Power Electronics & Drives

Index

Power Semiconductor Devices

"Power Electronics & Drives : Power Semiconductor Devices

1. **HISTORY OF POWER SEMICONDUCTOR DEVICES**

The first semiconductor device used in power circuits was the electrolytic rectifier - an early version was described by a French experimenter, A. Nodon, in 1904. These were briefly popular for the application of industries using aluminium sheets, and in domestic household appliances because they can withstand low voltages and have good efficiency.

The first solid-state power semiconductor devices were copper oxide rectifiers, used in early battery chargers and power supplies for radio equipment, announced in 1927 by L.O. Grundahl and P. H. Geiger.

The first germanium power semiconductor device appeared in 1952 with the introduction of the power diode by R.N. Hall. It had a reverse voltage blocking capability of 200 V and a current rating of 35 A.

Later, germanium bipolar transistors with substantial power handling capabilities (up to 100 mA collector current) were introduced around 1952. Silicon power transistors were introduced in 1957 and had made a big change in the industries because silicon power devices have better frequency response than germanium devices and could operate up to 150ºC junction temperature.

In 1957, thyristors were appeared & is able to withstand very high reverse breakdown voltage and is also capable of carrying high current. However, one disadvantage of the thyristor in switching circuits is that once it becomes 'latched-on' in the conducting state; it cannot be turned off by external control, as the thyristor turn-off is passive, i.e., the power must be disconnected from the device. Thyristors which could be turned off without any external control mechanism are called gate turn-off thyristors (GTO) which were introduced in late 1960’s. These overcome some limitations of the ordinary thyristor, because they can be turned on or off with an applied gate signal.

1. **POWER ELECTRONICS & ITS APPLICATION**

Power Electronics is a subject that concerns with the application of electronic principles into situations that are rated at power level rather than signal level.

In the modern era, power electronics has various application such as

- Commercial – Uninterruptible power supply (UPS)
- Aerospace – Aircraft power systems
- Industrial –Textile mills, cement mills, welding
- Residential –Personal computers, vacuum cleaners
- Transportation-Street cars, trolley buses.
- Utility systems-HVDC, static circuit breakers.

2.1. Basic Power Electronic Circuit Block Diagram:

The figure below shows a basic power electronic system. The output of the power electronic circuit may be variable DC/ variable AC voltage/ variable frequency. The feedback component measures parameters of load like speed in case of a rotating machine. The difference between the target speed and measured speed controls the behavior of power electronic circuit.

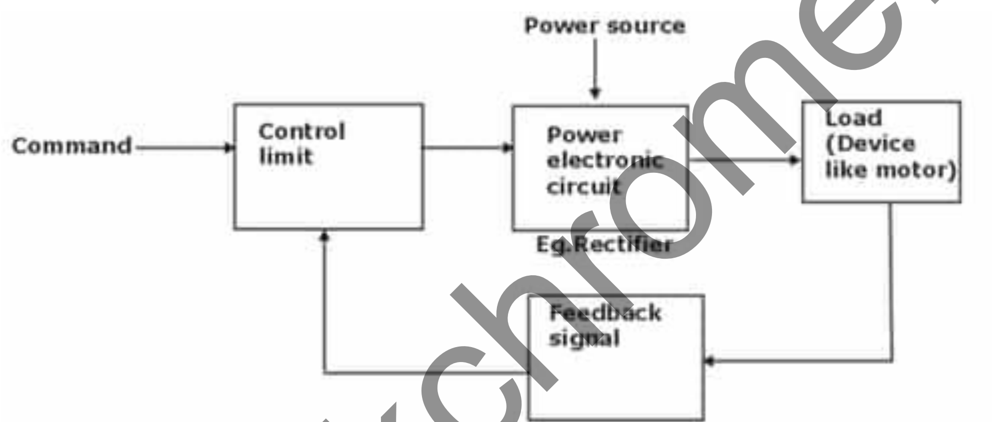


Figure 1: Block diagram of a typical power electronic system

1. **POWER SEMI-CONDUCTOR DEVICES**

Power semi-conductor devices should ideally constitute following characteristics:

- Must be able to carry large current.
- ON resistance should be lower (ideally 0) to reduce heat dissipation.
- OFF resistance should be higher (ideally ∞) to withstand switching transients.
- They must carry large currents with uniform distribution of current over device's area to avoid localized heating and breakdown.
- Device should be capable of high switching speed.
- Faulty switching due to applied voltage transient should not happen.

3.1. Classification of Power Semi-conductor devices based on Operating Characteristics:

3.1.1. Uncontrolled Devices:

Uncontrolled devices are the power semi-conductor devices whose V-I characteristics cannot be controlled. Their on and off states are controlled by power supply. These are typically used in uncontrolled rectifiers. For Example: Power diodes.

3.1.2. Fully Controlled Devices:

These devices can be switched ON/OFF by using a control signal. For Example: Power transistors, MOSFET’s.

3.1.3. Semi-Controlled Devices:

These devices can be partially controlled using a control signal. For Example: SCR can be turned ON using gate signal but can’t be turned OFF.

3.2. Classification of Power Semi-conductor devices based on Polarity & Direction of Current:

3.2.1. Unipolar switch:

The switch can block only one polarity of voltage when it is in OFF state.

3.2.2. Bipolar switch:

This switch can block both polarity of voltage when it is in blocking state.

3.2.3. Unidirectional switch:

This switch can carry current in only one direction when it is in conduction state.

3.2.4. Bidirectional switch:

This switch can carry current in both the direction when it is in conduction state.

1. **POWER SEMI-CONDUCTOR DIODE**

Power diodes belong to the class of uncontrolled power semiconductor devices. They are like p-n junction diodes but having large voltage and current rating. It has 3-layer diode which makes it suitable for high power application as they are constructed with n^- layer between p^+ and n^+ layers to support large blocking voltage by controlling the width of depletion region.

4.1. Basic Structure and Symbol of the Power Diode:

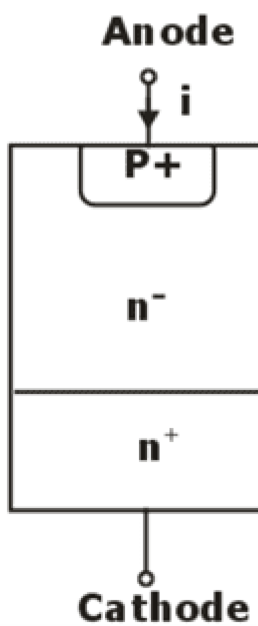


Figure 2: Constructional Structure of Power diode

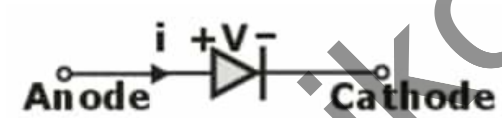


Figure 3: Symbol of Power diode

4.2. Transfer Characteristics of a Power Diode:

When anode is positive with respect to cathode, diode is forward biased. When forward voltage across diode is slowly increased from 0 to cut-in voltage, diode current is almost zero. Above cut-in voltage, the diode current rises rapidly and the diode is said to conduct. When anode is negative with respect to cathode, diode is reverse biased.

