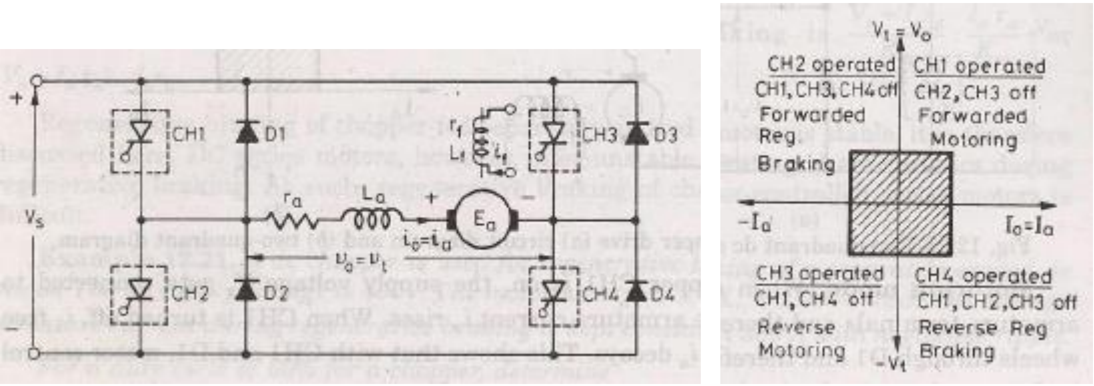


Fig. 19. Four Quadrant chopper Fed Drive

Multiple Choice Questions

1 The generating action and motoring action in d.c. motor is determined by

a. Fleming's left hand rule, Fleming's right hand rule

b. Both by Fleming's left hand rule

c. Both by Fleming's right hand rule

d. Fleming's right hand rule, Fleming's left hand rule
Answer d

2 To get the speed of DC motor below the normal speed without wastage of electrical energy we use ___________________

a) Ward Leonard control

b) Rheostatic control

c) Any of the Ward Leonard or rheostatic method can be used

d) Not possible

Answer: a

3 The consideration involved in the selection of the type of electric drive for a particular application depends upon

a)Speed control range and its nature

b) Starting Nature

c) Environmental condition

d) All of the above

Answer.4

4 For an application which requires smooth and precise speed control over the wide range, the motor is preferred is
a) Squirrel cage Induction Motor

b) Synchronous Motor

c) DC motor

d) Wound Rotor Induction Motor

Answer c

5 As the load on a dc shunt motor is increased, its speed

a) Increases proportionately

b) Remains constant

c) Increases slightly

d) Reduces slightly

Answer d

6 D.C. shunt motor is also called as

a. Constant flux motor

b. Constant voltage motor

c. Variable voltage motor

d. Constant current motor

Answer a

7. The speed of a DC shunt motor can be increased by _______

a) Increasing the resistance in armature circuit

b) Increasing the resistance in field circuit

c) Reducing the resistance in the field circuit

d) Reducing the resistance in the armature circuit

Answer: b

8 --------------- Method is an ideal choice for motor which undergoes frequent starting, stopping, speed reversal.

a) Ward Leonard method

b) Flux control method

c) Voltage control method

d) None

Answer: a

9 D.C. shunt motors are commonly used in

a. Cranes

b. Electric traction

c. Elevators

d. Lathe machines

Answer: a

10 When quick speed reversal is a consideration, the motor preferred is

Synchronous Motor

Squirrel cage Induction Motor

Wound Rotor induction motor

DC motor

Answer d

ASSIGNMENT

1. Describe following methods of speed control a) armature rheostat control b) Flux control.
2. Briefly explain any two control methods of chopper fed DC drives with relevant diagrams.

INDUCTION MOTOR DRIVES

UNIT V - INDUCTION MOTOR DRIVES

Induction Motor fundamentals – Speed control of Induction motors – Stator control: Voltage, Frequency, V/F control (AC chopper, Inverter fed drives) – Rotor resistance control – slip power recovery scheme – Introduction – Synchronous motor drive.

1. INTRODUCTION

Induction motors, particularly squirrel cage IM, have many advantages when compared to DC motors. They are,

- Ruggedness
- Lower maintenance requirements
- Better reliability
- Low cost, less weight and volume
- Higher efficiency
- Also induction motors are able to operate in dirty and explosive environments.

Because of the above said advantages, induction motors are predominantly used in many industrial applications. But induction motors were used only for applications requiring constant speed.

DC motors were used for variable speed applications as their speed control is cheap and efficient when compared to induction motors.

After the advent of power electronic converters, it was able to design variable speed drives for induction motors. Because speed control of IM using power electronic converters have become cheap and less costly when compared to dc drives.

2. SPEED CONTROL

The conventional methods of speed control of induction motors are,

Stator Side

- Stator voltage control
- Variable frequency control
- Stator current control
- V/f control
- Changing the number of poles on stator

Rotor Side

- Rotor resistance control
- Injecting emf in the rotor

3. STATOR VOLTAGE CONTROL

- Speed of induction motor can be varied in a narrow range by varying the voltage applied to the stator winding.
- Torque developed by 3 phase induction motor is directly proportional to the square of the stator voltage as given by the equation,

$$T_m = \frac{3}{2\pi N_s} \times \frac{S.E_2^2.R_2}{R_2^2 + (S.X_2)^2} ------1$$

Or

$$N_s = \frac{3}{2\pi T_m} \times \frac{S.E_2^2.R_2}{R_2^2 + (S.X_2)^2} --- --2$$

- In low slip region $(S.X2)^2$ is very small as compared to R2. So, it can be neglected. So equation 1 becomes,

$$T_m \propto \frac{S.E_2^2}{R_2}$$

- Since rotor resistance R2 is constant, the torque equation becomes,

$$T_m \propto S.E_2^2$$

Here E2 is proportional to the supply voltage V1. Hence,

$$T_m \propto S.V_1^2 ------3$$

- From equation 2, it is clear that any reduction in supply voltage will reduce the motor speed. But from equation 3, it is seen that any reduction in supply voltage will reduce the torque also.
- So in this method of speed control, torque reduces when supply voltage reduces. Hence this method is used in applications where torque demand reduces with reduction in voltage.
- In general, this method can be used for small range of speed variation.
- In this method of speed control, the slip increases at low speeds. Hence the efficiency of the drive reduces.
- Examples: Fans and pump drives.

Stator voltage control using AC voltage controllers

- The variation of motor voltage is obtained by ac voltage controllers. AC voltage controllers convert fixed ac to variable ac with same frequency.
- But this method produces harmonics in the output and the power factor is low.
- The harmonic content increases and power factor decreases with decrease in output voltage.
- Hence the torque produced by the motor reduces.
- This method is used in applications like fans, pumps and crane drives.

The circuit for star connected ac voltage controller feeding a 3 phase induction motor is shown in Fig.1

- By controlling the firing angle of the thyristors connected in each phase, the rms value of stator voltage can be varied.
- As a result of this, the motor torque and the speed of the motor are varied.
- In star connected controller, all the thyristors carry line currents. But in delta controller shown in Fig.2, all the thyristors carry phase current only. Hence low rating thyristors may be employed in delta controller.

