

**ONLINE COURSEWARE
FOR
POWER ELECTRONICS
EC 504A**

Prepared by: Dr. Nabaneeta Banerjee, Dr. Soumik Podder

Syllabus:

Module-1: [10L] Introduction, Applications of power electronics, Power electronics devices: Characteristics of power devices – characteristics of SCR, diac, triac, GTO, P.UJT, power transistors – power FETs – LASCR – two transistor model of SCR Protection of thyristors against over voltage – over current, dv/dt and di/dt . Power Semiconductor Switches: Rectifier diodes, fast recovery diodes

Module-2 [9L] Triggering techniques: Turn on circuits for SCR – triggering with single pulse and train of pulses synchronizing with supply – Thyristor turn off methods, natural and forced commutation, self-commutation series and parallel operations of SCRs. Rectifiers: Single phase and three phase controlled Rectifiers with inductive loads, RL load

Module-3[9L] INVERTERS Voltage and current source inverters, resonant, Series inverter, PWM inverter. AC and DC choppers – DC to DC converters – Buck, boost and buck – boost.

Module-4:[6L] AC Voltage Controllers, Single phase and three phase Cyclo-converters Industrial applications DC and AC Drives DC Motor Speed control Induction Motor Speed Control

MODULE 1

Applications of power electronics in automotive electrical and electronic systems includes high voltage systems, automotive power generation, switched mode power supply (SMPS), DC to DC converters, electric drives, traction inverter or DC to AC converter, power electronic component, high temperature requirement.

Aerospace -space shuttle power supply,satellite power supply,aircraft power system

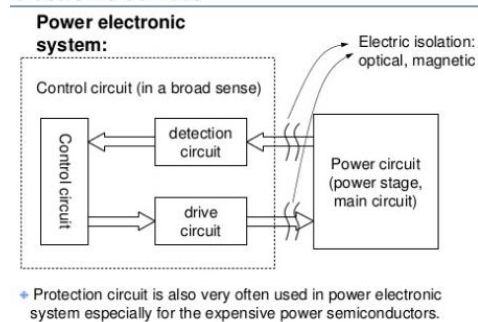
Commercial- heating ,air-conditioning , uninterruptable power supply,refrigeration.

Industrial- industrial blower ,fans , pumps, transformer tap changer, rolling and textile mills

Utility system-HVDC transmission, VAR compensation,static circuit breaker

Telecommunications-battery chargers,power supply.

Configuration of systems using power electronic devices



Power electronics devices:

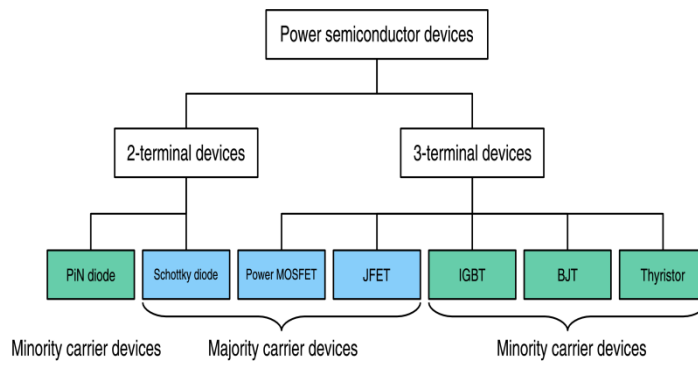
Power Diodes

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

Bipolar -Junction Transistor (BJT)

Insulated-Gate Bipolar Transistor (IGBT)

Thyristors (SCR, GTO, MCT)



Power Diode

A power diode has a P-I-N structure as compared to the signal diode having a P-N structure. Here, I (in P-I-N) stands for intrinsic semiconductor layer to bear the high-level reverse voltage as compared to the signal diode (n- , drift region layer shown in Fig. 2). However, the drawback of this intrinsic layer is that it adds noticeable resistance during forward-biased condition.

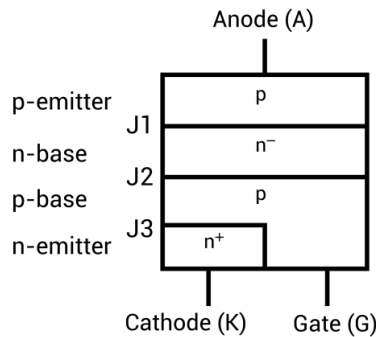
Thyristors (SCR, GTO, MCT)

Thyristors are the family of solid-state devices extensively used in power electronics circuitry such as SCR (silicon-controlled rectifier), DIAC (diode on AC), TRIAC (triode on AC), GTO (gate turn-off thyristors), MCT (MOS-controlled thyristor), RCT, PUT, UJT, LASCR, LASCS, SIT, SITh, SIS, SBS, SUS, SBS and etc. SCR is the oldest member and the head of this family; and usually referred with the name “thyristor”.

They are operated as bistable switches that are either working in non-conducting or conducting state. Traditional thyristors are designed without gate-controlled turn-off capability in which the thyristor can come from conducting state to non-conducting state when only anode current falls below the holding current. While GTO is a type of thyristor that has a gate-controlled turn-off capability.

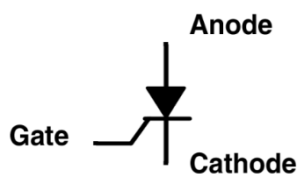
SCR

SCR usually has three terminals and four layers of alternating p and n-type materials as shown in Fig. 34. The structure of the thyristor can be split into two sections: npn and pnp transistors for simple analysis purposes as shown in Fig. 36. It has three terminals named as cathode, anode and gate.

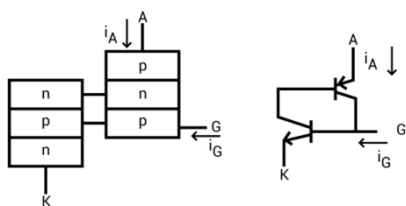


Structural View of Thyristor

N-base is a high-resistivity region and its thickness is directly dependent on the forward blocking rating of the thyristor. But more width of the n-base indicates a slow response time for switching. Symbol of thyristor is given in Fig. 35.



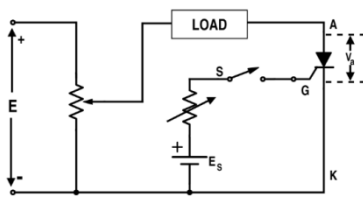
Schematic Symbol of Thyristor



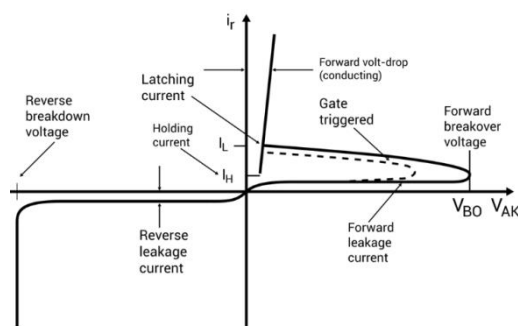
Two-Transistor Model of a Thyristor (A-Anode, G-Gate and K-Cathode)

Planar construction is used for low-power SCRs. In this type of construction, all the junctions are diffused. For high power, mesa construction is used where the inner layer is diffused and the two outer layers are alloyed on it.

The minimum anode current that causes the device to stay at forward conduction mode as it switch from forward blocking mode is called the latching current. If the SCR is already conducting and the anode current is reduced from forward conducting mode to forward blocking mode, the minimum value of anode current to remain at the forward conducting mode is known as the holding current.



Basic Circuit for Getting Voltage and Current Characteristics of Thyristor



Static Characteristics Curve of SCR

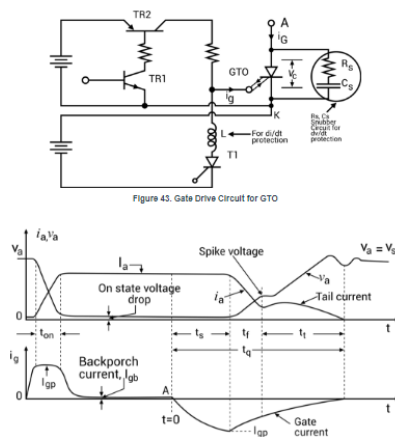
Switching characteristics of SCR are shown in Fig. Note that it can't be turned off with the gate. This is due to positive feedback or a regenerative feedback effect.

Four Layers and Three Junctions of GTO, Practical Form of GTO, Symbol of GTO

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

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

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



Gate Drive Circuit for GTO and Turn-On and Turn-Off Characteristics of GTO

TRIAC

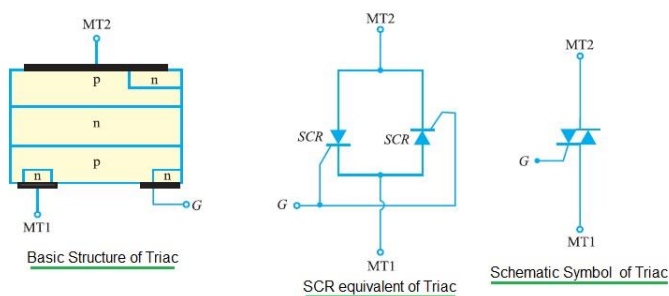


Figure-3 depicts structure and symbol of TRIAC.

- The name "TRIAC" is derived from combination of "TRI" means three and "AC" or alternating current.
- It is a three terminal semiconductor device.
- It has 5 layers of semiconductor.
- It can control both positive and negative half cycles of AC signal input.
- It is a bidirectional switch.

- The forward and reverse characteristics of TRIAC is similar to forward characteristics of SCR device.
- Construction of TRIAC is equivalent to 2 separate SCR devices connected in inverse parallel as shown in the figure.
- Similar to the SCR, once the triac is fired into conduction, the gate will lose all the control. At this stage, the TRIAC can be turned OFF by reducing current in the circuit below the holding value of current.
- The main demerit of TRIAC over SCR is that TRIAC has lower current capabilities. Typically most of the TRIACs are available in ratings less than 40 Amp and at voltages upto 600 Volt.

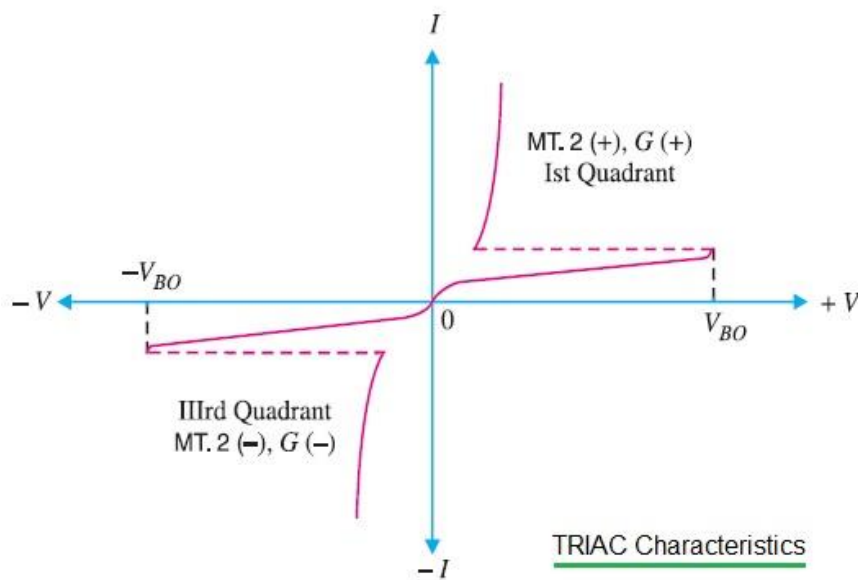


Figure-4 depicts V-I characteristics of TRIAC. Following can be derived from TRIAC characteristics.

- VI characteristics in first and third quadrants are same except direction of voltage and current flow. This characteristic in the 1st and 3rd quadrant is identical to SCR characteristic in the 1st quadrant.
- TRIAC can function with either positive(+ve) or negative(-ve) gate control voltage. In normal operation, gate voltage is +ve in 1st quadrant and -ve in 3rd quadrant.