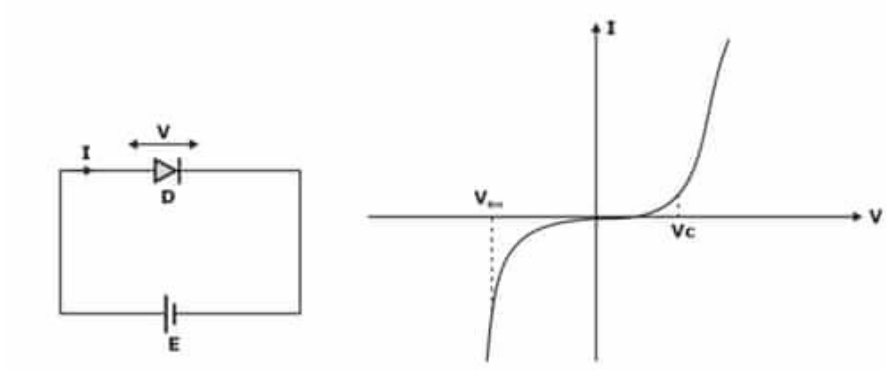
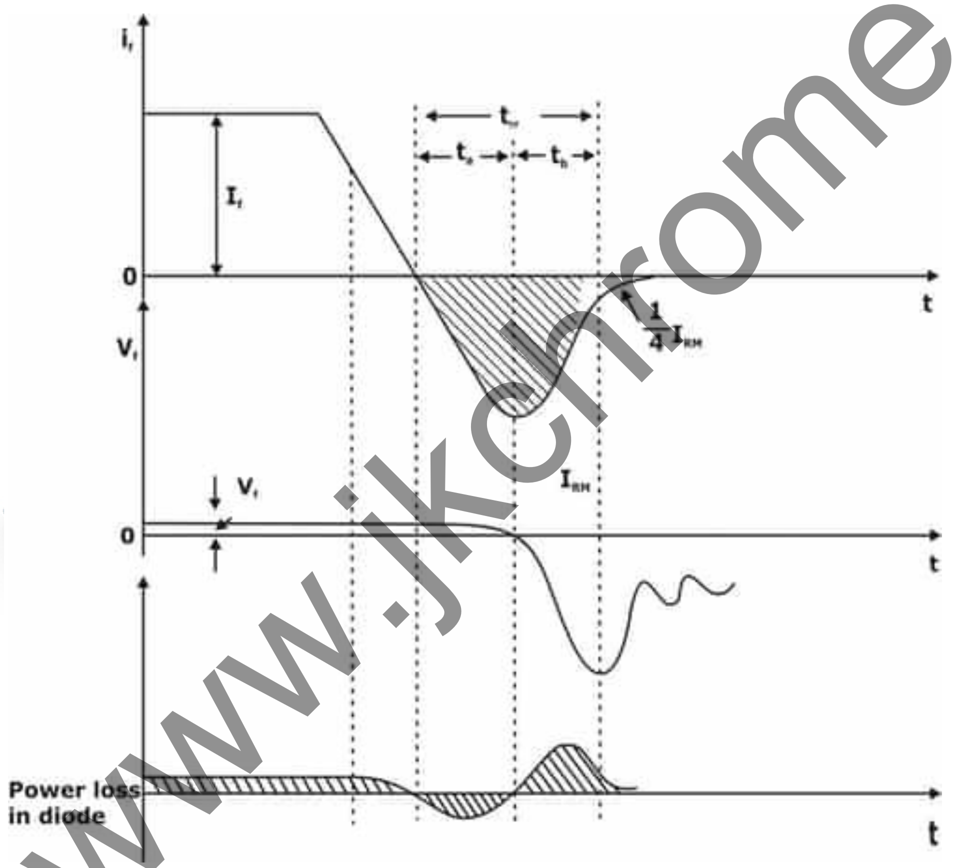


Figure 4: Transfer characteristics of power diode

4.3. Reverse recovery characteristics of Diode:



4.3.1. Reverse recovery time (t_{rr}):

When a diode is changed from forward biased state to reverse biased state, the diode continues to conduct in the reverse direction because of stored charges in two layers. The reverse current flows for reverse recovery time, t_{rr}. The reverse recovery time is defined as the time between the instant forward current becomes zero and the instant reverse recovery current decays to 25% of reverse peak value, I_{RM}.

Reverse recovery time, $t_{rr} = t_a + t_b$

Where t_a is time for diode current to reach I_{RM} from 0,

t_b is the time for diode current to reach I_{RM} from I_{RM}.

In time t_a, charge in depletion region is removed, hence the current through diode decays thereafter. During t_b, charge from two semiconductor layers is removed.

4.3.2. Softness factor (S):

Softness factor (S) is defined as ratio of t_b and t_a. Softness factor is a measure of voltage transients that occur during the time diode recovers.

$S = t_b/t_a$

Softness Factor	Class of diode	Nature of voltage
S=1	Soft recovery diode	Less voltage transient
S<1	Fast recovery diode	High voltage transient

Table 1: Classification of diode based on softness factor

4.3.3. Classification of Power Diodes:

Power diodes can be classified as below based on their use case. This classification is different from that of classification based on softness factor.

- **General Purpose Diodes:** These diodes have high reverse recovery time, t_{rr}. Application of this type of diodes include battery charging electric traction and uninterruptible power supplies (UPS).
- **Fast Recovery Diodes:** These diodes have low t_{rr}. To get low t_{rr}, platinum or gold doping is done while manufacturing these diodes. Hence these diodes have more forward voltage drop. These diodes are mainly used in choppers, commutation circuits and switched mode power supplies (SMPS).
- **Schottky Diodes:** These diodes use metal to semi-conductor junction. Hence these diodes have lesser t_{rr} and lesser forward voltage drop. In

these diodes, current flow is by majority carriers only and hence there is no turn off delay due to absence of minority carries combination.

4.3.4. Points to Remember in Power Semiconductor Diodes

- Power diodes are constructed with a vertically oriented structure that includes a 'n⁻' drift region to support large blocking voltages.
- The breakdown voltage is approximately inversely proportional to the doping density of the drift region, and the required minimum length of the drift region scales with the desired breakdown voltage.
- Achievement of large breakdown voltages requires special depletion layer boundary shaping techniques.
- Conductivity modulation of the drift region in the on state keeps the losses in the diode to manageable levels even for large on state currents.
- Low on-state losses require long carrier lifetimes in the diode drift region.
- Minority-carrier devices have lower on-state losses than majority-carrier devices such as MOSEFTs at high blocking voltage ratings.
- During the turn-on transient the forward voltage in a diode may have a substantial overshoot, on the order of tens of volts.
- Short turn-off times require short carrier lifetimes, so a trade-off between switching times and on-state losses must be made by the device designer.
- During turn-off, fast reverse recovery may lead to large voltage spike because of stray inductance.
- The problems with the reverse-recovery transient are most severe in diodes with large blocking voltage ratings.
- Schottky diodes turn on and off faster than p-n junction diodes and have no substantial reverse-recovery transient.
- Schottky diodes have lower on-state losses than p-n junction diodes but also have low breakdown voltage ratings, rarely exceeding 100 V.