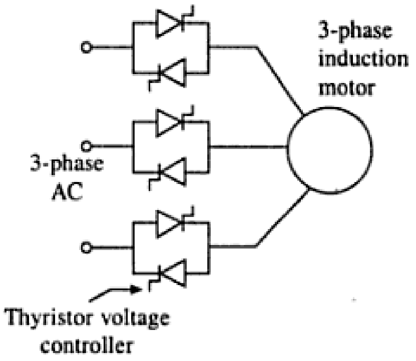


Fig. 1 Star connected controller

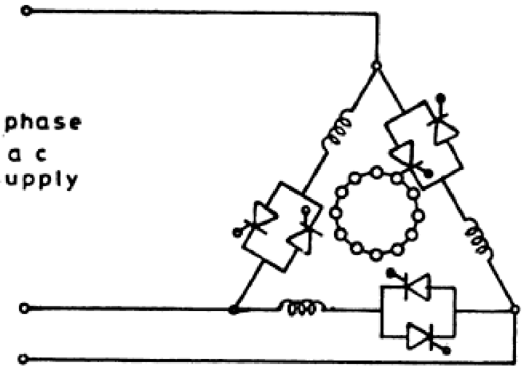


Fig. 2 Delta connected controller

- But delta controller produces circulating currents due to third harmonic voltages. This may increase power loss across each device.
- The speed range is limited in this method of speed control.
- This method is used for applications where load torque requirement reduces with reduction in speed as shown in Fig.3. When a voltage of V1 is applied, the load torque required is high and when a voltage V3 is applied. The load torque is low.

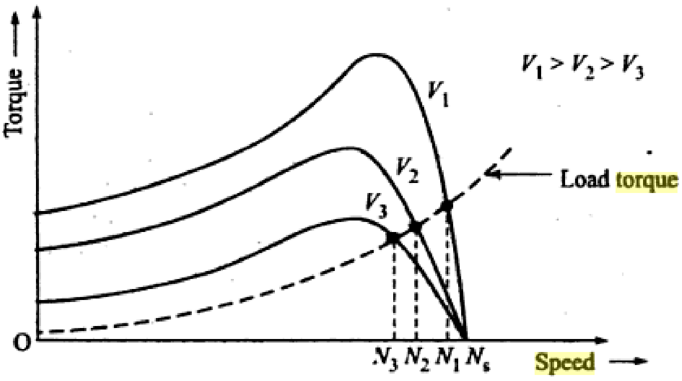


Fig. 3 Speed − Torque characteristics with stator voltage control

- These ac voltage controllers are also used as starters for soft start of motors.
- The power factor of ac voltage circuit is low.
- It can be used for fans and pump drives.

STATOR FREQUENCY CONTROL (OR) FIELD WEAKENING METHOD OF SPEED CONTROL

- In an induction motor, we know that,

$$N_s = \frac{120.f}{P} - - - - - - - 4$$

- From the above equation 4, it is clear that changing the supply frequency will change the synchronous speed and hence the rotor speed.

- Emf equation in ac machines is given by,

$$V_1 = 4.44.f.\varphi.K_w.N_1$$

$$\therefore \varphi = \frac{V_1}{4.44.f.K_w.N_1} ------5$$

- The above eqn 5 states that the flux φ will be constant if V1 and f are kept constant.
- If frequency is reduced with constant V1, then the flux φ increases. Hence the core gets saturated.
- This will increase the magnetizing current of the motor. Hence power losses increased and efficiency decreases. It also produces noise.

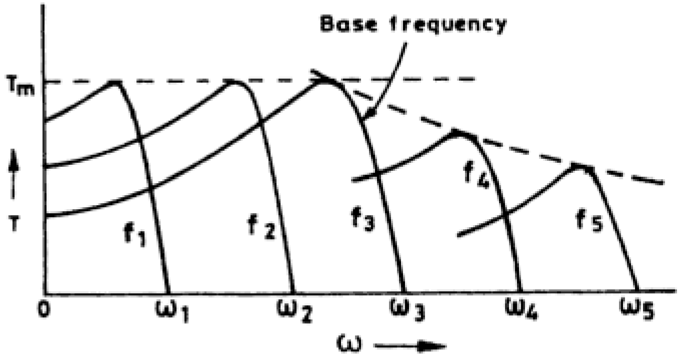


Fig. 4 Speed − Torque characteristics with stator frequency control

- If the frequency is increased by keeping the V1 constant, then flux decreases. This will reduce the maximum torque produced by the motor as shown in Fig. 4.
- So this method is rarely used in practice.
- With constant voltage, if the frequency is increased, the air-gap flux reduced. This control is also called as field weakening mode of speed control.

VOLTAGE / FREQUENCY CONTROL (OR) VOLTS / HERTZ CONTROL

- Varying the voltage alone or frequency alone has some disadvantages with regards to the operation of induction motor.
- The maximum torque in an induction motor is given by,

$$T_{max} = \frac{K(V/f)^2}{\frac{R_s}{f} \pm \sqrt{\left[\left(\frac{R_s}{f}\right)^2 + 4\pi^2(L_s + L_r')^2\right]}} ------6$$

- Here K is a constant and Ls & Lr' are the stator and stator referred rotor inductances.
- At high frequencies, the value of (Rs / f) will be very much less than 2π (Ls+ Lr'). So (Rs / f) can be neglected and hence the torque equation becomes,

$$T_{max} = \pm \frac{K(V/f)^2}{\sqrt{[4\pi^2(L_s + L_r')^2]}}$$

$$T_{max} = \pm \frac{K(V/f)^2}{2\pi(L_s \quad L_r')} ------ 7$$

- From equation 7, it is clear that if the ratio (V / f) is kept constant, the motor can produce a constant maximum torque, T_{max}. i.e constant torque operation.
- At low frequencies (when speed is reduced), the term (Rs / f) will be high and it cannot be neglected in equation 6. Hence the motor torque reduces.
- This is because of the fact that the flux reduces as the frequency is decreased as per eqn 5.
- Hence if maximum torque needs to be maintained constant at low speeds, then (V / f) ratio must be increased.
- Near to base speed (or rated speed), the supply voltage will be maximum and it cannot be increased further. Therefore, above base speed, the frequency is changed by keeping supply voltage constant.
- But this will decrease the maximum torque produced by the motor as per the eqn 7.