DIAC

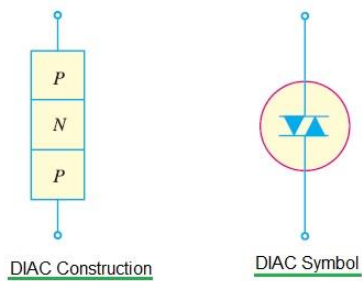


Figure-5 depicts structure and symbol of DIAC.

- It is a two terminal device.
- It is 3 layer bidirectional device.
- DIAC can be switched from its off state to ON state for either polarity of applied voltage.
- The DIAC can be made either in PNP or NPN structure form. The figure depicts DIAC in PNP form which has two p-regions of silicon separated by n-region.

REFERENCE:

<https://www.allaboutcircuits.com/technical-articles/a-review-on-power-semiconductor-devices/>

<http://www.rfwireless-world.com/Terminology/SCR-vs-Diac-vs-Triac-vs-UJT.html>

MODULE 2

SCR Triggering Methods Summary

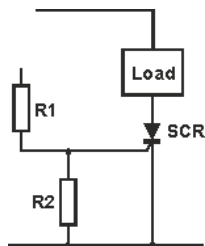
There are several ways in which an SCR can be triggered or fired. These methods include the following which are discussed below:

- **Gate triggering:** This form of SCR triggering is the one that is most commonly seen in the different circuits used. It is simple, reliable, efficient and also easy to implement for most applications - a simple trigger signal can be applied, with suitable processing if required. This means that other electronic circuits can be used to derive a suitable trigger signal and this can then be applied to the SCR.

For gate SCR triggering to be used, the SCR must operate below its breakdown voltage, and a suitable safety margin also allowed to accommodate any transients that may occur. Otherwise forward voltage or breakdown triggering may occur.

To turn-on of an SCR, a positive gate voltage between gate and cathode. This gives rise to a gate current where charges are injected into the inner p layer of the device. This effectively reduces the voltage at which forward break-over occurs. It can be gathered that the gate current determines the forward voltage at which the device switches to its conducting state. Higher the gate current, the lower the forward break-over voltage.

There are many simple methods of applying the trigger signal. Possibly one of the simplest arrangements is shown in the diagram below.



Gate resistors in SCR circuit

Here it can be seen that there are two resistors. The first is R1 which is included to limit the gate current to an acceptable level. This resistor is chosen to provide sufficient current to trigger the SCR while maintaining it within safe limits for the device. It can easily be calculated using the device ratings and Ohms law.

The second resistor, R2 is the gate cathode resistor. This is sometimes denoted as RGK and it is included to prevent spurious triggering. The action of the resistor can be seen with respect to the two transistor analogy of the SCR. It shows that a low external resistance between the gate and cathode bypasses some current around the gate junction. Accordingly a higher anode current is required to initiate and maintain conduction. It is particularly found that low current high sensitivity SCRs are triggered at very low current levels and therefore an external gate-cathode resistance is required to prevent triggering by thermally generated leakage current in the gate region. However the gate cathode resistance bypasses some of the internal anode current caused by the rapid rate of change of the anode voltage (dv/dt). It also raises the forward break-over voltage by reducing the efficiency of the NPN transistor region thus requiring a somewhat higher avalanche multiplication effect to initiate the triggering. The current that bypasses the gate junction also affects the latching and holding currents.

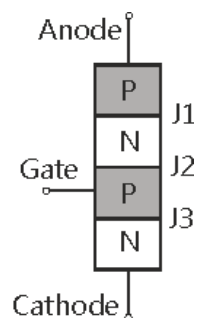
It can therefore be seen that the effects of using the gate cathode bypass resistor include:

Increase the dv/dt capability.

- Retain gate damping to assure the maximum repetitive peak off-state voltage VDRM capability.
- Lower the turn-off time, t_q .
- Raise latching and holding current levels

Although the simple circuit shown above is adequate for many applications, where a more controlled triggering mechanism is required, account needs to be taken of the gate characteristics before triggering, during triggering and afterwards. This is required because the gate characteristics change as a result of the current changes within the device.

- **Anode cathode forward voltage SCR triggering:** This form of SCR triggering or firing occurs when the voltage between the anode and cathode causes avalanche conduction to take place. The way in which this occurs can be seen in conjunction with the SCR structure.



SCR Structure

When the anode to cathode forward voltage is increased, diode junction, J2, comes under increasing stress as it is reverse biased. Ultimately the voltage gradient will increase beyond the breakdown point and avalanche breakdown will occur triggering the SCR. The voltage at which this occurs is known as the forward break-over voltage V_{B0} .

As the junction J2 breaks down, current will flow and triggering the SCR to its conducting state. The junctions J1, J3 are already forward biased, and therefore the breakdown of junction J2 allows the flow of carriers across all three junctions enabling the load current to flow. As with other forms of triggering the SCR, the device remains in its conducting condition.

The use of this method of turning the device on is not advised because exceeding the value of V_{B0} could destroy the device. Any circuit should be

designed to avoid this method of triggering, noting the maximum of any likely voltage spikes.

- **Temperature triggering:** This form of SCR triggering may occur under some circumstances. It may give rise to unexpected responses and therefore its effects should be noted as part of any design process.

Temperature triggering of SCRs occurs as the voltage across the junction J2 and any leakage current may raise the temperature of the junction. The increase in temperature further increases the temperature which will in turn increase the leakage current. This cumulative process may be sufficient to trigger the SCR, although it tends to only occur when the device temperature is high.

- **Light triggering:** This form of SCR triggering or firing is often used with high voltage systems. Here an electrical connection is not required from the firing mechanism, and an isolated light source can be used.

Where light SCR triggering is to be used, specially manufactured SCRs are available. The light triggering occurs within the inner P-type layer. When this area is irradiated by light, free charge carriers are generated and just like applying a gate signal, the SCR is triggered.

To achieve the maximum light absorption, specialised SCR structures are used, often having a recess in the inner P-type layer to enable maximum access to the light.

To enable the light triggering to take place, light is often directed to the correct point in the SCR using optical fibre. Once the light exceeds a certain intensity, switching occurs. An SCR of this type is often referred to as a Light-activated SCR or LASCR. These LASCRs have been used in high voltage power distribution switching centres. The optical switching enables very high levels of isolation to be achieved while still being able to switch with low level circuitry.

- **dv/dt triggering:** SCR triggering can also occur without any gate current if the rate of rise of anode to cathode voltage exceeds certain limits for the particular device.

SCR triggering methods summary

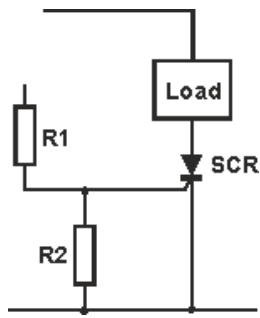
There are several ways in which an SCR can be triggered or fired. These methods include the following which are discussed below:

- **Gate triggering:** This form of SCR triggering is the one that is most commonly seen in the different circuits used. It is simple, reliable, efficient and also easy to implement for most applications - a simple trigger signal can be applied, with suitable processing if required. This means that other electronic circuits can be used to derive a suitable trigger signal and this can then be applied to the SCR.

For gate SCR triggering to be used, the SCR must operate below its breakdown voltage, and a suitable safety margin also allowed to accommodate any transients that may occur. Otherwise forward voltage or breakdown triggering may occur.

To turn-on of an SCR, a positive gate voltage between gate and cathode. This gives rise to a gate current where charges are injected into the inner p layer of the device. This effectively reduces the voltage at which forward break-over occurs. It can be gathered that the gate current determines the forward voltage at which the device switches to its conducting state. Higher the gate current, the lower the forward break-over voltage.

There are many simple methods of applying the trigger signal. Possibly one of the simplest arrangements is shown in the diagram below.



Gate resistors in SCR circuit

Here it can be seen that there are two resistors. The first is R1 which is included to limit the gate current to an acceptable level. This resistor is chosen to provide sufficient current to trigger the SCR while maintaining it within safe limits for the device. It can easily be calculated using the device ratings and Ohm's law.

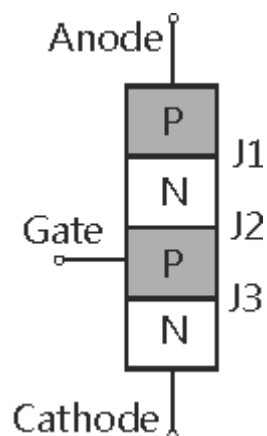
The second resistor, R2 is the gate cathode resistor. This is sometimes denoted as RGK and it is included to prevent spurious triggering. The action of the resistor can be seen with respect to the two transistor analogy of the SCR. It shows that a low external resistance between the gate and cathode bypasses some current around the gate junction. Accordingly a higher anode current is required to initiate and maintain conduction. It is particularly found that low current high sensitivity SCRs are triggered at very low current levels and therefore an external gate-cathode resistance is required to prevent triggering by thermally generated leakage current in the gate region. However the gate cathode resistance bypasses some of the internal anode current caused by the rapid rate of change of the anode voltage (dv/dt). It also raises the forward break-over voltage by reducing the efficiency of the NPN transistor region thus requiring a somewhat higher avalanche multiplication effect to initiate the triggering. The current that bypasses the gate junction also affects the latching and holding currents.

It can therefore be seen that the effects of using the gate cathode bypass resistor include:

- Increase the dv/dt capability.
- Retain gate damping to assure the maximum repetitive peak off-state voltage VDRM capability.
- Lower the turn-off time, t_q .
- Raise latching and holding current levels

Although the simple circuit shown above is adequate for many applications, where a more controlled triggering mechanism is required, account needs to be taken of the gate characteristics before triggering, during triggering and afterwards. This is required because the gate characteristics change as a result of the current changes within the device.

- **Anode cathode forward voltage SCR triggering:** This form of SCR triggering or firing occurs when the voltage between the anode and cathode causes avalanche conduction to take place. The way in which this occurs can be seen in conjunction with the SCR structure.



SCR Structure

When the anode to cathode forward voltage is increased, diode junction, J2, comes under increasing stress as it is reverse biased. Ultimately the voltage gradient will increase beyond the breakdown point and avalanche breakdown will occur triggering the SCR. The voltage at which this occurs is known as the forward break-over voltage V_{BO} .

As the junction J2 breaks down, current will flow and triggering the SCR to its conducting state. The junctions J1, J3 are already forward biased, and therefore the breakdown of junction J2 allows the flow of carriers across all three junctions enabling the load current to flow. As with other forms of triggering the SCR, the device remains in its conducting condition.

The use of this method of turning the device on is not advised because exceeding the value of V_{B0} could destroy the device. Any circuit should be designed to avoid this method of triggering, noting the maximum of any likely voltage spikes.

- **Temperature triggering:** This form of SCR triggering may occur under some circumstances. It may give rise to unexpected responses and therefore its effects should be noted as part of any design process.

Temperature triggering of SCRs occurs as the voltage across the junction J2 and any leakage current may raise the temperature of the junction. The increase in temperature further increases the temperature which will in turn increase the leakage current. This cumulative process may be sufficient to trigger the SCR, although it tends to only occur when the device temperature is high.

- **Light triggering:** This form of SCR triggering or firing is often used with high voltage systems. Here an electrical connection is not required from the firing mechanism, and an isolated light source can be used.

Where light SCR triggering is to be used, specially manufactured SCRs are available. The light triggering occurs within the inner P-type layer. When this area is irradiated by light, free charge carriers are generated and just like applying a gate signal, the SCR is triggered.

To achieve the maximum light absorption, specialised SCR structures are used, often having a recess in the inner P-type layer to enable maximum access to the light.

To enable the light triggering to take place, light is often directed to the correct point in the SCR using optical fibre. Once the light exceeds a certain intensity, switching occurs. An SCR of this type is often referred to as a Light-activated SCR or LASCR. These LASCRs have been used in high voltage power distribution switching centres. The optical switching enables very high levels of isolation to be achieved while still being able to switch with low level circuitry.

- **dv/dt triggering:** SCR triggering can also occur without any gate current if the rate of rise of anode to cathode voltage exceeds certain limits for the particular device.