1. **POWER BIPOLAR JUNCTION TRANSISTOR: (POWER BJT)**

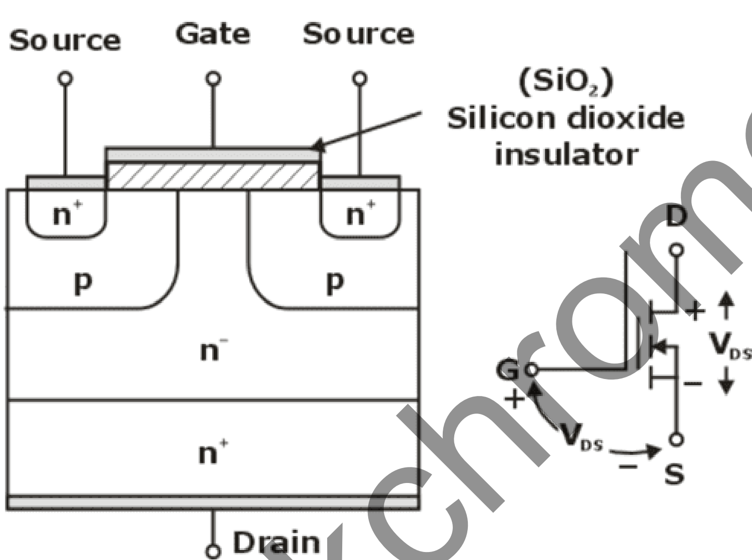
Power transistor is a current controlled device and the control current is made to flow through base terminal. Thus, the device can be switched ON or OFF by applying a positive/negative signal at base. The transistor remains in on-state if control signal is present. The need for a large blocking voltage in the off state and a high current carrying capability in the on state means that a power Bipolar junction Transistor (BJT) must have a substantially different structure than its logic level counterpart.

1. **POWER MOSFET**

MOSFET is a voltage-controlled device. It has three terminals, called drain, source and gate. As its operation is based on flow of majority carriers only, MOSFET is unipolar device. A metal oxide semiconductor field effect transistor (MOSFET) has three terminals called drain (D), source (S) and gate (G).

As power MOSFET is unipolar device, there is no minority storage effect so that high switching speed is possible. Here switching speed is limited by inherent capacitance only. Also due to large drain area, secondary breakdown and thermal runaway that destroy the device do not occur.

The basic structure and circuit symbol of power MOSFET is,



- Generally, MOSFET are low voltage and high current devices.
- These are very popular in dc to dc conversion (choppers).
- These are very fast devices compared to BJT.
- BJT is a minority carrier device where MOSFET is a majority carrier device.
- MOSFET has a very high input impedance.
- Gate is insulated from the rest of the device.
- No steady current flows through the gate. (Only displacement current like in parallel plate capacitor will flow.)
- MOSFET is in cutoff region when gate to source voltage (V_{GS}) is less than threshold value.
- When V_{GS}> Threshold (V_{Th}). It converts silicon surface below the gate into an N-type channel.
- The threshold value depends upon oxide layer and it can be reduced by reducing the thickness of SiO_2

- A BJT is a current controlled device whereas a power MOSFET is a voltage-controlled device.
- The control signal, or base current in BJT is much larger than the control signal (or gate current) required in a MOSFET. This is because gate circuit impedance in MOSFET gate to be driven directly from microelectronic circuits.

SILICON CONTROLLED RECTIFIER (SCR) OR THYRISTOR

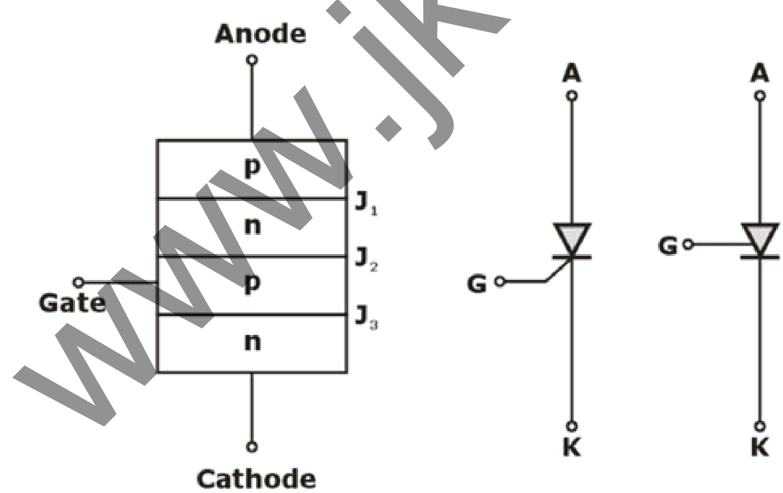
The first SCR was developed in late 1957. Silicon controlled rectifier which is shortly referred as SCR belongs to thyristor family. It's a solid-state device like transistor. It is a four-layer three junction p-n-p-n device and has three terminals; anode, cathode and gate.

SCR can be turned on by using a gate signal controlling the charge near the p-n junction. Hence SCR is a charge-controlled device. However, SCR can't be turned off by using gate signal. Thus,

SCR belongs to the class of semi-controlled semi-conductor device.

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

The schematic diagram and circuit symbol of thyristor are shown in figure below:



1.1. Operating Modes of Thyristor:

Depending on polarity of Anode (A) and Cathode (K) voltage and gate signal, SCR can be operated in following modes:

1.1.1. Reverse Blocking Mode:

In this mode, terminal K is positive with respect to terminal A and also the gate terminal is open. Hence the junctions, J_1 and J_3 are reverse biased and J_2 is forward biased. If reverse voltage is increased above $V_{BR,}$ avalanche breakdown occurs at J_1 and J_3 and reverse current increases rapidly. A large current associated with V_{BR} gives rise to more losses in SCR. This may lead to thyristor damage as the junction temperature may exceed permissible limit. Therefore, it should be ensured that maximum reverse voltage doesn't exceed V_{BR}.

When cathode of the thyristor is made positive with respect to anode with switch open thyristor is reverse biased. Junctions J_1 and J_2 are reverse biased where junction J_2 is forward biased. The device behaves as if two diodes are connected in series with reverse voltage applied across them.

A small leakage current of the order of few mA only flows. As the thyristor is reverse biased and in blocking mode. It is called as acting in reverse blocking mode of operation.