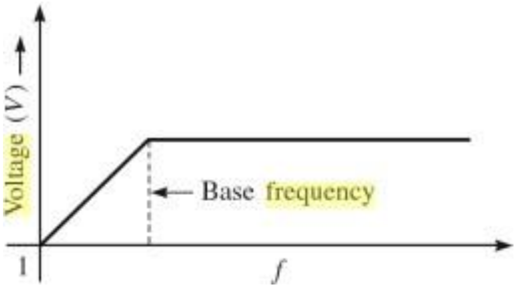


Fig. 5. V – f relationship

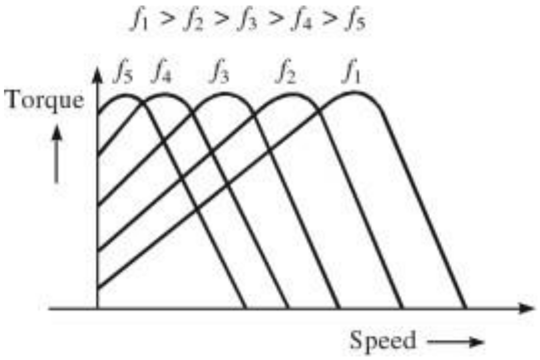


Fig. 6.Speed – Torque characteristics

- From the graph of Fig.5, it is clear that
  - (V/f) ratio is increased at low frequency to keep maximum torque constant.
  - (V/f) ratio is kept constant at high frequencies up to base frequency
  - V is kept constant and frequency is varied above base frequency.
- From Fig.6, it is clear that the maximum torque is same at all different speeds.
- This volts / Hertz control offers speed control from standstill up to rated speed of IM.
- This (V/f) control is achieved by using VSI and CSI fed induction motor drives.
- If a six step inverter is used, the frequency alone can be varied at the inverter output and the output voltage is controlled by varying the input dc voltage.
- If a PWM inverter is used, both voltage and frequency can be varied inside the inverter itself by changing the turn on and off periods of the devices.

VOLTAGE SOURCE INVERTER (VSI) FED INDUCTION MOTOR DRIVES

- In voltage source inverters, the input voltage is kept constant.
- The magnitude of output voltage of VSI is independent of the load.
- But the magnitude of output current depends on the type of load.
- A VSI converts the input dc voltage into an ac voltage with variable frequency at its output terminals.
- VSI using normal transistors is shown in Fig..7. Any other self commutated device can be used in place of transistors.

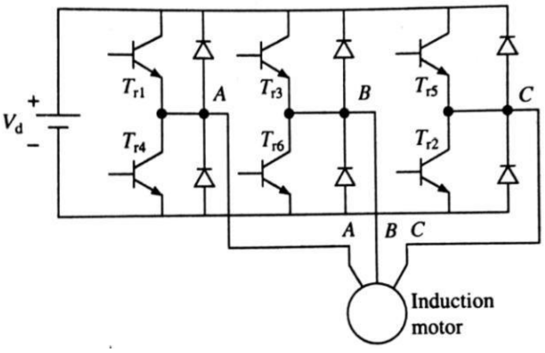


Fig. 7. VSI fed Induction motor drive

- MOSFET is used in low voltage and low power inverters.
- IGBT and power transistors are used up to medium power levels.
- GTO and IGCT are used for high power levels.
- VSI may be a six step inverter or PWM inverter.
- When VSI is operated as a six step inverter, the transistors are turned ON in the sequence of their numbers with a time interval of T/6 seconds if T is the total time period of one output cycle.
- Frequency of the inverter output is varied by varying the time period (T) of one cycle.
- If the supply is dc, then a variable dc voltage is obtained by connecting a chopper between input dc and the inverter as shown in Fig. 8

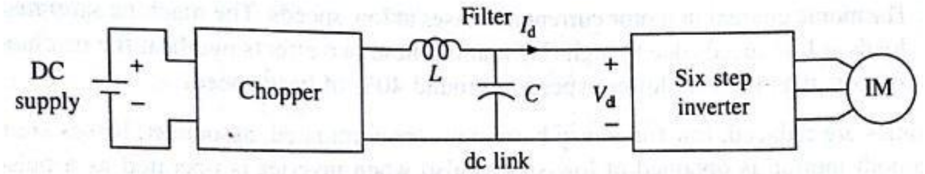


Fig. 8 Chopper and inverter fed IM

- If the input supply is ac, then a variable dc is obtained by connecting a controlled rectifier between the input ac and the inverter as shown in Fig. 9. The output voltage waveform of a six step inverter is shown in Fig. 10

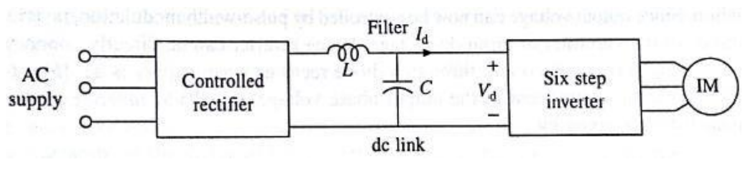


Fig. 9.Rectifier with inverter fed IM

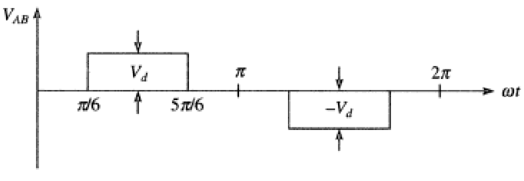


Fig. 10. Output voltage waveform of inverter

Disadvantages of six step inverter

- Low frequency harmonics are more and hence the motor losses are increased at all speeds.
- Motor develops pulsating torques due to 5th, 7th, 11th and 13th harmonics.
- Harmonic content increases further when the motor rotates at low speeds. This will overheat the machine.

The above said problems are rectified when a PWM inverter is used.

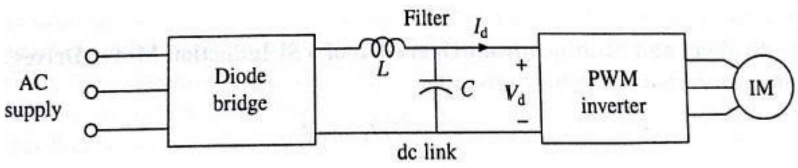


Fig. 11 PWM inverter fed IM

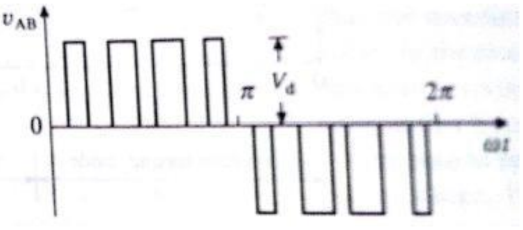


Fig. 12 waveforms

If a PWM inverter is used as VSI as shown in Fig 11, then the input voltage may be a constant dc which is obtained from a simple diode rectifier. The output of a PWM inverter is a variable voltage and variable frequency.

- In a PWM inverter, it is possible to control the output voltage and frequency as well as the harmonic content can be minimized.
- The output voltage waveform of a PWM inverter is shown in Fig. 12
- The motors having high leakage inductance are used when a VSI is used to feed the induction motors.

CURRENT SOURCE INVERTER (CSI) FED INDUCTION MOTOR DRIVES

In current source inverters, the input current is constant but adjustable. The magnitude of output current of CSI is independent of the load. But the magnitude of output voltage depends on the type of load. A CSI converts the input dc current into an ac current at its output terminals. The output frequency of ac current depends upon the triggering of SCRs. Magnitude of output current can be adjusted by controlling the magnitude of dc input current. Out of the force commutated CSIs; Auto Sequential Commutated Inverter (ASCI) is the most popular CSI.