Turning Off SCR (Commutation)

Thyristor Commutation Techniques

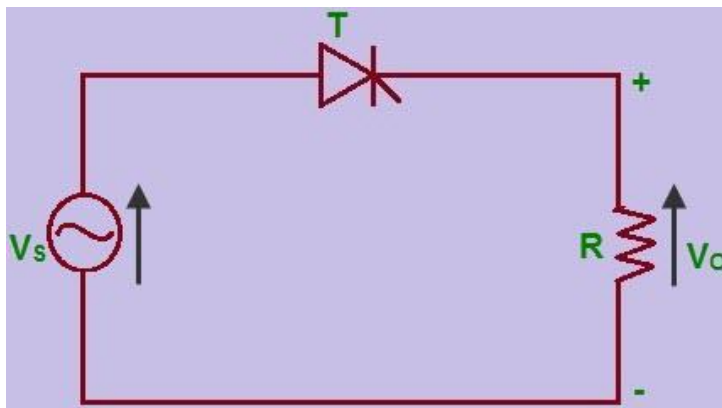
As we have studied above, a thyristor can be turned on by triggering gate terminal with low voltage short duration pulse. But after turning on, it will conduct continuous until the thyristor is reverse biased or the load current falls to zero. This continuous conduction of thyristors causes problems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

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 as natural commutation as thyristor is turned off naturally without using any external components or circuit or supply for commutation purpose.



Natural Commutation

Natural commutation can be observed in AC voltage controllers, phase controlled rectifiers and cycloconverters.

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 basic electronics and electrical components such as inductance and capacitance are used as commutating elements for commutation purpose.

Forced commutation can be observed while using DC supply; hence it is also called as DC commutation. The external circuit used for forced commutation process is called as commutation circuit and the elements used in this circuit are called as commutating elements.

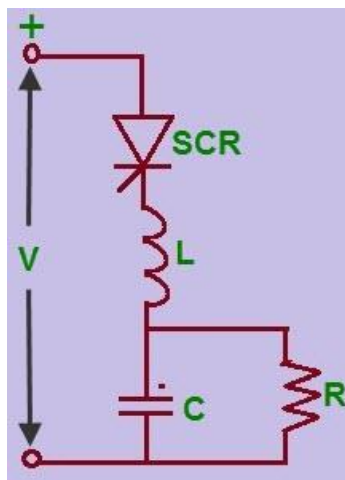
Classification of Forced Commutation Methods

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

Class A is one of frequently used thyristor commutation techniques. 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 thyristor.

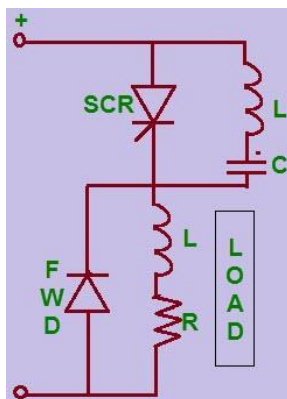


Class A-Commutation

After the thyristor commutation or turning off the thyristor, the capacitor will start discharging from its peak value 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 thyristor commutation techniques is that the LC is connected in series with thyristor in class A, whereas in parallel with thyristor in class B. Before triggering on the SCR, the capacitor is charged up (dot indicates positive). If the SCR is triggered or given triggering pulse, 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 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.

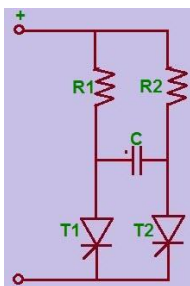


The total current flowing through the SCR becomes zero with the reverse current flowing through the SCR opposing the load current for a small a small fraction of

the negative swing. If the resonant circuit current or reverse current becomes just greater than the load current, then the SCR will be turned OFF.

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

In the above thyristor commutation techniques we observed only one SCR but in these class C commutation techniques of thyristor there will be two SCRs. One SCR is considered as main thyristor and the other as auxiliary thyristor. In this classification both may act as main SCRs carrying load current and they can be designed with four SCRs with load across the capacitor by using a current source for supplying an integral converter.

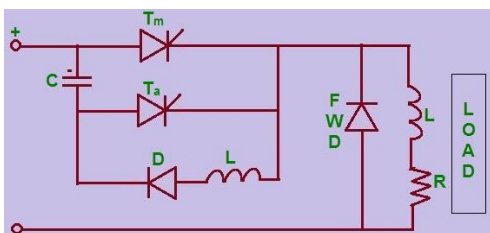


Class C-Commutation

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 class C and class D thyristor commutation techniques can be differentiated with 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. The auxiliary thyristor consists of resistor in its anode which is having resistance of approximately ten times the load resistance.



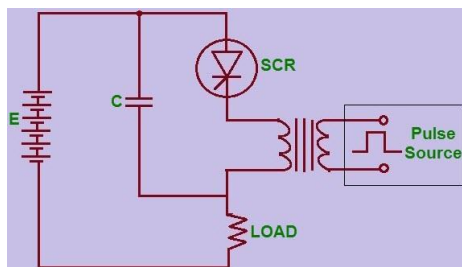
Class D-Commutation

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.

Class E: External Pulse Source for Commutation

For the class E thyristor commutation techniques, a transformer which cannot saturate (as it is having a sufficient iron and air gap) and capable to carry the load current with small voltage drop compared with the supply voltage. If the thyristor T is triggered, then the current will flow through the load and pulse transformer.



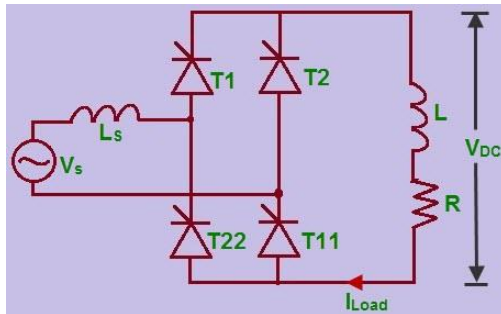
Class E-Commutation

An external pulse generator is used to generate a positive pulse which is supplied to the cathode of the thyristor through 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 electrical transformer which supplies the reverse recovery current, and for the required turn off time it holds the negative voltage.

Class F: AC Line Commutated

In class F thyristor commutation techniques, an alternating voltage is used for supply and, during the positive half cycle of this supply, load current will flow. If the load is highly inductive, then the current will remain until the energy stored in the inductive load is dissipated. During the negative half cycle as the load current

becomes zero, then thyristor will turn off. If voltage exists for a period of rated turn off time of the device, then the negative polarity of the voltage across the outgoing thyristor will turn it off.



Class F-Commutation

Here, the duration of the half cycle must be greater than the turn off time of thyristor. This commutation process is similar to the concept of 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 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 thyristor should be continued until the forward blocking state is reached.

Thyristor can be simply called as a controlled rectifier. There are different types of thyristors, which are used for designing power electronics based innovative electrical projects. The process of turning on thyristor by providing triggering pulses to gate terminal is called as triggering. Similarly, the process of turning off thyristor is called as commutation. Hope this article give brief information about different commutation techniques of the thyristor. Further technical assistance will be provided based on your comments and queries in the comments section below.

Single Phase Fully Controlled Rectifier

Single phase uncontrolled rectifiers are extensively used in a number of power electronic based converters. In most cases they are used to provide an intermediate unregulated dc voltage source which is further processed to obtain a regulated dc or ac output. They have, in general, been proved to be efficient and robust power stages. However, they suffer from a few disadvantages. The main among them is their inability to control the output dc voltage / current magnitude when the input ac voltage and load parameters remain fixed. They are also unidirectional in the sense that they allow electrical power to flow from the ac side to the dc side only. These two disadvantages are the direct consequences of using power diodes in these converters which can block voltage only in one direction. As will be shown in this module, these two disadvantages are overcome if the diodes are replaced by

thyristors, the resulting converters are called fully controlled converters. Thyristors are semicontrolled devices which can be turned ON by applying a current pulse at its gate terminal at a desired instance. However, they cannot be turned off from the gate terminals. Therefore, the fully controlled converter continues to exhibit load dependent output voltage / current waveforms as in the case of their uncontrolled counterpart. However, since the thyristor can block forward voltage, the output voltage / current magnitude can be controlled by controlling the turn on instants of the thyristors. Working principle of thyristors based single phase fully controlled converters will be explained first in the case of a single thyristor halfwave rectifier circuit supplying an R or R-L load. However, such converters are rarely used in practice.

Single phase fully controlled halfwave rectifier

Resistive load

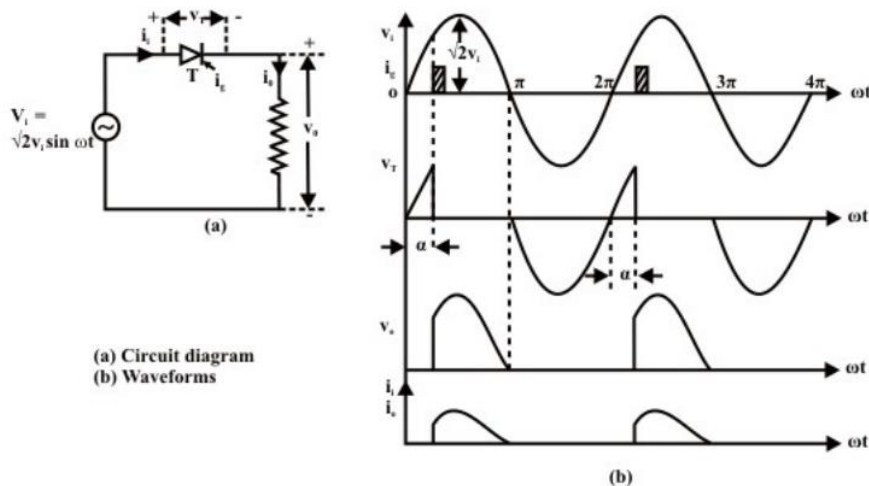


Fig. shows the circuit diagram of a single phase fully controlled halfwave rectifier supplying a purely resistive load. At $\omega t = 0$ when the input supply voltage becomes positive the thyristor T becomes forward biased. However, unlike a diode, it does not turn ON till a gate pulse is applied at $\omega t = \alpha$. During the period $0 < \omega t \leq \alpha$, the thyristor blocks the supply voltage and the load voltage remains zero as shown in fig 10.1(b). Consequently, no load current flows during this interval. As soon as a gate pulse is applied to the thyristor at $\omega t = \alpha$ it turns ON. The voltage across the thyristor collapses to almost zero and the full supply voltage appears across the load. From

this point onwards the load voltage follows the supply voltage. The load being purely resistive the load current i_o is proportional to the load voltage. At $\omega t = \pi$ as the supply voltage passes through the negative going zero crossing the load voltage and hence the load current becomes zero and tries to reverse direction. In the process the thyristor undergoes reverse recovery and starts blocking the negative supply voltage. Therefore, the load voltage and the load current remains clamped at zero till the thyristor is fired again at $\omega t = 2\pi + \alpha$. The same process repeats thereafter.

$$v_o = v_i = \sqrt{2} V_i \sin \omega t$$

$$i_o = \frac{v_o}{R} = \sqrt{2} \frac{V_i}{R} \sin \omega t$$

$$v_o = i_o = 0 \text{ otherwise.}$$

$$\text{Therefore } V_{OAV} = \frac{1}{2\pi} \int_0^{2\pi} v_o d\omega t = \frac{1}{2\pi} \int_\alpha^\pi \sqrt{2} V_i \sin \omega t d\omega t$$

$$\text{Or } V_{OAV} = \frac{V_i}{\sqrt{2}\pi} (1 + \cos \alpha)$$

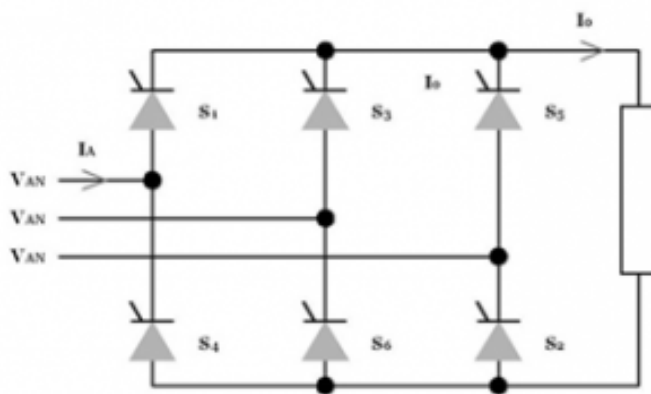
$$\begin{aligned} V_{ORMS} &= \sqrt{\frac{1}{2\pi} \int_0^{2\pi} v_o^2 d\omega t} \\ &= \sqrt{\frac{1}{2\pi} \int_\alpha^\pi 2V_i^2 \sin^2 \omega t d\omega t} \\ &= \sqrt{\frac{V_i^2}{2\pi} \int_\alpha^\pi (1 - \cos 2\omega t) d\omega t} \\ &= \sqrt{\frac{V_i^2}{2\pi} \left[\pi - \alpha + \frac{\sin 2\alpha}{2} \right]} \\ &= \frac{V_i}{\sqrt{2}} \left(1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi} \right)^{\frac{1}{2}} \end{aligned}$$

$$\therefore FF_{VO} = \frac{V_{ORMS}}{V_{OAV}} = \frac{\pi \left(1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi} \right)^{\frac{1}{2}}}{(1 + \cos \alpha)}$$

Similar calculation can be done for i_o . In particulars for pure resistive loads $FF_{i_o} = FF_{v_o}$.