Now if the reverse voltage is increased, at a critical breakdown level called reverse breakdown voltage V_{BR}, an avalanche occurs at J_1 and J_3 and the reverse current increases rapidly. As a large current associated with V_{BR} and hence more losses to the SCR. This results in Thyristor damage as junction temperature may exceed its maximum temperature rise.

1.1.2. Forward Blocking Mode:

In this mode, terminal A is positive with respect to terminal K and gate terminal is open. Hence junction J_1 and J_3 are forward biased and J_2 and SCR starts conducting. But this method of triggering the SCR is not preferred as it may damage the device. Hence in forward blocking state, thyristor can be treated as an open switch. When anode is positive with respect to cathode, with gate circuit open, thyristor is said to be forward biased.

Thus, junction J_1 and J_3 are forward biased and J_2 is reverse biased. As the for ward voltage is increases junction J_2 will have an avalanche breakdown at a voltage called forward breakover voltage V_{BO}. When forward voltage is less then V_{BO} thyristor offers high impedance. Thus, a thyristor acts as an open switch in forward blocking mode.

1.1.3. Forward Conduction Mode:

A thyristor is brought from forward blocking mode to forward conduction mode by increasing V_{AK} above V_{BO} or by applying a gate pulse between gate and cathode. In this mode, thyristor is in on-state and behaves like a closed-switch.

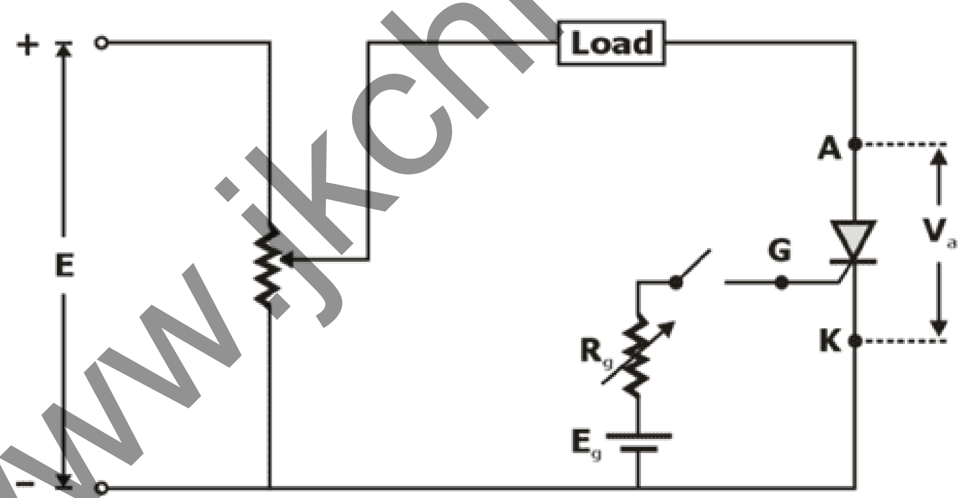
Here thyristor conducts current from anode to cathode with a very small voltage drop across it. So, a thyristor can be brought from forward blocking mode to forward conducting mode:

- By exceeding the forward breakover
- By applying a gate pulse between gate and

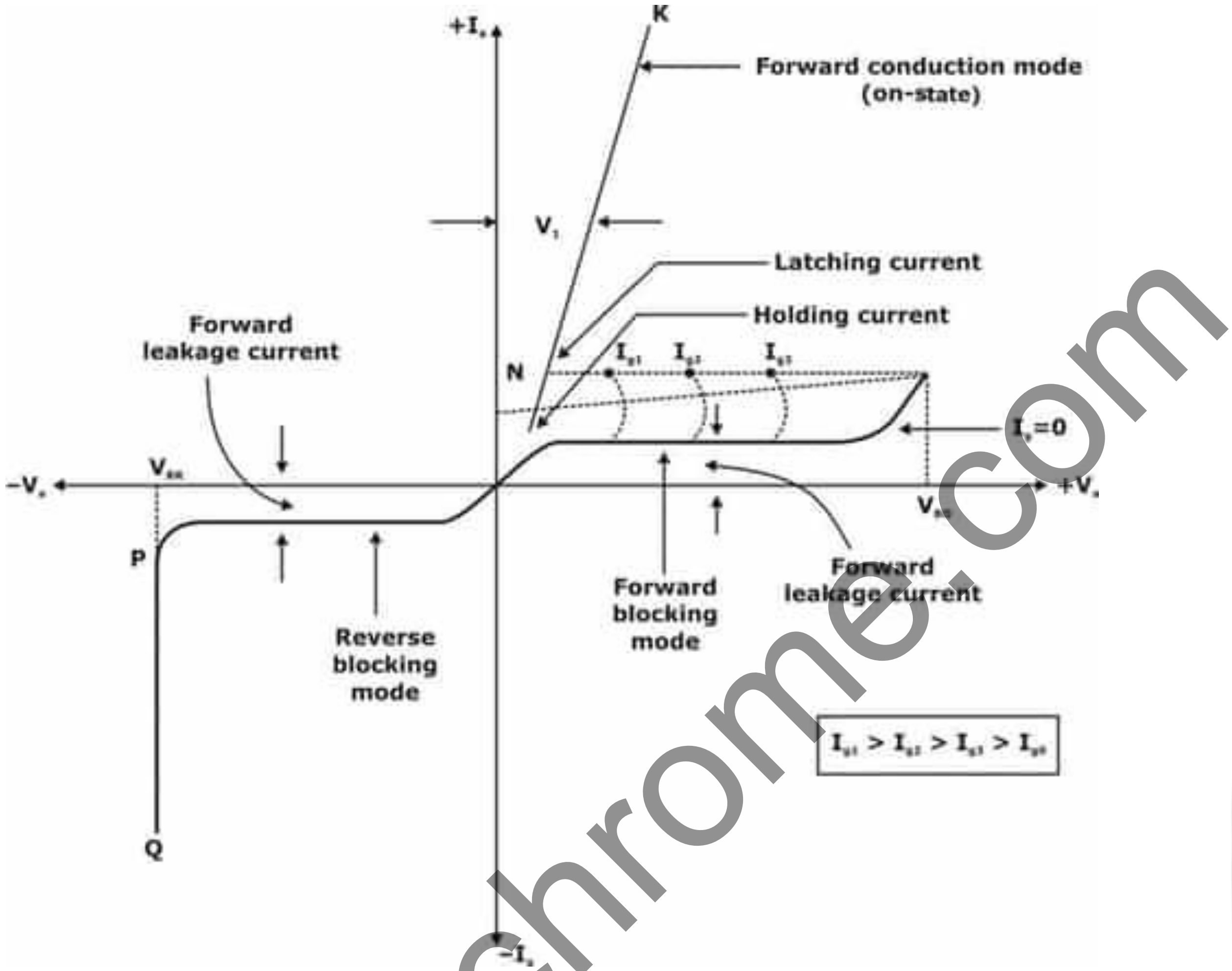
During forward conduction mode of operation thyristor is in on state and behave like a close switch. Voltage drop is of the order of 1 to 2mV. This small voltage drop is due to ohmic drop across the four layers of the device.