A single phase ASCI is shown in Fig. 13

A large inductance is connected to make this inverter as current source inverter. Capacitors C1 to C6 are used for commutating the thyristors. These thyristors are fired in sequence with 60^0 intervals. Diodes D1 to D6 are connected in series with thyristors to prevent the discharge of capacitors through load. The inverter output frequency is controlled by adjusting the period ***T*** through triggering circuits of thyristors.

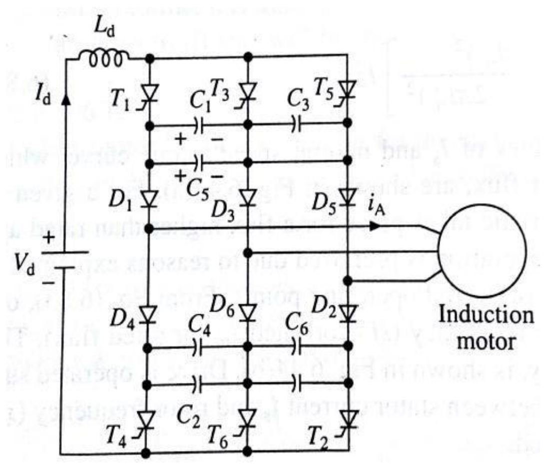


Fig. 13 CSI fed Induction Motor Drive

The fundamental component of motor phase current is

$$I_s = \frac{\sqrt{6}}{\pi} I_d$$

For any given speed, the motor torque is controlled by varying the dc current **Id**. This **Id** can be varied by varying **Vd**. Different types of circuit configurations are shown in Fig. 14 and Fig. 15. When the available supply is AC, then a controlled rectifier is connected between the input supply and the inverter as shown in Fig.14

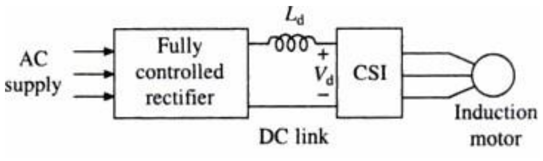


Fig. 14. Converter with CSI fed IM

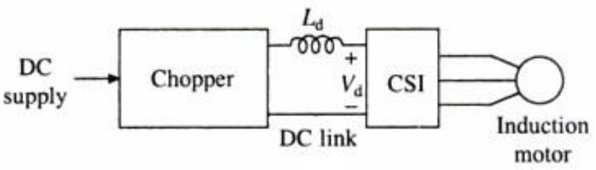


Fig. 15. Chopper with CSI fed IM

The output of fully controlled rectifier will be a variable DC which will vary **Id**. This DC current is converted into AC using a CSI and it is given to the induction motor. If the available supply is a fixed DC, then a chopper may be added between the supply and the inverter as shown in Fig. 15.

Chopper will give a variable DC voltage Vd which further varies Id. This DC current is converted into AC using a CSI and it is given to the induction motor. In VSI, in case of commutation failure, two SCRs in the same leg may conduct. This will short circuit the input supply and hence the current through SCRs will rise to a high value. Hence high speed semiconductor fuses are needed to protect the devices and thus making the system costly. In case of CSI, no such problem arises even if two devices in same leg conduct. Because the current is controlled by the large inductance connected in series with the source. Hence CSI is more reliable than VSI. The output current of CSI shown rises and falls very rapidly. This creates a huge voltage across the leakage inductance of the motor windings. Hence a motor with less leakage inductance is used.

Using large values of commutation capacitors can reduce these voltage spikes. But because of large values of capacitors and inductors, the CSI drive becomes expensive and bulky. These types of auto sequentially commutated inverters are used widely in medium and large power current source inverter drives.

SPEED CONTROL OF INDUCTION MOTOR ON ROTOR SIDE

This method of speed control is applicable only to wound round or slip ring induction motors. The portion of air-gap power which is not converted to mechanical energy is called slip power. Hence the mechanical power developed is controlled by varying the slip power by some methods. This further controls the speed of the motor. Controlling the slip power is done by three different methods.

- Static rotor resistance control
- Emf injection into rotor circuit
  - Static Scherbius drive
  - Static Kramer drive

Rotor resistance control

- In this method of speed control, an external resistance is added with rotor circuit and it is varied to control the speed of the induction motor. This method is applicable only to slip ring induction motor.
- We know that

$$T \propto \frac{S}{R_2} \quad \text{and hence} \quad R_2 \propto \frac{S}{T}$$

- From the above equation, it is clear that any increase in R2 will increase slip S. Increase in slip means reduction in speed. Hence rotor resistance varies the speed.
- Rotor resistance does not affect the value of maximum torque produced by the motor. But it changes the speed at which the maximum torque is produced. It is shown in Fig. 16
- It is clear from Fig. 16 that for the same value of motor torque, the speed reduces with an increase in rotor resistance.
- In this method of speed control, the motor torque does not change even at low speeds. Also this method is less costly when compared to variable frequency operations.
- Because of its low cost and high torque producing capabilities, this method is used in cranes.
- But major disadvantage of this method is its low efficiency due to additional power losses in the external resistance connected to the rotor.
- These losses occur in the external resistor. So the heat produced around the external resistor does not increase the heat of the motor.

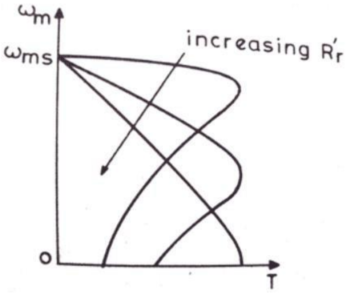
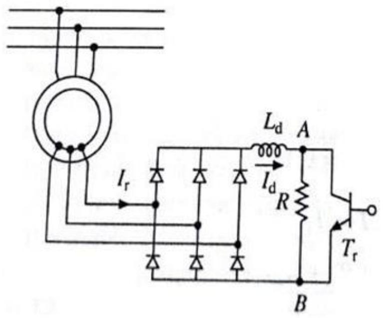


Fig. 16. Speed – Torque characterictics .

Static Rotor resistance control

- In a three phase slip ring induction motor, a three phase diode rectifier, a chopper and a single resistor is connected as shown in Fig. 17.



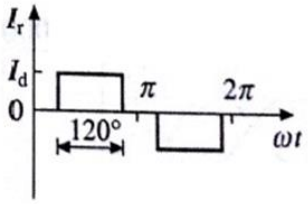


Fig. 17 Rotor resistance control **Fig. 18 Rotor current waveform**

- An inductor **Ld** is connected to reduce the ripple present in the dc link current.
- The rotor current waveform is shown in Fig. 18.
- The rms value of rotor current is given by,

$$I_r = \sqrt{\frac{2}{3}} I_d ------1$$

- The ac output voltage from rotor windings is rectified using diode bridge and it is fed to the parallel combination of fixed resistor and a transistor.
- The effective value of this resistance connected between the terminals A & B is varied by varying the duty cycle of the transistor.
- The resistance between A & B is zero when transistor is ON. Resistance between A & B is maximum (i.e R) when transistor is off.
- The effective resistance connected between A & B is given by,

$$R_{AB} = (1-\alpha)R ----- 2$$

Where α is the duty cycle.