Three Phase Full Wave Controlled Rectifier

The 3-phase half wave converter combines three single phase half wave controlled rectifiers in one single circuit feeding a common load. The thyristor S1 in series with one of the supply phase windings 'a-n' acts as one half wave controlled rectifier. The second thyristor S2 in series with the supply phase winding 'b-n' acts as the second half wave controlled rectifier. The third thyristor S3 in series with the supply phase winding acts as the third half wave controlled rectifier. Figure below shows three phase fully controlled rectifier.



- When thyristor S2 is triggered at $\omega t = (5\pi/6 + \alpha)$, S1 becomes reverse biased and turns-off. The load current flows through the thyristor and through the supply phase winding 'b-n'. When S2 conducts the phase voltage v_{bn} appears across the load until the thyristor S3 is triggered.
- The 3-phase input supply is applied through the star connected supply transformer as shown in the figure. The common neutral point of the supply is connected to one end of the load while the other end of the load connected to the common cathode point.
- When the thyristor S1 is triggered at $\omega t = (\pi/6 + \alpha) = (30^\circ + \alpha)$, the phase voltage V_{an} appears across the load when S1 conducts. The load current flows through the supply phase winding 'a-n' and through thyristor S1 as long as S1 conducts.
- When the thyristor S3 is triggered at $\omega t = (3\pi/2 + \alpha) = (270^\circ + \alpha)$, S2 is reversed biased and hence S2 turns-off. The phase voltage V_{an} appears across the load when S3 conducts.
- When S1 is triggered again at the beginning of the next input cycle the thyristor S3 turns off as it is reverse biased naturally as soon as S1 is triggered. The figure shows

the 3-phase input supply voltages, the output voltage which appears across the load, and the load current assuming a constant and ripple free load current for a highly inductive load and the current through the thyristor T1.

- For a purely resistive load where the load inductance ' $L = 0$ ' and the trigger angle $\alpha > (\pi/6)$, the load current appears as discontinuous load current and each thyristor is naturally commutated when the polarity of the corresponding phase supply voltage reverses. The frequency of output ripple frequency for a 3-phase half wave converter is f_s , where f_s is the input supply frequency. The 3-phase half wave converter is not normally used in practical converter systems because of the disadvantage that the supply current waveforms contain dc components.

Module 3

VOLTAGE SOURCE INVERTER (VSI)

INTRODUCTION

In the past two decades several strategies of speed and torque control of induction motor were reported. Among them proportional controller (P), proportional plus integral controller (PI) and fuzzy logic controller are popular one. Furthermore, the proposed fuzzy based SVPWM algorithm is successfully generalized to allow equally efficient real time implementation of SVPWM to dc/ac converters with virtually any number of levels.

More induction motors are used in industry because they are more rugged and reliable than DC machines. However, their dynamic behavior is considerably more complex than that of a DC machine due to the highly nonlinear and time varying mathematical equations of the induction machine. Many industrial applications require ac/ac power conversion and ac/ac

converters take power from one ac system and deliver it to another with voltage waveforms of different amplitude, frequency or phase.

Therefore, induction motors are often used in a closed loop for adjustable speed applications (Burnay 1989) while DC machines or stepping motors are preferred for high precision positioning tasks. Nevertheless, with the recent advances made in both power electronics data processing and control techniques, the speed control of induction motors can be reliably carried out. High performance electric drives require decoupled torque and flux control. This control is commonly provided through Field Oriented Control (FOC) which is based on decoupling of the torque producing current component and the flux producing component.

FOC drive scheme requires current controllers with coordinates transformation techniques. Current regulated pulse width modulation inverter and inner current loops degrade the dynamic performance in the operating regions wherein the voltage margin is insufficient for the current control, particularly in the field weakening region (Leonhard 1996). The problem of decoupling the stator current in a dynamic fashion is avoided by Direct Torque Control.

Direct torque control is nowadays widely used for induction motor drives. It provides a very quick and precise torque response without the complex field orientation block and the inner current regulation loop. Due to this shortcoming the application of fuzzy logic attracts the attention of many scientists and researchers all over the world. The fuzzy logic control strategy has been chosen for its simplicity and its robustness to external and plant parameter disturbances.

Indeed, the fuzzy logic theory offers the advantage of requiring only a simple mathematical model to formulate the algorithm. These features are appreciated for non linear processes for which there is no reliable model and for fast drives such as the induction motor. On the other hand, the ongoing research has concentrated on the elimination of the speed sensor at the machine shaft without deteriorating the dynamic performance of the drive control system.

The advantages of fuzzy controller based speed sensor induction motor drives are reduced hardware complexity, lower cost, reduced size of the drive machine, better noise immunity, increased reliability and less maintenance requirements. In this work, the performance of the DTC based speed control of induction motor and torque pulsation strategies are presented. The Fuzzy Logic technique then replaces the switching table and hysteresis regulator of the conventional direct torque control while the rotation speed is estimated by the Adaptive System method.

PRINCIPLE OF VOLTAGE SOURCE INVERTER

Rectifier fed inverter system has two stage converters. In this research inverter side control is described. Rectifier side control is used to find out duty cycle. Most inverter applications require a means of voltage control. This control may be required because of variations in the inverter source voltage and regulation within the inverter. It can be grouped into three categories,

- ☐ Control of voltage supplied to the inverter
- ☐ Control of voltage within the inverter
- ☐ Control of voltage delivered by the inverter

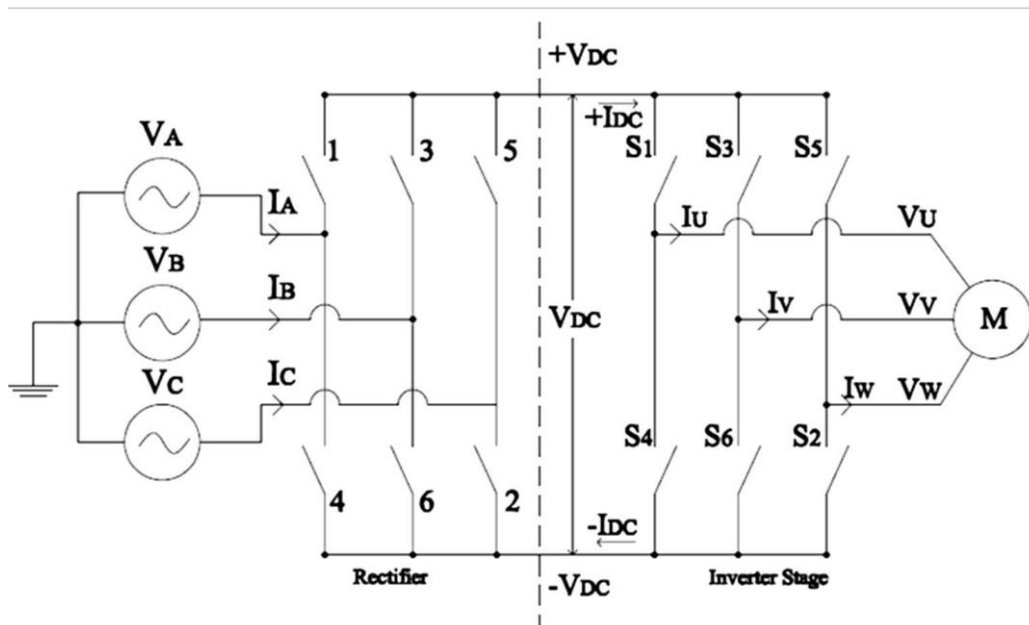
There are a number of well-known methods of controlling the d-c voltage supplied to an inverter or the a-c voltage delivered by an inverter. It includes the use of saturable reactor, magnetic amplifier, induction regulator, phase controlled rectifiers and transistor series or shunt regulators.

With the introduction of high speed, efficient and extremely reliable solid state switching devices, including transistor and silicon controlled rectifier, considerable effort has been put to develop new methods of voltage control. In general, these improved controls involve switching techniques where the voltage control is achieved by some form of switching time-ratio control.

One of the most advantageous means of controlling inverter output voltage is to incorporate switching time-ratio controls within the inverter circuit. This basic form of inverter voltage control is the principal emphasis of this chapter. With implementation of this technique, it is often possible to include inverter output voltage control without significantly adding to the total number of circuit components. A single phase pulse width control technique is discussed here to illustrate the important principles of this means of controls. By properly gating the inverter controlled rectifying device it is possible to vary the amplitude of fundamental component of inverter output voltage.

With this method of control, it is possible to substantially reduce or eliminate lower frequency harmonics (Bowes 1975). Therefore with a minimum filtering a good output waveform is obtained over a wide inverter voltage control range.

Figure shows basic rectifier fed inverter system. There are six switches arranged in a sequence at inverter side. The upper end legs contain S1, S3 and S5. The lower end legs contain S4, S6 and S2. At the same instant, no two devices in a leg should be switched on simultaneously. It causes input short circuit. Possible „On“ and „Off“ states are tabulated in Table



Three Phase Rectifier Fed Inverter

Table Switching States of Voltage Source Inverter

Switching	Leg U			Leg V			Leg W		
State	S_1	S_4	V_{UN}	S_3	S_6	V_{VN}	S_5	S_2	V_{WN}
P	On	Off	V_d	On	Off	V_d	On	Off	V_d
O	Off	On	0	Off	On	0	Off	On	0

The aim is to propose a controller to reduce torque and speed pulsation. The problem posed is to find the ripple and harmonic frequency

content of squirrel cage induction machine characteristics (i.e. current, torque, rotor speed, and voltage) when various space vector modulation (SVM) algorithms are applied to the stator voltage. The discontinuous as well as continuous SVM with active pulses centered in each half-carrier cycle was implemented using basic SVM theory (Holmes and Lipo 2003).

This thesis investigates space vector modulation algorithms conventional with active vectors. Space vector theory states that the conventional SVM to outperform the discontinuous modulation algorithms with respect to unwanted harmonic content and ripples. One may question the use of discontinuous modulation when faced with this fact. The reason to use discontinuous modulation is to decrease the switching losses in the transistors by periodically clamping one of the three phases to a rail to produce a zero vector. The decrease in switching losses associated with discontinuous

modulation allows the system to utilize higher carrier switching frequency. However, this analysis only uses one carrier frequency which governs the period of modulation and switching of the inverter gates. It is desired the amplitude of the stator voltage V , to reach $460 \cdot \sqrt{2/3} V$ on each phase for rated operation.

TORQUE AND SPEED PULSATION REDUCTION

Torque control is one method used in variable frequency drives to control the torque (and thus finally the speed) of three phase induction motor. This involves calculating an estimate of the motor's magnetic flux and torque

based on the measured voltage and current of the motor. Figure shows the basic torque control technique. It contains the following main blocks.

- a. Torque estimator
- b. Torque controller
- c. Flux controller
- d. Lookup table for pulse generator

Stator flux linkage is estimated by integrating the stator voltages. Torque is estimated as a cross product of estimated stator flux linkage vector and measured motor current vector. The estimated flux magnitude and torque are then compared with their reference values. If either the estimated flux or torque deviates from the reference more than allowed tolerance, the transistors of the variable frequency drive are turned Off and On in such a way that the flux and torque will return to their tolerance bands as fast as possible. Thus direct torque control is one form of the hysteresis or bang-bang control.