1. **STATIC V-I CHARACTERISTICS OF SCR**

An elementary circuit diagram for obtaining static V-I characteristics of SCR is shown in figure



- The Anode and Cathode are connected to main source through the load.
- The Gate and Cathode are fed from another source 'E_g'
- The static V-I characteristics of SCR are shown below:



Where,

V_a=Anode voltage : I_a=Anode current

V_{BO} = Forward breakover voltage

V_{BR}= Reverse breakdown voltage

1. **SWITCHING CHARACTERISTICS OF SCR**

- SCR voltage and current waveforms during turn-on and turn–of process.
- Switching characteristics are also known as dynamic characteristics or transient characteristics.
- The time variations of the voltage across the SCR and the current through it during turn-on and turn-off processes give the dynamic or switching characteristics.

3.1. Switching Characteristics During Turn-on:

SCR turn on time, is defined as the time during which SCR changes from forward blocking mode to final on state.

Total turn on-time can be divided into three intervals;

1. Delay time (t_d)
2. Rise time (t_r)
3. Spread time (t_p)

3.1.1. Delay Time (t_d):

The delay time (t_d) is the time between the instant at which gate current reaches 0.9 I_g to the instant at which anode current reaches 0.1 I_a. Here I_g and I_g are respectively the final values of gate and anode currents or the delay time (t_d) may also be defined as the time during which anode voltage falls from V_a to 0.9 V_a where V_a =initial value of anode voltage. The time during which anode current rises from forward leakage current to 0.1 I_a=final value of anode current.

3.1.2. Rise Time (t_r):

The time taken by the anode current to rise from $0.1I_a$ to $0.9I_a$. The rise time is also defined as the time required for the forward blocking off state voltage to fall from 0.9 to 0.1 of its initial value OA. During rise time, turn-on losses in the thyristor are high due to high anode voltage (V_a) and large anode current(I_a) occurring together in the thyristor.

3.1.3. Spread Time(t_p):

The time taken by the anode current to rise from $0.9I_a$ to I_a. It is also defined as the time for the forward blocking voltage to fall from 0.1 of its initial value to the on-state voltage drop.

3.2. Switching Characteristics During Turn-off:

SCR turn-off means that it has changed from on to off state and can block the forward voltage. The dynamic process of the SCR from conduction state to forward blocking state is called commutation process or turn-off process.

Note: If forward voltage is applied to the SCR now its anode current falls to zero, the device will not be able to block this forward voltage, as the carriers (holes and electrons) in the four layers are still favorable for conduction. The device will therefore go into conduction immediately even though gate signal is not applied. So to solve this problem it is essential that the thyristor is reverse biased for a finite period after the anode current has reached zero.

Turn-off time (t_q):

It is the time between the instant anode current becomes zero and the instant SCR regains forward blocking capability.

During this time (t_q) all the excess carriers from four layers of SCR must be removed.

The turn-off time is divided into two intervals:

1. Reverse recovery time (t_{rr})
2. Gate recovery time (t_{gr})

After t_1: anode current builds up in the reverse direction with the same di/dt slope. The reason for the reversal of anode current is due to the presence of charge carriers stored in the four layers.

At instant t_3 when reverse recovery current has fallen to nearly zero value, end junction J_1 and J_3 recover and SCR is able to block the reverse voltage.

At the end of reverse recovery period t_3: the middle junction J_2 still has charges, therefore, the thyristor is not able to block the forward voltage at t_3

The charge carriers at J_2 cannot flow to the external circuit, therefore they must decay only by recombination. This is possible if a reverse voltage is maintained across SCR. The time taken for this ($t_4 - t_3$) is called gate recovery time (t_{gr}).

The thyristor turn-off time t_q is depended upon magnitude of forward current, di/dt at the time of commutation and junction temperature.

Circuit Turn-off Time 't_c':

It is defined as the time between the instant anode current becomes zero and the instant reverse voltage due to practical circuit reaches zero.

Note: $t_c > t_q$ for reliable turn-off, otherwise the device may turn-on at an undesired instant, a process called commutation failure.

- Thyristors with slow turn-off time are called converter grade SCR's.

EX: Phase controlled rectifiers, cyclo-converters and ac voltage controllers.

- SCR with fast turn-off time are called inverter grade SCR's.

EX: Inverters, choppers and forced commutation converters.

4. THYRISTOR TURN-ON METHODS

All the thyristor methods involve increasing carriers near junction J_2. When anode is positive with respect to cathode, thyristor can be turned on by any of the methods listed below:

4.1. Forward Voltage Triggering:

When anode to cathode forward voltage is increased with gate circuit open, the reverse biased junction, J_2 will break due to avalanche breakdown. But this mechanism is never employed as it may damage the device.

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

- Junction J_1 and J_3 is forward
- Junction J_2 is reverse
- As the anode to cathode voltage is increased breakdown of the reverse biased junction

J_2 occurs. This is known as avalanche breakdown and the voltage at which this phenomenon occurs is called forward breakover voltage.

- The conduction of current continues even if the anode cathode voltage reduces below

V_{BO} till I_a will not go below I_h. Where I_h is the holding current for the thyristor.

4.2. Gate Triggering:

By applying the current at gate terminal, forward break- over Voltage, V_{BO} can be reduced. Thus, SCR is made to conduct. With gate current, charges are injected into inner P layer and voltage at which forward break over occurs is reduced. Figure below shows a basic circuit for gate triggering and variation of break over voltage with gate current.

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

First step is to choose a thyristor with forward breakover voltage (say 800V) higher than the normal working voltage. The benefit is that the thyristor will be in blocking state with normal working voltage applied across the anode and cathode with gate open. When we require the turning ON of a SCR a positive gate voltage between gate and cathode is applied. The point to be noted that cathode n- layer is heavily doped as compared to gate p-layer. So when gate supply is given between gate and cathode gate p-layer is flooded with electron from cathode n-layer. Now the thyristor is forward biased, so some of these electron reach junction J_2 .As a result width of J_2 breaks down or conduction at J_2 occur at a voltage less than V_{BO}.As I_g increases V_{BO} reduces which decreases then turn ON time. Another important point is duration for which the gate current is applied should be more then turn ON time. This means that if the gate current is reduced to zero before the anode current reaches a minimum value known as holding current, SCR can't turn ON. In this process power loss is less and low applied voltage is required for triggering.

4.3. dv/dt Triggering:

When a SCR in forward blocking state, junction J2 acts a capacitor so large anode current flows when is higher. Thus, SCR starts conducting. Anode current, I_a=C_j= where C_j is function capacitance.

This is a turning ON method but it may lead to the destruction of SCR and so it must be avoided.