- From eqn. 1,

$$I_d = \sqrt{\frac{3}{2}} I_r ----- 3$$

- Thus the total resistance in the rotor circuit is,

$$R_{rT} = R_r + 0.5\, R(1-\alpha)$$

- From the above equation, it is clear that rotor resistance is varied from R_r to $(R_r+0.5R)$ when α is varied from 1 to 0.

Advantages of rotor resistance control method

- Smooth and step less control is possible.
- Quick response
- Less maintenance
- Compact size.

Disadvantages of rotor resistance control method

- Increase in rotor resistance leads to increase of power loss in the rotor resistance. This will reduce the system efficiency.

Energy efficient drive (Or) Slip Power Recovery Schemes

- In rotor resistance control method of speed control, the slip power is wasted in the external resistance and hence the efficiency reduces.
- However instead of wasting the slip power in external resistor, it can be recovered and supplied back in order to improve the overall efficiency.
- This scheme of recovering the power is called slip power recovery scheme and this is done by connecting an external source of emf of slip frequency to the rotor circuit.
- The injected emf can either oppose the rotor induced emf or aids the rotor induced emf.
- If it opposes the rotor induced emf, the total rotor resistance increases and hence speed decreases
- If the injected emf aids the main rotor emf the total resistance decreases and hence speed increases.
- Therefore by injecting induced emf in rotor circuit the speed can be easily controlled.

Static Kramer Drive

- In this method of speed control, the slip power flows in only one direction. It flows from the rotor back to main supply. Hence the speed can be controlled below synchronous speed only.
- The circuit for static Kramer drive is shown in Fig. 19. The slip power from the rotor circuit is converted to dc voltage Vd by diode rectifier.
- The inductor Ld filters the ripples present in the dc voltage Vd.

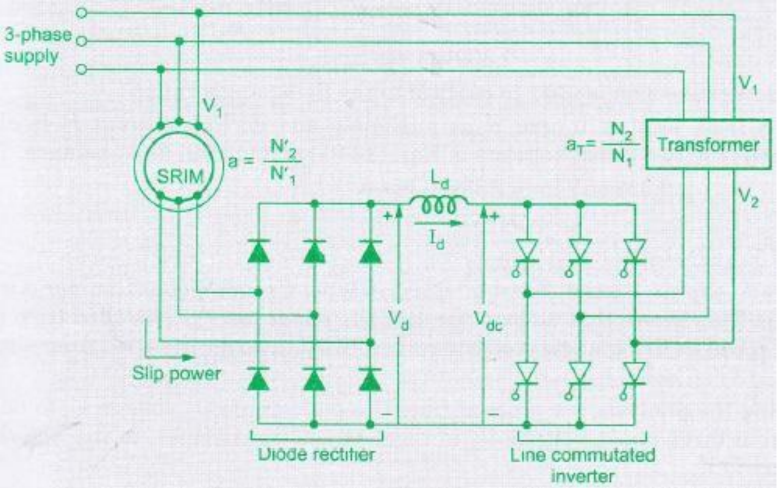


Fig.19. Static Kramer Drive

- This dc voltage is then converted to ac voltage at line frequency (50 Hz) using a line commutated inverter and pumped back to ac source.

- This drive offers a constant torque operation.

Static Kramer systems are used in large power pumps and compressor type loads where speed control range is less and below synchronous speed.

Static Scherbius Drive

In static Kramer drive, the speed of slip ring induction motor can be controlled below synchronous speed only. For controlling the speed below and above synchronous speed, the static Scherbius drive is used. There are two configurations of this drive. They are,

1. DC link Scherbius Drive
2. Cycloconverter Scherbius Drive

DC link Scherbius Drive

- For controlling the speeds below synchronous speed (Sub Synchronous), the slip power is removed from the rotor circuit and it is fed back into the input AC supply.
- For controlling the speeds above synchronous speed (Super Synchronous), an additional power is fed into the rotor circuit at slip frequency.
- The circuit of dc link Scherbius drive is shown in Fig. 20 and it has a slip ring induction motor, two controlled converters, a smoothing inductor and a transformer.
- Smoothing inductor is used to suppress the ripples present in the dc link.

Sub synchronous speed control

- Bridge 1 is operated with a firing angle range of 0° to 90°. It means that bridge 1 works as rectifier.
- Bridge 2 is operated with a firing angle range of 90° to 180°. It means that bridge 2 works as inverter.
- Now the slip power flows from the rotor circuit to the supply through bridge 1, bridge 2 and transformer.
- Here transformer steps up the rotor voltage to the level of ac input supply.

Sub synchronous speed control

- Bridge 1 is operated with a firing angle range of 90° to 180°. It means that bridge 1 works as inverter°
- Bridge 2 is operated with a firing angle range of 0° to 90°. It means that bridge 2 works as rectifier.
- Now the slip power flows from the input ac supply to the rotor circuit through transformer, bridge 2 and bridge 1.
- Here transformer steps down the input ac supply to the level of rotor voltage.

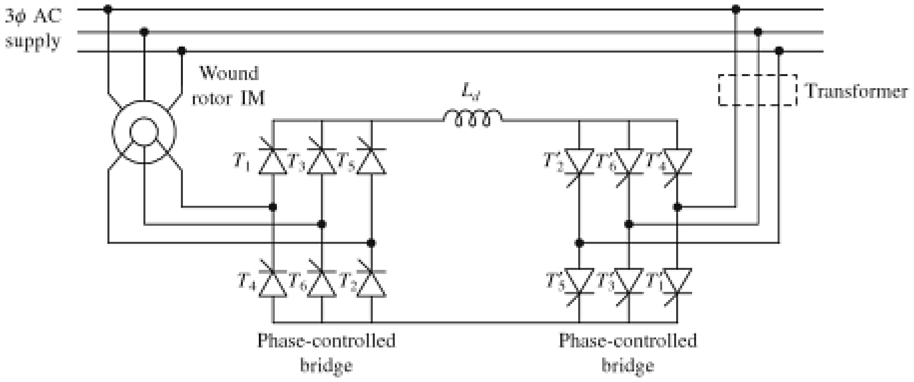


Fig. 20 DC Link Static Scherbius Drive

Rotor voltages at slip frequency are used to commutate the thyristors present in the converters.

At low speeds, the voltage across rotor will be less and it may not be sufficient to naturally commutate the thyristors.

This difficulty can be overcome by using forced commutation. It means that an additional forced commutation circuitry is necessary for Scherbius drives where both below and above synchronous speeds are possible.

Also this Scherbius scheme requires 6 thyristors in place of 6 diodes present in Kramer drive. Hence the drive becomes costly compared to static Kramer drive.