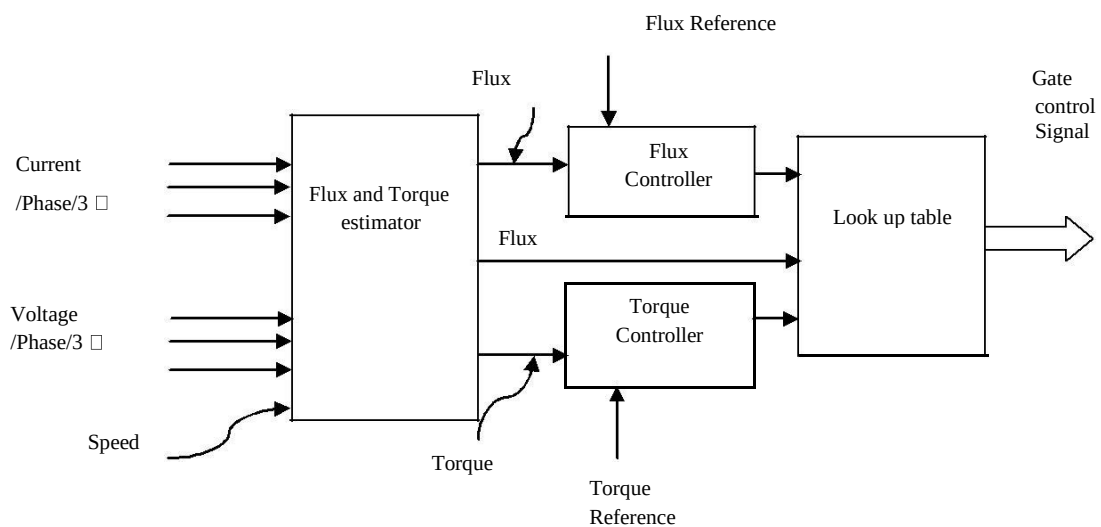


Figure Basic DTC Control (Sensor based)

PROPERTIES OF TORQUE CONTROL TECHNIQUE

- ☐ Torque and flux can be changed by changing the voltage and current references of the inverter
- ☐ The step response of torque control has no overshoot.
- ☐ Calculations are done using stationary coordinate system.
- ☐ The switching frequency of the inverter side switches is not constant.
- ☐ The torque and current ripple are minimized by controlling switching frequency.
- ☐ Digital simulation is possible and very easy to implement in real time.
- ☐ Its control algorithm is performed with high speed operation (10 - 30 microseconds).
- ☐ The direct torque method performs without speed sensors.
- ☐ The flux estimation is usually based on the integration of the motor phase voltages.
- ☐ This will perform well with speed sensor.

CONCLUSION

In this chapter three level inverter and theory of torque control are illustrated. The induction motor voltages and currents are sensed to estimate the torque and the stator flux vector. Direct torque control ensures fast transient response and generates simple implementations due to the absence of closed loop current control. It can be implemented with speed sensor as well as in sensor less configurations. Here sensor based control is used.

Current Source Inverter

Single-phase Current Source Inverter

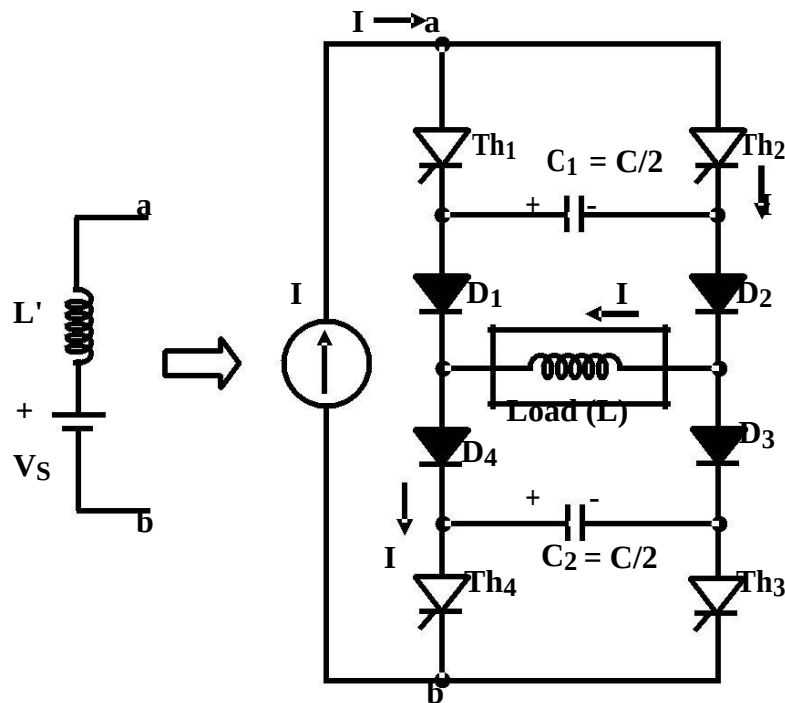


Fig. Single phase current source inverter (CSI) of ASCII type.

The circuit of a Single-phase Current Source Inverter (CSI) is shown in Fig. The type of operation is termed as Auto-Sequential Commutated Inverter (ASCII). A constant current source is assumed here, which may be realized by using an inductance of suitable value, which must be high, in series with the current limited dc voltage source. The thyristor pairs, Th_1 & Th_3 , and Th_2 & Th_4 , are alternatively turned ON to obtain a nearly square wave current waveform. Two commutating capacitors – C_1 in the upper half, and C_2 in the lower half, are used. Four diodes, D_1 – D_4 are connected in series with each thyristor to prevent the commutating capacitors from discharging into the load. The output frequency of the inverter is controlled in the usual way, i.e., by varying the half time period, $(T/2)$, at which the thyristors in pair are triggered by pulses being fed to the respective gates by the control circuit, to turn them ON, as can be observed from the waveforms . The inductance (L) is taken as the load in this case, the reason(s) for which need not be stated, being well known.

PWM INVERTER

Pulse Width Modulation or PWM technology is used in Inverters to give a steady output voltage of 230 or 110 V AC irrespective of the load. The Inverters based on the PWM technology are more superior to the conventional inverters. The use of MOSFETs in the output stage and the PWM technology makes these inverters ideal for all types of loads. In addition to the pulse width modulation, the PWM Inverters have additional circuits for protection and voltage control.

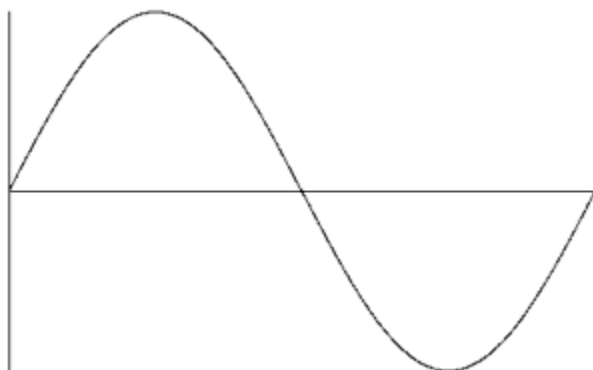
The quality of the output wave form (230 / 110 volt AC) from the inverter determines its efficiency. The quality of the inverter output wave form is expressed using **Fourier analysis data** to calculate the Total Harmonic Distortion (THD). THD is the square root of the sum of the squares of the harmonic voltage divided by the fundamental voltage.

$$\text{THD} = \sqrt{V_2^2 + V_3^2 + V_4^2 + \dots + V_n^2} / V_1$$

Based on the output waveforms, there are three types of Inverters. These are Sine wave, Modified Sine wave or Quasi sine wave and Square wave inverters.

Sine wave

Alternating current has continuously varying voltage, which swings from positive to negative. This has an advantage in power transmission over long distance. Power from the Grid is carefully regulated to get a pure sine wave and also the sine wave radiate the least amount of radio power during long distance transmission. But it is expensive to generate sine wave in an inverter. Its quality is excellent and almost all electrical and electronic appliances work well in sine wave inverter.

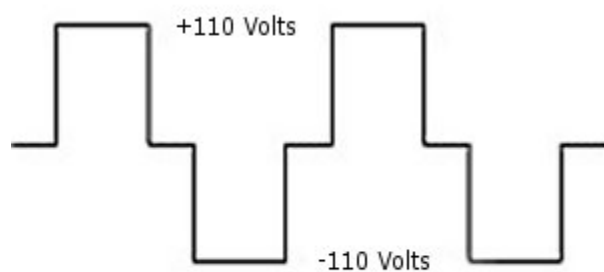


Sine Wave

The sine wave is the AC waveform we get from the domestic lines and from the generator. The major advantage of sine wave inverter is that all of the house hold appliances are designed to operate in sine wave AC. Another advantage is that the sine wave is a form of soft temporal rise voltage and it lacks harmonic oscillations which can cause unwanted counter forces on engines, interference on radio equipments and surge current on condensers.

Modified Sine wave or Quasi Sine wave

Modified sine wave is designed to simulate a sine wave since the generation of sine wave is expensive. This waveform consists of a Flat Plateau of positive voltage, dropping abruptly to zero for a short period, then dropping again to a flat plateau of negative voltage. It then go back to zero again and returning to positive. This short pause at zero volts gives more power to 50 Hz fundamental frequency of AC than the simple square wave.

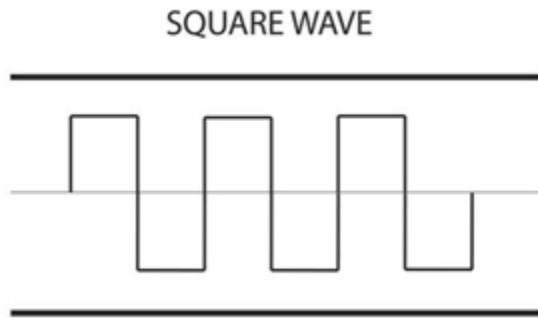


Modified Sine Wave

Inverters providing modified sine wave can adequately power most house hold appliances. It is more economical but may present certain problems with appliances like microwave ovens, laser printers, digital clocks and some music systems. 99% of appliances run happily in modified sine wave. Instruments using SCR (Silicon Controlled Rectifier) in the power supply section behave badly with modified sine wave. The SCR will consider the sharp corners of the sine wave as trashes and shut off the instrument. Many of the Laser printers behave like this and fail to work in inverters and UPS providing modified sine wave power. Most variable speed fans buzz when used in modified sine wave inverters.

Square wave

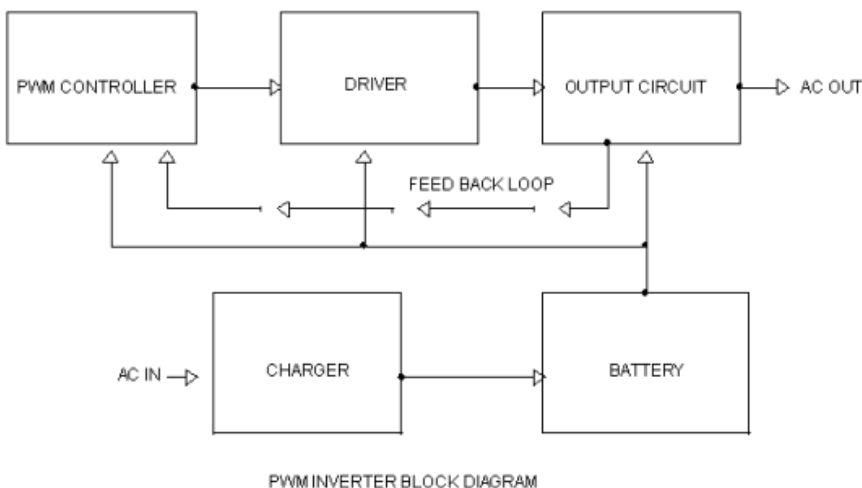
This is the simplest form of output wave available in the cheapest form of inverters. They can run simple appliances without problems but not much else. Square wave voltage can be easily generated using a simple oscillator. With the help of a transformer, the generated square wave voltage can be transformed into a value of 230 volt AC or higher.