When SCR is forward biased, junction J_1 and J_3 are forward biased and junction J_2 is reversed biased so it behaves as if an insulator is place between two conducting plate. Here J_1 and J_3 acts as a conducting plate and J_2 acts as an insulator. J_2 is known as junction capacitor. So, if we increase the rate of change of forward voltage instead of increasing the magnitude of voltage. Junction J_2 breaks and starts conducting. A high value of changing current may damage the SCR. So, SCR may be protected from high dv/dt.

4.4. Temperature Triggering:

By increasing the temperature at junction J_2 (when a SCR is in forward blocking state) carriers at J_2 are increased. Above a limit, SCR starts conducting.

During forward biased, J_2 is reverse biased so a leakage forward current always associated with SCR. Now as we know the leakage current is temperature dependent, so if we increase the temperature the leakage current will also increase and heat dissipation of junction J_2 occurs. When this heat reaches a enough value J_2 will break and conduction starts.

Disadvantages

This type of triggering causes local hot spot and may cause thermal run away of the device. This triggering cannot be controlled easily.

It is very costly as protection is costly.

Some Definitions:

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

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

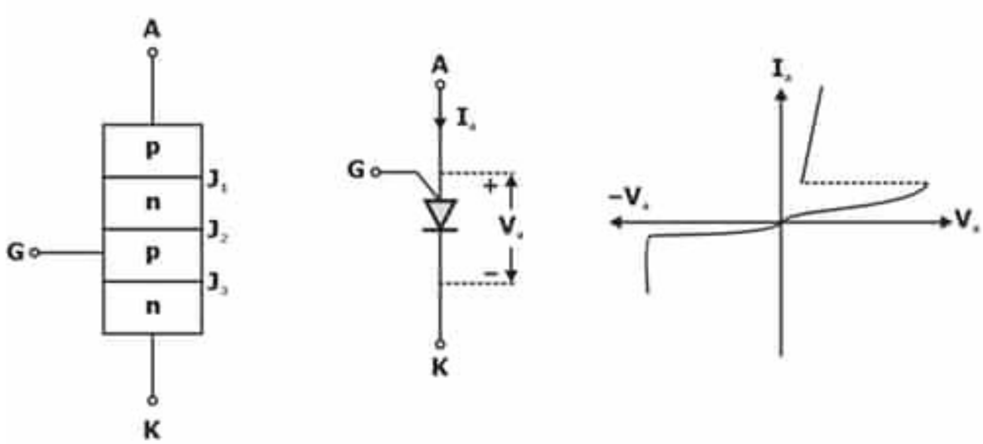
4.5. Light triggering:

Increase carriers near junction J_2, by applying light signal near J_2. This mechanism is used is a class of SCRs called light activated SCR (LASCR).

5. THYRISTORS FAMILY

5.1. Programmable Unijunction Transistor (PUT):

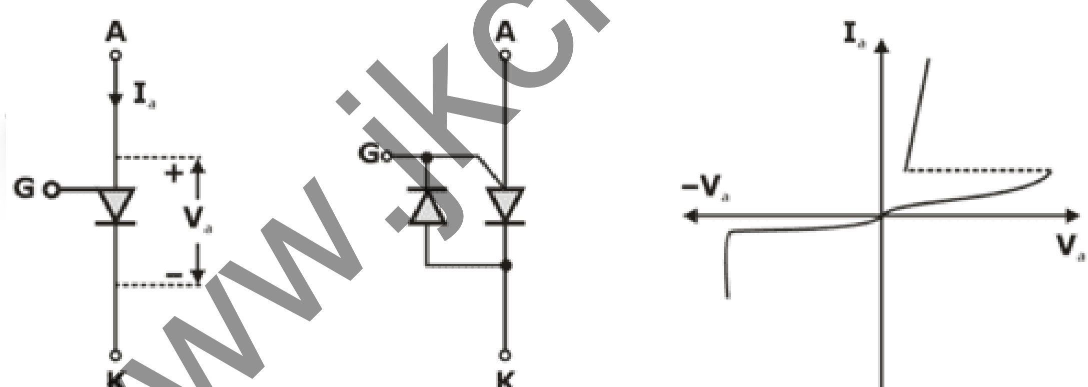
PUT is like SCR, but gate is connected to n terminal. It is mainly used in time delay, logic and SCR trigger circuits. The circuit symbol and V-I characteristics of PUT are shown in figure below.



In PUT, G is always biased positive with respect to cathode. If $V_a > (V_g+0.7)$, junction J_1 gets forward biased and PUT turns on. If $V_a < (v_g+0.7)$, PUT is turned off.

5.2. Silicon Unilateral Switch (SUS):

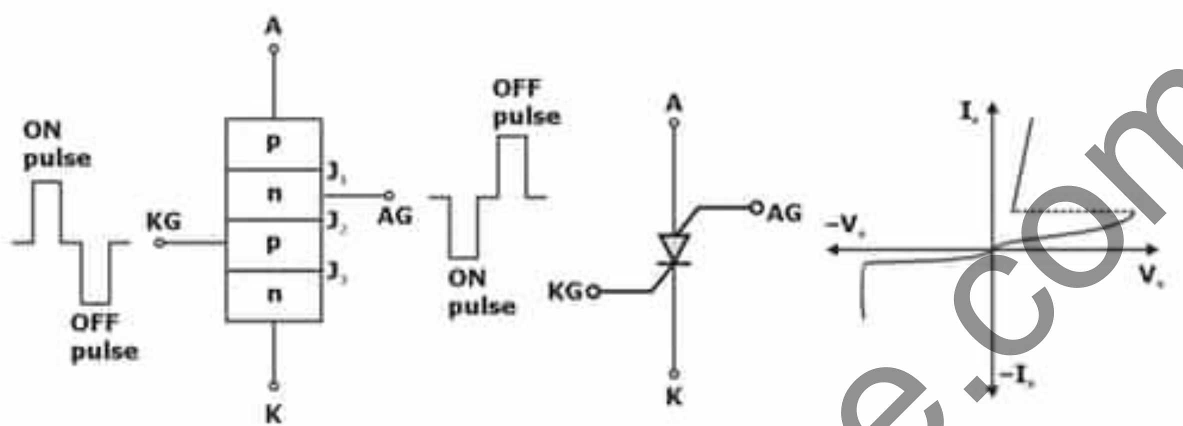
SUS is like PUT with an inbuilt avalanche diode between G & K. Here diode is to compensate for changes in ambient atmosphere. So SUS gets turned on for a fixed anode to cathode voltage. Its mainly used in timing, logic and trigger circuits. Its circuit symbol, equivalent circuit and V-I characteristics are shown in figure below.