Cycloconverter Scherbius Drive

- A 3 phase Cycloconverter can be used to control the speed of a 3 phase induction motor.
- Cycloconverter fed induction motors are used in applications such as high power pumps and blower type drives.
- Using a Cycloconverter, it is possible to send power in both the directions and hence speed control below and above synchronous speed is possible.
- Also it allows regenerative braking during which the power is fed back to the supply.
- Like dc link Scherbius drive, this scheme also offers a constant torque operation.

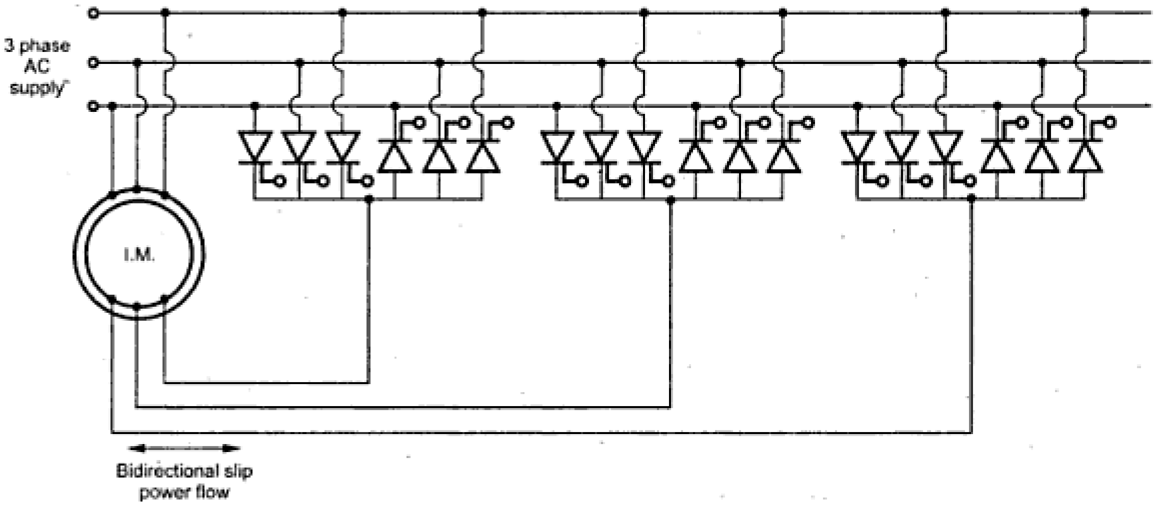


Fig. 21 Cyclo converter Static Scherbius Drive

SYNCHRONOUS MOTOR DRIVES

Introduction

Synchronous motor drives are close competitors to induction motor drives in many industrial applications. They are generally more expensive than induction motor drives, but the advantages is that the efficiency is higher, which is tends to lower the life cycle cost. The development of semiconductor variable frequency sources, such as inverters and cyclo converters has allowed their use in variable speed applications such as high power and high speed compressors, blowers ,induced and forced draft fans, main line traction, servo drives etc…

Synchronous motor variable speed Drives

Variable frequency control

Synchronous speed is directly proportional to frequency, similar to induction motors constant flux operation below base speed is achieved by operating the synchronous motor with constant (V / f) ratio. The synchronous motor either run at synchronous speed (or) it will not run at all. Hence variable frequency control may employ any of the following two modes

1. True synchronous mode

2. Separate controlled mode

3. Self controlled mode

SEPARATE CONTROLLED MODE

This method can also be used for smooth starting and regenerative braking. An example for true synchronous mode is the open loop (V/f) speed control shown in fig. 22.

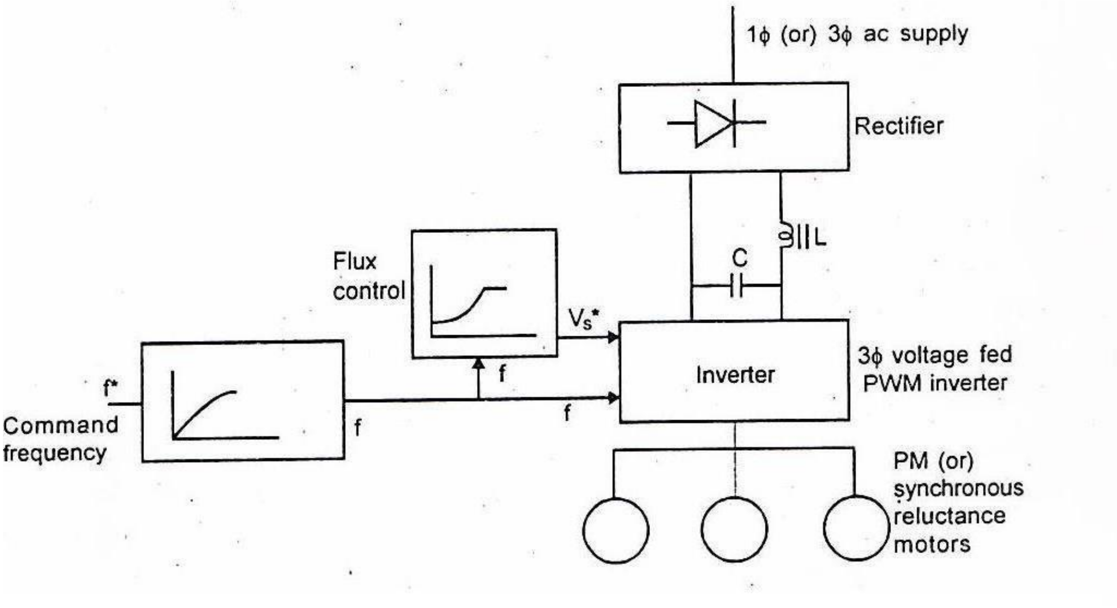


Fig 22 Separate Controlled Mode

Here all the machines are connected in parallel to the same inverter and they move in response to the command frequency f* at the input. The frequency command f* after passing through the delay circuit is applied to the voltage source inverters (or) a voltage fed PWM inverter. This is done so that the rotor source is able to track the change in frequency. A flux control black is used which changes the stator voltage with frequency so as to maintain constant flux for speed below base speed and constant terminal voltage for speed above base speed. The front end of the voltage fed PWM inverter is supplied from utility line through a diode rectifier and LC filter. The machine can be built with damper winding to prevent oscillations.

SELF CONTROLLED MODE

In self controlled mode, the supply frequency is changed so that the synchronous speed is same as that of the rotor speed.Hence, rotor cannot pull-out of slip and hunting eliminations are eliminated. For such a mode of operation the motor does not require a damper winding.