Advantage of Pulse Width Modulation

In a standard Inverter without the PWM technology, the output voltage changes according to the power consumption of the load. The PWM technology corrects the output voltage according to the value of the load by changing the Width of the switching frequency in the oscillator section. As a result of this, the AC voltage from the Inverter changes depending on the width of the switching pulse. To achieve this effect, the PWM Inverter has a PWM controller IC which takes a part of output through a feedback loop. The PWM controller in the Inverter will make corrections in the pulse width of the switching pulse based on the feedback voltage. This will cancel the changes in the output voltage and the Inverter will give a steady output voltage irrespective of the load characteristics.

PWM Inverter Block Diagram



How it Works?

To design an Inverter, many power circuit topologies and voltage control methods are used. The most important aspect of the Inverter technology is the output waveform. To filter the waveform (Square wave, quasi sine wave or Sine wave) capacitors and inductors are used. Low pass filters, are used to reduce the harmonic components. Resonant filter can be used if the Inverter has a fixed output frequency. If the inverter has adjustable output frequency, the filter must be tuned to a level above the maximum fundamental frequency. Feedback rectifiers are used to bleed the peak inductive load current when the switch turns off.

As per the Fourier analysis, a square wave contains odd harmonics like third, fifth, seventh etc only if it is anti-symmetrical about 180 degree point. If the waveform has steps of certain width and heights, the additional harmonics will be cancelled. If a Zero voltage step is introduced between the positive and negative parts of the square wave, the harmonics that are divisible by three can be eliminated. The width of the pulse should be $\frac{1}{3}$ of the period for each positive and negative steps and $\frac{1}{6}$ of the period for each of the Zero voltage steps. This leaves on the fifth, seventh, eleventh, thirteenth harmonics etc

.

The Pulse Width Modulation technology is meant for changing the characteristics of the square wave. The switching pulses are Modulating, and regulating before supplied to the load. When the Inverter requires no voltage control, fixed pulse width can be used.

Multiple Pulse Width Modulation (MPWM) Technology

In Multiple Pulse width technology, waveforms that contain a number of narrow pulses are used. The frequency of these narrow pulses is called Switching or Carrier frequency. The MPWM technology is used in Inverters driving variable frequency motor control systems. This allows wide range of output voltages and frequency adjustments. More over the MPWM technology overall improves the quality of the waveform.

PWM Inverter Characteristics

In order to increase the efficiency of the PWM inverter, the electronic circuit is highly sophisticated with battery charge sensor, AC mains sensor, Soft start facility, output control etc. The PWM controller circuit uses PWM IC KA 3225 or LM 494 .These ICs have internal circuits for the entire operation of the pulse width modulation. The Oscillator circuit to generate the switching frequency is also incorporated in the IC. Output driver section uses Transistors or Driver IC to drive the output according to the switching frequency. Output section uses an array

of Switching MOSFETs to drive the primary of the stepping transformer. Output voltage is available in the secondary of the stepping transformer.

Choppers

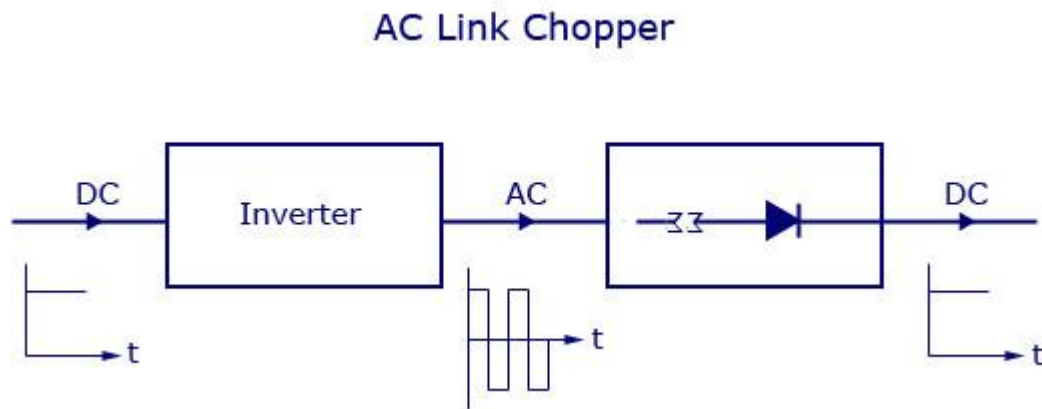
A chopper is basically a dc to dc converter whose main function/usage is to create adjustable dc voltage from fixed dc voltage sources through the use of semiconductors.

Types of choppers

There are two types of choppers – AC and DC.

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.



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 choppers are 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.

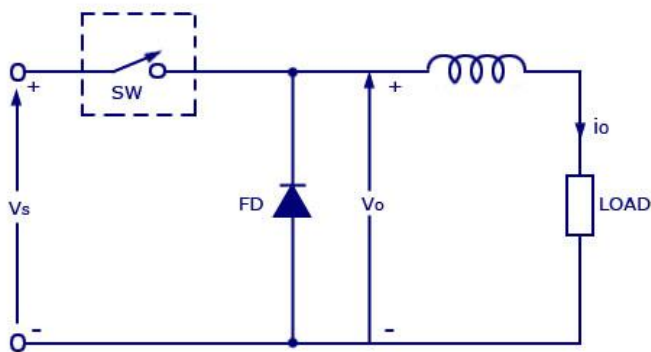
DC Chopper



Principle of Chopper Operation

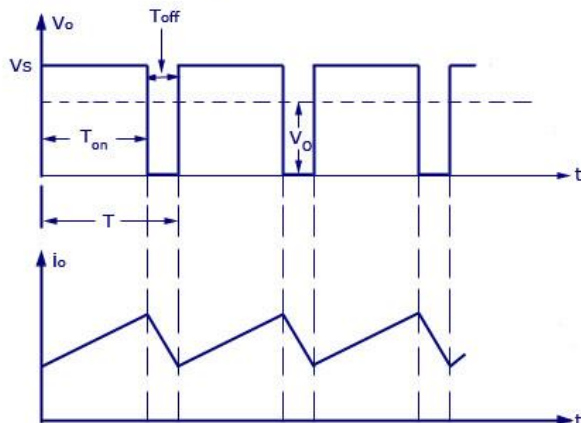
A chopper can be said as a high speed on/off semiconductor switch. Source to load connection and disconnection from load to source happens in a rapid speed. Consider the figure, here a chopped load voltage can be obtained from a constant dc supply of voltage, which has a magnitude V_s . Chopper is the one represented by "SW" inside a dotted square which can be turned on or off as desired.

Chopper Circuit



Output Voltage and Current Waveforms

Output Voltage and Current Waveforms



Let us now take a look of the output current and voltage wave forms of a chopper. During the time period T_{on} the chopper is turned on and the load voltage is equal to source voltage V_s . During the interval T_{off} the chopper is off and the load current will be flowing through the freewheeling diode FD . The load terminals are short circuited by FD and the load voltage is therefore zero during T_{off} . Thus, a chopped dc voltage is produced at the load terminals. We can see from the graph that the load current is continuous. During the time period T_{on} , load current rises but during T_{off} load current decays .

Average load Voltage is given by

$$V_0 = T_{on} / (T_{on} + T_{off}) * V_s = (T_{on}/T) V = A V_s \dots \dots \dots (1.0)$$

T_{on} : on -time

T_{off} : off- time

$T = T_{on} + T_{off}$ = chopping period

$A = T_{on} / T$ = duty cycle

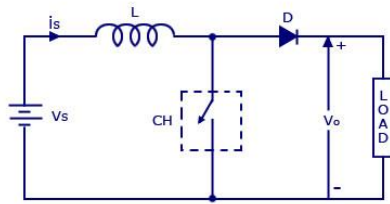
So we know that the load voltage can be controlled by varying the duty cycle A. equation 1.0 shows that the load voltage is independent of load current it can be also written as

$$V_0 = f \cdot T_{on} \cdot V_s$$

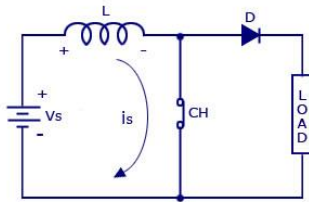
$f = 1/T$ = chopping frequency

Step – up Choppers

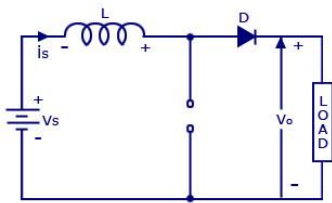
In the case of the chopper circuit (*Refer figure named – “chopper circuit”*) shown in beginning of this article, V_0 or the average output voltage is less than the input voltage V_s so this type of chopper is called a step down chopper. For a step-up chopper we can obtain an average output voltage V_0 greater than input voltage. Figure (a) shows the elementary form of a step-up chopper.



(a)



(b)



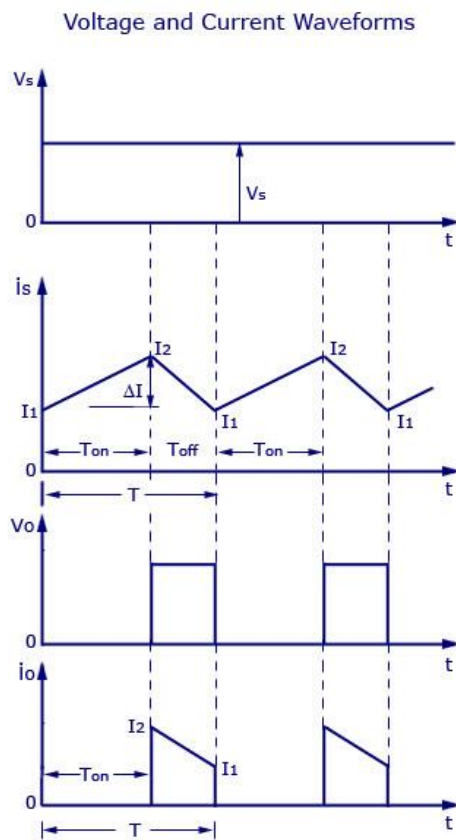
(c)

(a) Step-up chopper (b) L stores energy (c) di/dt is added to V_s

Working Principle of a Step-up Chopper

In step-up chopper a large inductor, L is in series with the source voltage V_s . This forms a closed path as shown in the figure (b). During the time period T_{on} the chopper is on the inductor stores energy. When the chopper is turned off the current is forced to flow through the diode and load for a time T_{off} and as the inductor current cannot die suddenly. When the current decreases the polarity of the emf induced in L is reversed. Fig (c). As a result the total voltage available across the load is given by the equation $V_0 = V_s + L (di/dt)$. The voltage V_0 exceeds the source voltage and hence the circuit acts as a step-up chopper and the energy which is stored in L is released to the load.

Voltage and current waveforms



When the chopper is turned ON the current through the inductance L will increase from I_1 to I_2 . As the chopper is on the source voltage is applied to L that is $v_L = V_s$.

When the chopper is OFF, the KVL for the figure (c) can be written as

$v_L - V_0 + V_s = 0$ or $v_L = V_0 - V_s$ where v_L is the voltage across L . Variation of source voltage v_s , source current I_s , load voltage v_0 and load current i_o is sketched in the fig (d). Let us assume that the variation of output current is linear, the energy input to inductor from the source, during the time period T_{on} , is

$$W_{in} = V_s (I_1 + I_2/2) T_{on}$$

During the time T_{off} the chopper is off, so the energy released by the inductor to the load is

$$W_{off} = (V_0 - V_s)(I_1 + I_2/2) T_{off}$$

Let us assume that the system is lossless, then the two energies say W_{in} and W_{off} are equal.

So equating these two we will get

$$V_s (I_1 + I_2/2) T_{on} = (V_0 - V_s)(I_1 + I_2/2) T_{off}$$

$$V_s T_{on} = (V_0 - V_s) T_{off}$$

$$V_0 T_{off} = V_s (T_{off} + T_{on}) = V_s \cdot T$$

$$V_0 = V_s (T/T_{off}) = V_s (T/T - T_{on}) = V_s (1/(1-A)) \quad \dots\dots\dots(2.0)$$

From the equation 2.0 we can see that the average voltage across the load can be stepped up by varying the duty cycle. If the chopper in the figure (a) is always off, $A=0$ and $V_0 = V_s$. If the chopper is always on, $A=1$ and $V_0 = \text{infinity}$ as we can see from the graph. In practical applications the chopper is turned on and off so that the required step-up average output voltage, more source voltage is obtained.