5.3. Silicon Controlled Switch (SCS):

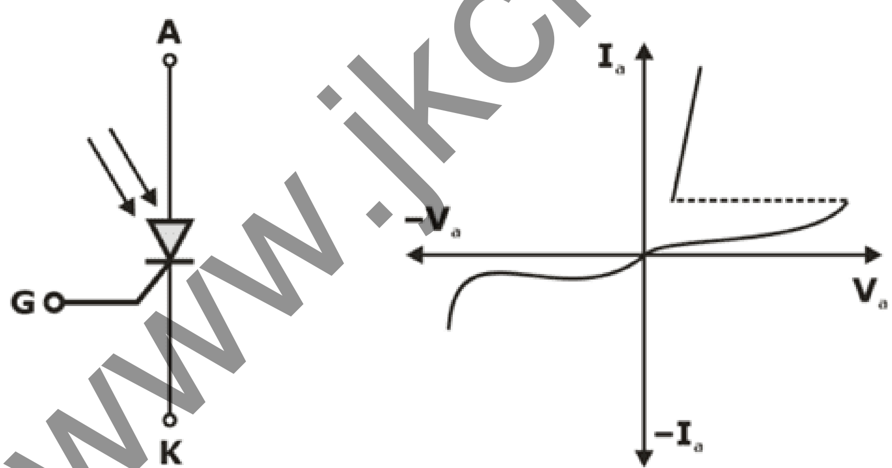
CSC has two gates, anode and cathode gates as shown in figure below and it can be turned on by either gate. When a negative pulse is applied at AG, junction J_1 gets forward biased and SCS is turned on. Similarly: a positive pulse at AG will reverse bias junction J_1 and turns off SCS.

Similarly, a positive pulse at KG turns on the device and a negative pulse at KG turns it off. Its application includes pulse generators, voltage sensors and oscillators. Its schematic diagram, circuit symbol, equivalent circuit and V-I characteristics are shown in figure below.



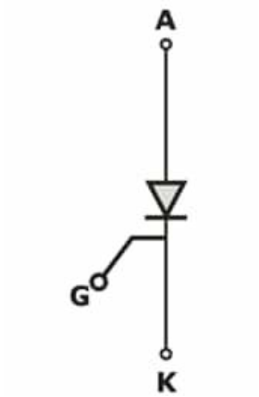
5.4. Light Activated Thyristors (or LASCR):

Light-activated thyristors can be turned on by throwing pulse of light on gate terminal of thyristor. Due to the generation of excess electron-hole pairs due to radiation light activated thyristor gets turned on. The circuit symbol and V-I characteristics of LASCR are shown in figure below.



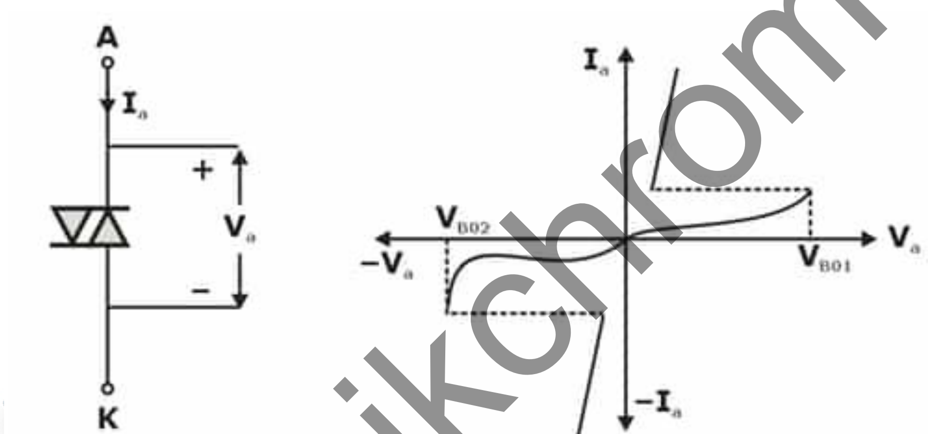
5.5. Static Induction Thyristor (SITH):

SITH is like SCR. It can be turned on by applying positive pulse and turned off by applying negative pulse between gate and cathode. The circuit symbol of SITH is as shown in figure below.



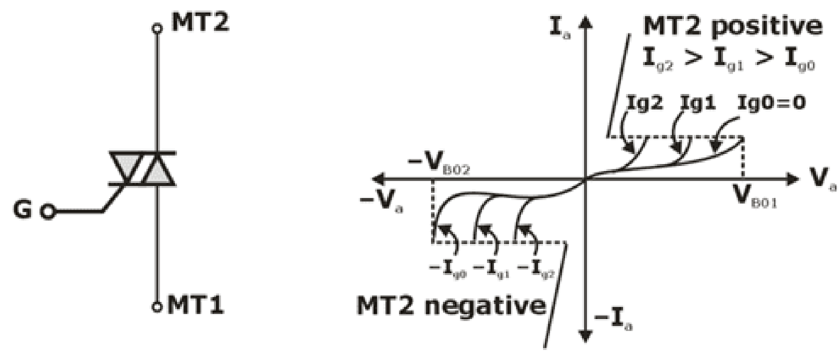
5.6. DIAC:

DIAC refers to bidirectional thyristor diode. It has symmetrical breakdown characteristics. A DIAC is similar to gateless TRIAC. The circuit symbol and V-I characteristics of DIAC are shown in figure below:



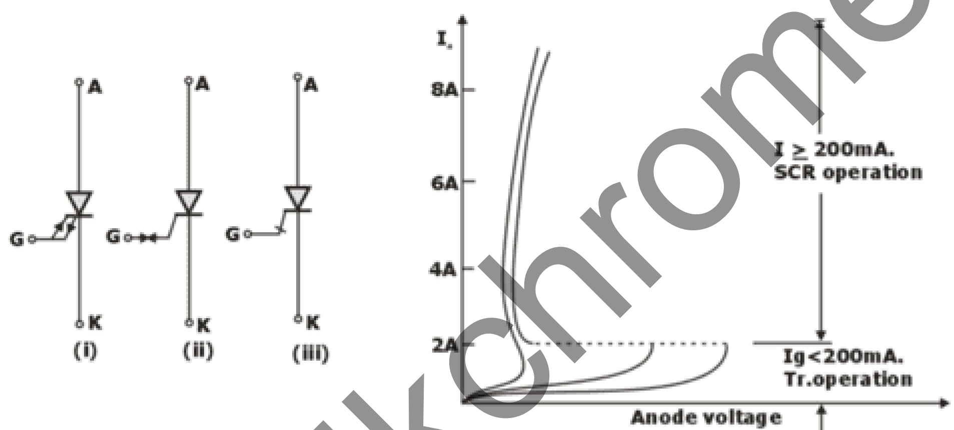
5.7. TRIAC:

TRIAC is like SCR but can conduct in both directions. Thus, it’s bidirectional thyristor with three terminals. Its operation is similar to two SCRs connected in antiparallel. The circuit symbol and V-I characteristics of TRIAC are as shown in figure below.



5.8. GTO

GTO refers to gate turn off thyristor. It's like SITH in operation. It can be turned off by a negative pulse at gate terminal. Hence, it's used in inverter and chopper circuits. The circuit symbol of GTO is as shown in figure below.