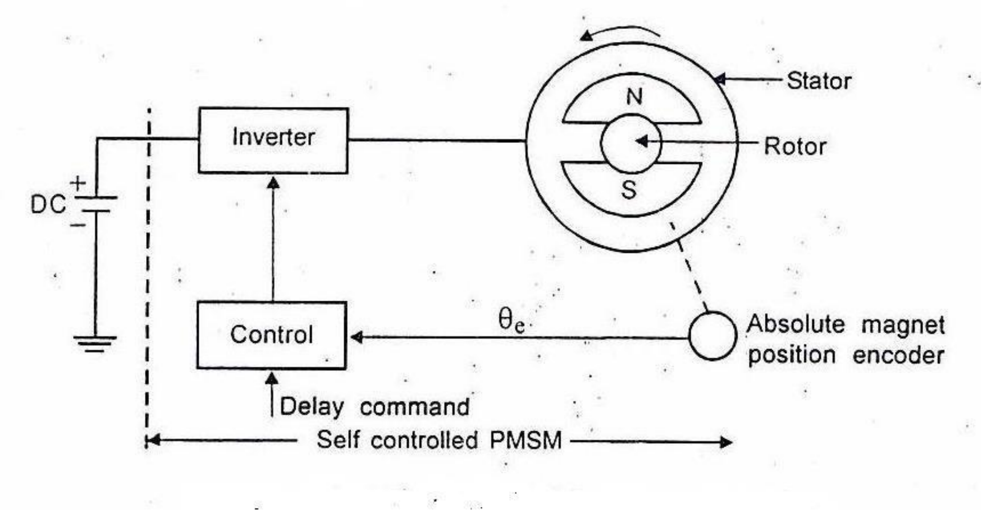


Fig.23. Self Controlled Mode

Fig shows a synchronous permanent magnet machine with self control. The stator winding of the machine is fed by an inverter that generates a variable frequency voltage sinusoidal supply. Here the frequency and phase of the output wave are controlled by an absolute position sensor mounted on machine shaft, giving it self-control characteristics. Here the pulse train from position sensor may be delayed by the external command as shown in fig.23.

In this kind of control the machine behavior is decided by the torque angle and voltage/ current. Such a machine can be looked upon as a dc motor having its commutator replaced by a converter connected to stator. The self controlled motor run has properties of a dc motor both under steady state and dynamic conditions and therefore, is called commutator less motor (CLM).These machines have better stability behavior. Alternatively, the firing pulses for the inverters can also be obtained from the phase position of stator voltages in which case the rotor position sensor can be dispensed with. When synchronous motor is over excited they can supply the reactive power required for commutation thyristors.

In such a case the synchronous machine can supply with inverter works similar to the line commutated inverter where the firing signals are synchronized with line voltages. Here, the firing signals are synchronized with the machine voltages then these voltages can be used both for control as well as for commutation. Hence, the frequency of the inverter will be same as that of the machine voltages. This type of inverters are called load commutated inverter (LCI).Hence the commutation has simple configurations due to the absence of diodes, capacitors and auxiliary thyristors. But then this natural commutation its not possible at low speeds up to 10% of base speed as the machine voltage are insufficient to provide satisfactory commutation. At that line some forced commutations circuit must be employed.

Multiple Choice Questions

1 Which of the following motors is preferred for traction work?

a) Synchronous Motor

b) 3 phase induction motor

c) DC Shunt Motor

d) Single phase induction motor

Answer. b)

2. The method which can be used for the speed control of induction motor from stator side is

a. V / f control

b. Controlling number of stator poles to control Ns

c. Adding rheostats in stator circuit

d. All of these

Answer: d

3. The slip frequency of an induction motor is

a) The frequency of rotor currents

b) The frequency of stator currents

c) Difference of the frequencies of the stator and rotor currents

d) Sum of the frequencies of the stator and rotor currents

Answer: a)

4 A three-phase synchronous machine is a

a) Single excited machine

b) Double excited machine

c) Machine in which three-phase supply is fed to both stator and rotor winding

d) None of these

Answer: c)

5. In a synchronous machine, the phase sequence can be reversed by reversing the __________

a) Rotor direction

b) Field polarities

c) Armature terminal

d) Rotor direction and armature terminal

Answer: a

6 Induction motor speed control method ------

a. Stator voltage control
b. Stator frequency control
c. Stator current control
d. All the above

Answer d

7 Which motor is usually preferred for the elevator nowadays?

a) Induction Motor
b) Synchronous Motor
c) Capacitor Start Single Phase Motor
d) None of the above

Answer a)

8 Starters are used in induction motor because
a) Its starting torque is high
b) It is run against heavy load
c) It cannot run in reverse direction
d) Its starting current is five times or more than its rated current

Answer (d)

9 As compared to three phase induction motor the advantage of synchronous Motor in addition to its constant speed is

a) Higher Power factor
b) Better efficiency
c) Both 1 & 2
d) None of the above

Answer c)

10 The power factor of a squirrel cage induction motor is ____________
a) High at light load only
b) High at heavy loads only
c) Low at the light and heavy loads both
d) Low at rate load only

Answer: b

ASSIGNMENT

1. Explain the method of speed control of three phase induction motor by frequency control.
2. Describe the self control of synchronous motor fed from VSI. Discuss about separately controlled synchronous motor fed from VSI.

CONCLUSIONS

Power electronic devices play a key role in various applications that are using converters and inverters. Power electronics is one of the main technologies to realize energy conversion with high efficiency. Choppers are used to convert fixed dc into variable dc and converter / chopper fed dc drives are used in various industries. DC drives are widely used in industries. Converters employed in DC drives gives smooth and wide range of speed control without much expensive. Moreover these drives and controller occupies lesser area and provide precise control of DC drives. AC motors like Induction motors, synchronous motor drive's speed can be controlled by various methods using power electronic components for various applications in industries.

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3. Dubey G.K, "*Fundamentals of Electric Drives*", 2nd edition, 2002.

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3. Pillai S.K., "*A first course on Electrical Drives*", New Age International (p) Ltd., 1989, 2nd edition.

4. Vedam Subramaniyam, "*Thyristor Control of Electric Drives*", Tata McGraw Hill Publishing company Ltd., New Delhi, 1994.

3. Sen P.C, "*Thyristor - DC Drives*", John Wiley & Sons, New York, 1981.

4. Bose B.K, "*Power Electronics and AC Drives*", Prentice Hall, Englewood cliffs, New Jersey, 1986

5. Ramamoorthy M., "*An Introduction to Thyristor and their Application*", Affiliated East West Press (P) Ltd, 2nd Edition , 1991.

VIDEO LINKS

1. **https://www.youtube.com/watch?v=AQqyGNOP_3o – Three phase Induction motor**
2. **https://www.youtube.com/watch?v=Vk2jDXxZIhs – Synchronous motor**

QUESTION BANK - POWER ELECTRONICS AND INDUSTRIAL DRIVES

UNIT 1 - POWER SEMICONDUCTOR DEVICES

TWO MARK QUESTIONS

1. Define latching and holding current of SCR
2. What are the advantages of MOSFET?
3. Define the term pinch off voltage of MOSFET
4. Power BJT is a current controlled device. Why?
5. How can a thyristor turned off?
6. Write down the applications of IGBT?
7. What are the different methods to turn on the thyristor?
8. Define forward break over voltage.
9. IGBT is a voltage controlled device. Why?
10. Power MOSFET is a voltage controlled device. Why?
11. Distinguish between SCR and TRIAC?
12. Compare MOSFET and BJT?
13. Draw the symbols of TRIAC, IGBT & LASCR
14. List the merits and demerits of MCT
15. What is the use of Snubber circuit?