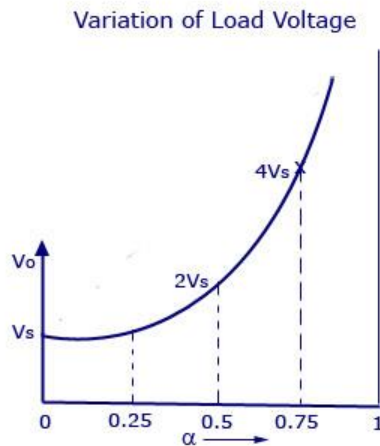


Figure shows variation of load voltage V_0 with duty cycle .

Application of Step-up Chopper

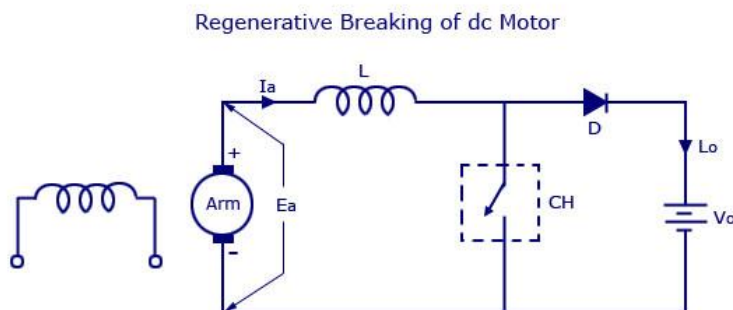


Figure shows regenerative braking of dc motor.

The principle of step-up chopper can be used for the regenerative braking of DC motors. The armature voltage E_a is analogy to the V_s and voltage V_0 is the dc source voltage. When the chopper is on the inductor L stores the energy and when it is off the inductor release the energy. If $E_a / (1-A)$ exceeds V_0 , the dc machine will work as a dc generator and the armature current will flow in a direction opposite to the motoring mode. As the power now is flowing from dc machine to the source V_0 it will cause regenerative braking of the dc motor. Even at decreasing

motor speeds, regenerative braking can be provided as the motor armature E_a is directly proportional to the field flux and motor speed.

Buck-Boost Converters

A Buck-Boost converter is a type of switched mode power supply that combines the principles of the Buck Converter and the Boost converter in a single circuit. Like other SMPS designs, it provides a regulated DC output voltage from either an AC or a DC input.

The Buck converter described in produces a DC output in a range from 0V to just less than the input voltage. The boost converter will produce an output voltage ranging from the same voltage as the input, to a level much higher than the input.

There are many applications however, such as battery-powered systems, where the input voltage can vary widely, starting at full charge and gradually decreasing as the battery charge is used up. At full charge, where the battery voltage may be higher than actually needed by the circuit being powered, a buck regulator would be ideal to keep the supply voltage steady. However as the charge diminishes the input voltage falls below the level required by the circuit, and either the battery must be discarded or re-charged. By combining these two regulator designs it is possible to have a regulator circuit that can cope with a wide range of input voltages both higher or lower than that needed by the circuit. Fortunately both buck and boost converters use very similar components; they just need to be re-arranged, depending on the level of the input voltage.

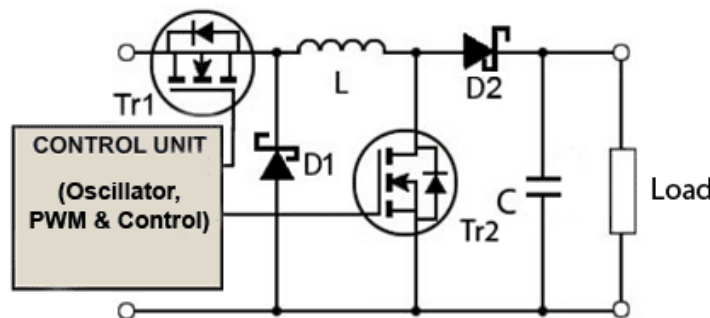


Fig. Buck and Boost Converters Combined

In Fig. the common components of the buck and boost circuits are combined. A control unit is added, which senses the level of input voltage, then selects the appropriate circuit action. (Note that in the examples in this section the transistors are shown as MOSFETs, commonly used in high frequency power converters, and the diodes shown as Schottky types. These

diodes have a low forward junction voltage when conducting, and are able to switch at high speeds).

Operation as a Buck Converter

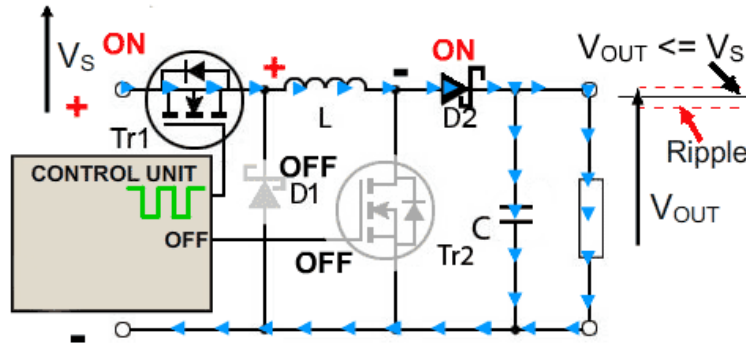


Fig. Operation as a Buck Converter During Tr1 'on' Period

The basic operation of the buck boost converter is illustrated in Figs. 3.3.2 to 3.3.5

Fig. shows the circuit operating as a Buck Converter. In this mode Tr2 is turned off, and Tr1 is switched on and off by a high frequency square wave from the control unit. When the gate of Tr1 is high, current flows through L, charging its magnetic field, charging C and supplying the load. The Schottky diode D1 is turned off due to the positive voltage on its cathode.

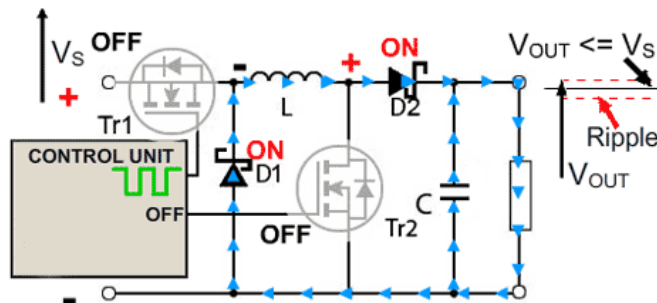


Fig. Operation as a Buck Converter During Tr1 'off' Period

Fig shows the current flow during the buck operation of the circuit when the control unit switches Tr1 off. The initial source of current is now the inductor L. Its magnetic field is collapsing, the back e.m.f. generated by the collapsing field reverses the polarity of the voltage across L, which turns on D1 and current flows through D2 and the load.

As the current due to the discharge of L decreases, the charge accumulated in C during the on period of Tr1 now also adds to the current flowing through the load, keeping V_{OUT} reasonably constant during the off period. This helps keep the ripple amplitude to a minimum and V_{OUT} close to the value of V_S .

Operation as a Boost Converter

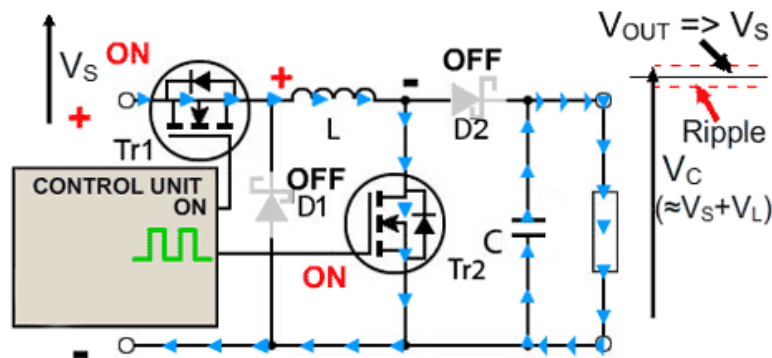


Fig. Operation as a Boost Converter During Tr2 'on' Period

In Boost Converter mode, Tr1 is turned on continually and the high frequency square wave applied to Tr2 gate. During the on periods when Tr2 is conducting, the input current flows through the inductor L and via Tr2, directly back to the supply negative terminal charging up the magnetic field around L. Whilst this is happening D2 cannot conduct as its anode is being held at ground potential by the heavily conducting Tr2. For the duration of the on period, the load is being supplied entirely by the charge on the capacitor C, built up on previous oscillator cycles. The gradual discharge of C during the on period (and its subsequent recharging) accounts for the amount of high frequency ripple on the output voltage, which is at a potential of approximately $V_s + V_L$.

The Off Period

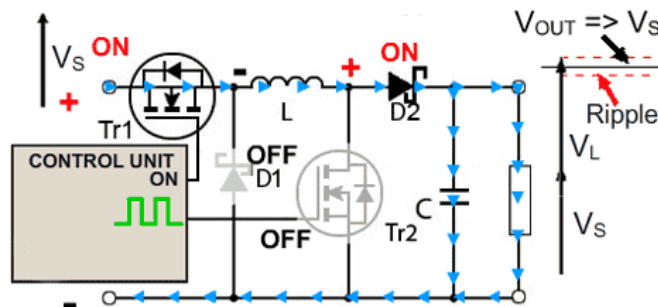


Fig. Operation as a Boost Converter During Tr2 'off' Period

At the start of the off period of Tr2, L is charged and C is partially discharged. The inductor L now generates a back e.m.f. and its value that depends on the rate of change of current as Tr2 switches off and on the amount of inductance the coil possesses; therefore the back e.m.f. can be any voltage over a wide range, depending on the design of the circuit. Notice particularly that the polarity of the voltage across L has now reversed, and so adds to the input voltage

V_S giving an output voltage that is at least equal to or greater than the input voltage. D2 is now forward biased and so the circuit current supplies the load current, and at the same time re-charges the capacitor to $V_S + V_L$ ready for the next on period of T_{r2} .

References :

<http://www.nptel.ac.in/courses/Webcourse>

<http://www.completepowerelectronics.com/vsi-vs-csi-comparison-inverters>

<http://www.electronics-tutorial.net>

MODULE-4

AC VOLTAGE CONTROLLER: 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 '

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

3.1 On-Off control

3.2 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 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 controller 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.

1. Single Phase AC Controllers.
2. 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.

Each type of controller may be sub divided into

- Uni-directional or half wave ac controller.
- Bi-directional or full wave ac controller.

In brief different types of ac voltage controllers are

- Single phase half wave ac voltage controller (uni-directional controller).
- Single phase full wave ac voltage controller (bi-directional controller).
- Three phase half wave ac voltage controller (uni-directional controller).
- Three phase full wave ac voltage controller (bi-directional controller).

APPLICATIONS OF AC VOLTAGE CONTROLLERS

- Lighting / Illumination control in ac power circuits.
- Induction heating.
- Industrial heating & Domestic heating.
- Transformer 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 and three phase Cyclo-converters Industrial applications

In industrial applications two forms of electrical energy Direct Current (DC) and Alternate current (AC) are used. Constant voltage and constant current AC is directly available. However, for different applications different forms, different voltages and/or different currents are needed. Converters are needed to achieve different forms. These converters are classified as rectifiers, choppers, inverters and cycloconverters.

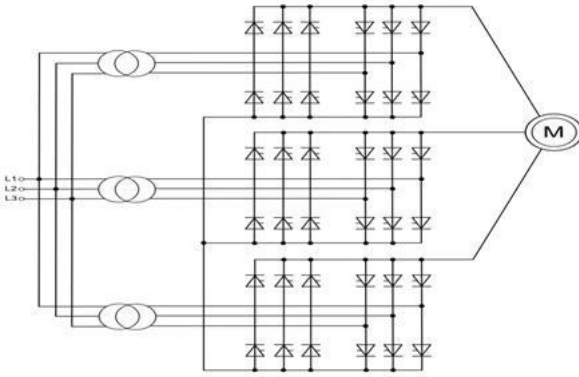
A cycloconverter is a device that converts AC, power at one frequency into AC power of an adjustable but lower frequency without any direct current, or DC, stage in between. It can likewise be acknowledged as a static recurrence charger and holds silicon-regulated rectifiers. Cyclo-converters are used in very large variable frequency drives with ratings from few megawatts up to many tens of megawatts.

Rectifier converts from Single-phase or three-phase AC to variable dc Voltage. Choppers converts from DC to variable dc voltage. Inverters convert from DC to variable magnitude variable frequency single-phase or three-phase AC. Cyclic converters convert from single-phase or three-phase AC to variable magnitude variable frequency single-phase or three-phase AC. A cycloconverter is having four thyristors divided into a positive and negative bank of two thyristors each.

Cycloconverter Basic Schematic:

The cycloconverter is connected input between 30 and 31 as shown below. Motor is connected between 25 & 26.

Depending upon the triggering pulses fed to a set of 8 SCRs between their gate and cathode we get F or $F/2$ or $F/3$.



Types of Cycloconverters:

There are mainly two types of cycloconverters

- Blocking mode type
- Circulating mode type.

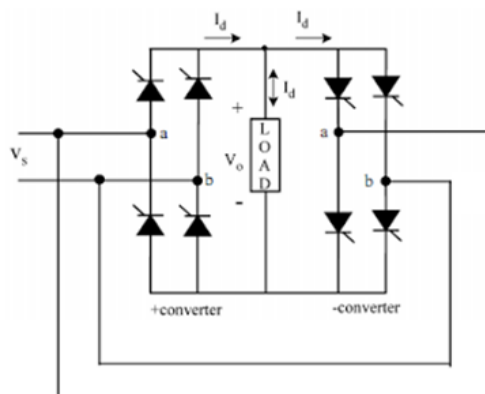
When the load current is positive, the positive converter supplies the required voltage and the negative converter is blocked. Suppose if the load current is negative, then the negative converter supplies the voltage and the positive converter is blocked. This operation is called blocking mode operation. The cycloconverters which are using this method are called blocking mode cycloconverters.

By chance if the both converters are enabled, then the supply will be short circuited. To avoid this, an intergroup reactor (IGR) must be connected between the converters. If both the converters are enabled, then a circulating current is produced. This is unidirectional because the thyristors allow the current to flow in only one direction. The cycloconverters using this approach are called circulating current converters.

Principles of Cycloconverters:

The operation principles of cycloconverters can be classified into the following three types based on the type of input AC supply applied to the circuit.

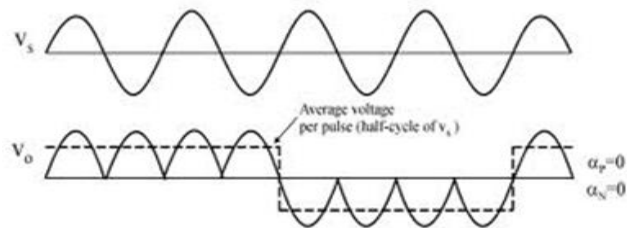
Single-Phase to Single-Phase Cycloconverter:



Understanding of operation principles of cycloconverters should begin with single-phase to single-phase cycloconverter. This converter is having back to back connection of two full wave rectifiers. Suppose for getting one fourth of input voltage at the output, for the first two cycles of

V_s the positive converter operates supplying current to the load and it rectifies the input voltage. In the next two cycles the negative converter operates supplying current in the reverse direction. When one of the converters operates the other one is disabled, so that there is no current circulating between rectifiers. In the below figure V_s represents input supply voltage and V_o is the required output voltage which is one fourth of supply voltage.

Image for One fourth of input voltage at the output using 1-phase to 1-phase Cycloconverter



Three-Phase to Single-Phase Cycloconverters:

Like as above converters, three-phase to single-phase cycloconverter applies rectified voltage to the load. Positive Cycloconverters will supply positive current only while negative converters will supply negative current only. The cycloconverters can operate in four quadrants as $(+v, +i)$, $(+v, -i)$ rectification modes and $(-v, +i)$, $(-v, -i)$ inverting modes. The polarity of the current determines if the positive or negative converter should be supplying power to the load. When there is a change in current polarity, the converter previously supplying current is disabled and the other one is enabled. During the current polarity reversal, the average voltage supplied by both the converters should be equal.

Three-Phase to Three-Phase Cycloconverter:

Two basic configurations are available for three-phase cycloconverters such as delta and wye. If the outputs of above converter are connected in wye or delta and if the output voltages are 120° phase shifted the resulting converter is three-phase to three-phase converter. The three-phase converters are mainly used in machine drive systems running three-phase synchronous and induction machines.

Applications of Cycloconverters:

Cycloconverters can produce harmonic rich output voltages. When cycloconverters are used for a running AC machine, the leakage inductance of the machine filters most of the high frequency harmonics and reducing voltage of the lower order harmonics.

Drives are electromechanical systems that employ an electric motor as the prime mover instead of a diesel engine, steam and gas turbines, or hydraulics to control the motion and processes of various mechanisms. Examples in which electric drives would be utilized include: conveyors, fans, ventilators, compressor pumps, cranes, hoists, excavators, escalators, electric locomotives and cars.

Electric drives generally include both an electric motor and a speed control unit or system. The term drive is often applied to the controller without the motor. In the early days of electric drive

technology, electromechanical control systems were used. Later, electronic controllers were designed using various types of vacuum tubes. As suitable solid state electronic components became available, new controller designs incorporated the latest electronic technology.

In the past, a variety of terms have been used to describe a system that permits a mechanical load to be driven at user-selected speeds. Some of these terms are Variable-Speed Drive, Variable Frequency Drive, Adjustable-Frequency Drive, and Adjustable-Speed Drive.

With these various names, the term "variable" implies a change that may or may not be under the control of the user. "Adjustable" is the preferred term, since this refers to a change directly under control of the user. Lastly, the term "frequency" can only be applied to drives with an ac output, while the term "speed" is preferred since this includes both ac and dc drives. The term most commonly accepted is Adjustable-Speed Drive (ASD). Each of the general types of electric drives can be further divided into numerous variations. Some of the most popular types of electric drives include adjustable voltage DC drives, adjustable frequency AC drives, adjustable voltage AC drives, servo drives, eddy current drives and wound-rotor motor drives. For the purposes of this document, some of the more common electric drives have been highlighted.

AC Drives

An AC Drive is an electronic device that converts a fixed frequency and voltage to an adjustable frequency and AC voltage source. It controls the speed, torque, horsepower and direction of an AC motor. AC Drive is also a term used for an AC inverter and is sometimes used to describe a particular section of an AC drive. The section uses the DC voltage from a previous circuit stage (DC Bus) to produce an AC current or voltage having the desired frequency.

AC Drives are also referred to as Variable Frequency Drives (VFD's) or Adjustable Speed Drives (ASD's). These drives are gaining in popularity due to the energy savings that can be obtained related to the AC technology. In addition, AC motors are simpler than DC and usually an "off-the-shelf" item compared to DC motors. Advances in technology have made the size, cost, reliability and performance of AC drives very appealing in industrial variable speed applications.

The AC Drive system is very simple. It consists of three components:

- **AC Motor** - Usually NEMA Design B, squirrel cage induction, 3-phase motor. The AC motor drives the device (fan, pump, etc.) by converting the electrical power to mechanical power.
- **Motor Control Section** - (also called Inverter section) The motor control section controls the motor's speed by converting utility power into adjustable frequency power.
- **Operator Interface** - The operator control allows the operator to command the motor to function as desired through the use of motor control inputs and outputs.

Today the variable-frequency drive is perhaps the most common type of output or load for a control system. As applications become more complex, the frequency drive has the ability to control the speed of the motor, the direction the motor shaft is turning, the torque the motor provides to a load and any other motor parameter that can be sensed. Newer drives have a variety of parameters that can be controlled by numbers programmed into it or downloaded from another microprocessor-controlled system such as a programmable controller (PLC).

DC Drives

Despite the popularity of AC drives, DC drives have favorable characteristics that prove to be appropriate for many applications. The characteristics of a DC Drive include: speed changes that are made by increasing or decreasing the amount of DC voltage fed to the motor from the drive, low cost for medium and high HP applications, wide speed range and good speed regulation. DC drives can also be very compact in size.

A diagram of a modern DC drive would show that much of the circuitry appears similar to an AC drive. The main difference is that the rectifier stage and output stage of the DC drive are shared because the DC drive simply adjusts the DC voltage and current instead of inverting it back to AC. Since the output voltage for the drive is DC, SCRs will be used in rectifier circuits. The newest drives have programmable parameters similar to AC drives in that they set the maximum voltage, current, and speed, as well as supply protection against overcurrent, over temperature, phase loss of incoming power, and field loss.

DC drives are best used in applications where:

- The DC motor exists in a reasonably clean and dry environment, and the use of DPG, DPG-FV, TENV, or TEFC motor enclosures is required.
- The application requires a wide range of changing loads.
- Motor speeds can reach 2500 RPM
- Starting torque is greater than 150% or unpredictable.
- Application HP requirements are medium to large.

Speed Control Methods of Induction Motor:

In this post let us see what are the various methods to control the speed of Induction Motor...We know that the speed of the induction motor is given by,

$$N = \frac{120f}{P}$$

From the above equation, the speed of the motor can be controlled by changing supply frequency and by changing number of poles in the stator.

Control From Stator Side:

- By changing the supply frequency
- By changing number of stator poles
- By changing the supply voltage

Control From Rotor Side:

- By inserting resistance in rotor circuit
- By various ways of cascade connection
- By injecting EMFs in the rotor circuit.

Speed Control by frequency variation:

- By varying supply frequency (on small amount), we can vary the speed.

- But a decrease in supply frequency decreases the speed and increases the flux, core losses which leads heating and low efficiency.
- Increase in frequency increases the speed and reduces the torque.
- A separate costlier auxiliary equipment is required to provide a variable frequency.
- So this method is not used in practical.

Speed Control By Pole Changing:

- The change of number of poles is done by having two or more entirely independent stator windings in the same slots.
- Each winding gives a different number of poles, so we will get different speeds.
- Due to cost and complex switching arrangements, it is not practical to provide more than two arrangements of poles (ie, two normal speeds).
- This method is applicable to squirrel cage induction motor only.
- It is not practically applicable with wound rotor.

Speed control by varying Supply voltage:

- The speed of induction motor can be varied by changing supply voltage.
- The torque developed in this method is proportional to the square of the supply voltage.
 $T \propto V^2$
- This is the cheapest and easiest method, but it is rarely used because of the below reasons.

1. A small change in speed requires a large change in voltage.
2. This large change in voltage will result in a large change in the flux density.

Speed control by varying Rotor Resistance:

- This method is applicable to three-phase slip-ring induction motor only.
- By introducing external resistance in the rotor circuit, the speed of the motor can be reduced.
- The change in speed depends upon both rotor circuit resistance and load.
- Due to power loss in the resistance, this method is used where speed changes are required for short period only.
- This method is similar to armature rheostat control method of DC shunt motors.

Speed control by injected EMF:

- Instead of applying the resistance into the rotor circuit of the motor, the speed can be varied by applying EMFs into the circuit.
- These EMFs are applied at the rotor by a suitable source whose frequency should be same as slip frequency.
- Inserting the EMF in phase with the rotor induced EMF is equivalent to decreasing the rotor resistance.

- Inserting the EMF in phase opposition to the induced rotor EMF is equivalent to increasing its resistance.
- Thus by injecting EMF into the rotor the speed can be controlled.

Speed control by Cascade Connection:

- This method needs two motor, one of them is wound motor.
- The two motors are mechanically coupled together to drive a common load.
- The starter of slip ring induction motor is connected to three-phase supply and its rotor is connected to stator of the other machine.
- There are four possible speeds can be obtained by this arrangement.

$$N = \frac{120f}{P_1}$$

$$N = \frac{120f}{P_2}$$

$$N = \frac{120f}{P_1 + P_2}$$

$$N = \frac{120f}{P_1 - P_2}$$

Where f = supply frequency
P1 = No of poles in slip ring motor
P2 = No of poles in other motor

Reference:

<https://elektroftunp.files.wordpress.com/2009/04/7-ac-voltage-controller.pdf>

<http://www.galco.com/comp/prod/driv.htm>

<http://www.electricalbasicprojects.com/induction-motor-speed-control-methods/>