SIXTEEN MARK QUESTIONS

3. What is meant by SCR? Explain its characteristic curve in detail using suitable diagram and mention how it can be used as a power device?
4. a. Discuss the basic structure and working of an IGBT with diagram.
   b. Enumerate the switching characteristics of IGBT.
5. Describe the turn off characteristics of SCR with its characteristic curve.
6. Explain the working of IGBT with neat diagram. Also, discuss in detail the static and switching characteristics of IGBT.
7. Explain the construction, working and switching characteristics of MOSFET.
8. Explain thyristor protection circuits with neat diagrams.
9. Draw and explain the working principle and switching characteristics of a power transistor.
10. Write short notes on i) MCT ii) LASCR
11. With neat diagram explain the thyristor triggering circuits.
12. Draw the construction and characteristic curve of a TRIAC and explain.

UNIT 2 – CONVERTERS

TWO MARKS QUESTIONS

1. What is meant by phase controlled rectifier?
2. Mention the applications of controlled rectifier.
3. State the principles of phase control in AC-DC converter.
4. What is dual converter?
5. What is the function of freewheeling diode in controlled rectifier?
6. What are the advantages of freewheeling diodes in a controlled rectifier?
7. What are the advantages of single phase bridge converter over single phase mid-point converter?
8. What is commutation angle or overlap angle?
9. What are the different methods of firing circuits for line commutated converter?
10. What is meant by full converter?
11. What is the difference between half controlled & fully controlled bridge rectifier?
12. Explain the effect of source inductance and load inductance on the performance of converters?
13. What is Cyclo converter?
14. List the types of Cyclo converter.
15. List the industrial applications of Cyclo converters?
16. Define AC voltage controllers

SIXTEEN MARKS QUESTIONS

3. Describe the operation of single phase half wave circuit with RL load with necessary waveforms and obtain the expression for load voltage and load current.
4. Describe the operation of single phase full wave midpoint convertor, and obtain the various voltage and current waveforms?
5. Examine the circuit and output wave form and explain the working of single phase full convertor bridge with RLE load.
6. Discuss the operation of three phase to single phase cyclo converter with neat diagram and wave forms.
7. Explain the operation of a single phase semi converters for RL- load application.
8. Describe single phase AC voltage regulator circuit with relevant diagrams.

UNIT 3 – INVERTERS AND CHOPPERS

TWO MARKS QUESTIONS

1. What is meant by dc chopper?
2. List the applications of dc chopper?
3. Mention the advantages of dc chopper?

4. What is meant by step-up and step-down chopper?
5. Define duty-cycle?
6. What are the different types of control strategies in chopper?
7. What is meant by TRC and mention its types?
8. What is two quadrant chopper?
9. What is AC chopper? List its applications.
10. How is the inverter circuit classified?
11. What is meant by commutation and what are its types?
12. What do you mean by an inverter?
13. Mention the applications of an inverter?
14. Compare VSI & CSI
15. What is a series inverter?
16. What is a parallel inverter?
17. Describe the applications of a series inverter?
18. Define PWM inverter?
19. Summarize the disadvantages of PWM control.
20. What is CSI inverter?
21. Mention the applications of CSI inverter?

SIXTEEN MARKS QUESTIONS

4. Enumerate the working principle of single pulse width modulation PWM inverter and multiple pulse width modulation PWM inverters with suitable diagrams.
5. Explain the four quadrant operation of using class-E chopper with aid of diagrams and waveforms.
6. Describe in detail, the various types of PWM methods available for voltage control employed in an inverter.
7. Explain the operation of a series inverter circuit with relevant waveforms.
8. Explain the operation of a parallel inverter circuit with relevant waveforms.
9. Explain the operation of a bridge inverter circuit with relevant waveforms.
10. Explain the operation of a CSI inverter circuit with relevant diagrams.
11. Explain the principle of step up dc- chopper operation and explain it with relevant waveforms.
12. Write the different control strategies employed in chopper? Explain in detail?
13. Discuss the operation of class –C type two quadrant chopper.

UNIT 4 – DC DRIVES

TWO MARK QUESTIONS

1. List the advantages of electrical drives.
2. Summarize the types of electrical drives?
3. Mention the methods of selection of electrical drives?
4. What are the speed control methods of DC motors?
5. Define Ward Leonard Method of Speed Control?
6. Mention the applications of chopper fed dc drives.
7. Mention the applications of electrical drives
8. What are the advantage and disadvantages of D.C. drives?
9. Mention the drawbacks of rectifier fed dc drives?
10. What is a two quadrant dc drive?
11. What is meant by four quadrant operation?

SIXTEEN MARKS QUESTIONS

3. Briefly describe the functions of field control DC motor with suitable diagram and derivations.
4. Draw the block diagram of converter fed DC motor drive and describe its functions with necessary equations?
5. i) Give a brief explanation on selections of drives.
   ii) Explain the four quadrant operations of electric drives.
6. Explain the operation of chopper fed drive for forward motoring and braking control of separately excited DC motor with aid of diagrams, waveforms and speed-torque curves.
7. Explain the closed loop speed control of DC drives.
8. Describe following methods of speed control a) armature rheostat control
   b) Flux control.
9. Briefly explain any two control methods of chopper fed DC drives with relevant diagrams.
10. Explain the construction and working of four quadrant DC-DC converter drives.
11. i) Give a brief explanation on the rating of drives.
    ii) Explain the four quadrant operation of electric drives.
12. Explain the speed control of DC shunt motor using flux control method.

UNIT 5 – INDUCTION MOTOR DRIVES

TWO MARKS QUESTIONS

1. What is an induction motor? How it works?
2. What are the applications of AC drives?
3. Explain the principle of induction motor.

4. Why induction motor is not self starting?
5. How is speed control achieved by voltage/frequency control in a 3 phase induction motor?
6. What are the advantages of voltage/frequency control?
7. Define Speed Control of Three Phase Induction Motor.
8. State the methods of speed control of induction motor.
9. Define Stator Voltage Control of an Induction Motor
10. What is meant by rotor resistance control of motor?
11. Define slip power recovery schemes
12. Define Synchronous Motor Drives
13. What is synchronous speed?

SIXTEEN MARKS QUESTIONS

3. Briefly describe the function of any one type of synchronous motor with suitable diagram.
4. i) Describe the self control of synchronous motor fed from VSI. Discuss about separately controlled synchronous motor fed from VSI.

   ii) Compare the above two schemes.
5. Explain briefly the construction and working principle of different types of an induction motor.
6. Discuss the various starting methods of 3phase induction motor?
7. i) Explain and define the various torques associated with synchronous motor.

   ii) Discuss the methods of starting of synchronous motor.
8. Discuss the operation of an open loop variable frequency voltage source inverter fed induction motor drive.
9. Explain the method of speed control of three phase induction motor by frequency control.