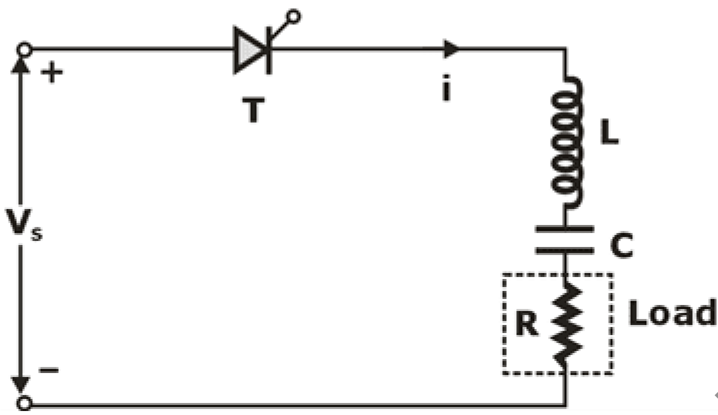
6. THYRISTOR COMMUTATION TECHNIQUES

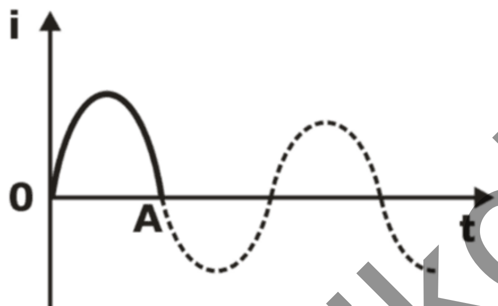
Commutation is defined as process of turning off a thyristor. Thyristor commutation is a necessary mechanism for obtaining the controlled output in many of the thyristor circuits. As thyristor is a semi-controlled device, it can't be turned off directly by gate signal. Hence external means are required for turning off thyristor. As discussed, thyristor turn-off requires that anode current falls below holding current and a reverse voltage is applied to thyristor for sufficient time to enable it to recover to blocking state.

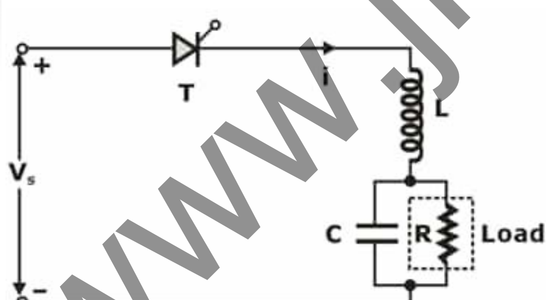
Various thyristor commutation techniques are discussed in detail below. In these techniques, it's assumed that holding current is zero and load draws a constant current of I_0.

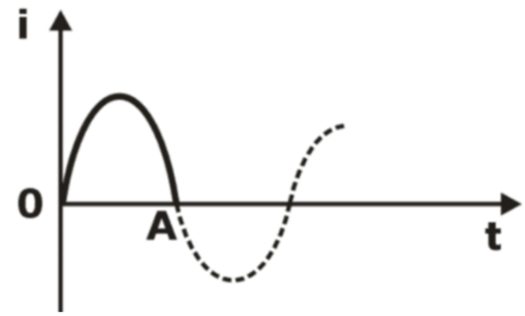
6.1. Class-A or Load Commutation:

Circuit shown below corresponds to load commutation. Here the elements L & C are chosen such that, circuit is underdamped. Hence, the current through the load decays to zero in finite-time and Thyristor gets turned-off. But this technique can be only applied to circuits which are energized from dc source. This type of commutation is also called resonant or self commutation. For low values of R, elements L and C are connected in series for commutation. For high values for R, capacitor element is connected in parallel with R for commutation.



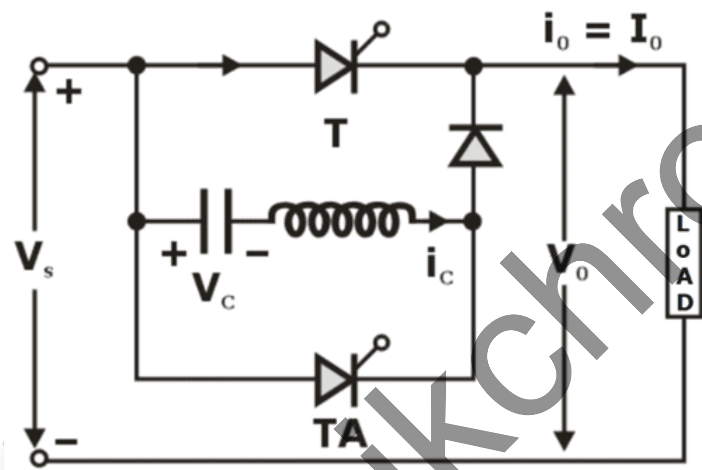


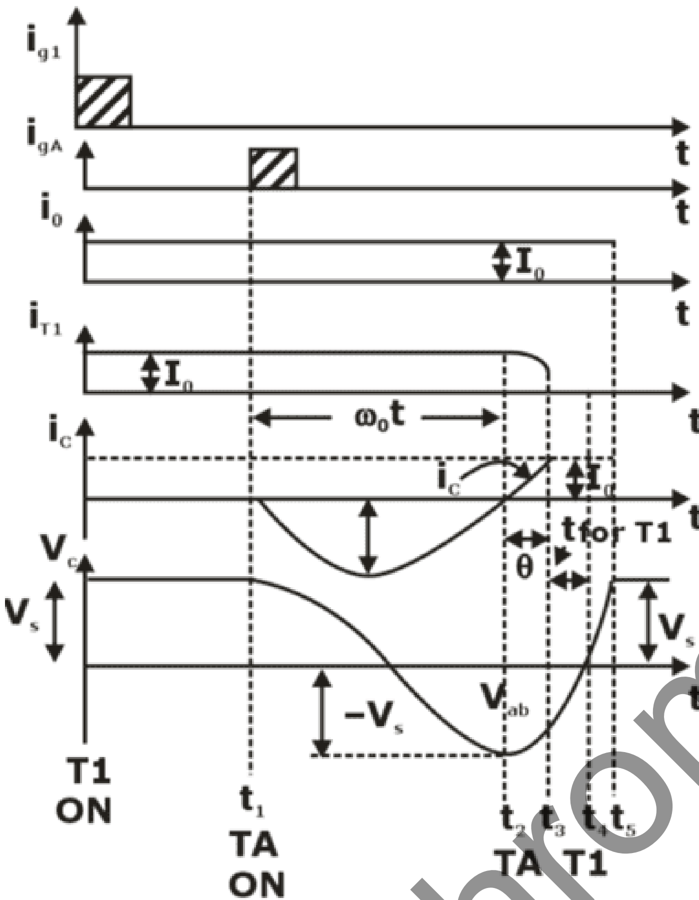




6.2. Class-B or Resonant Pulse Commutation:

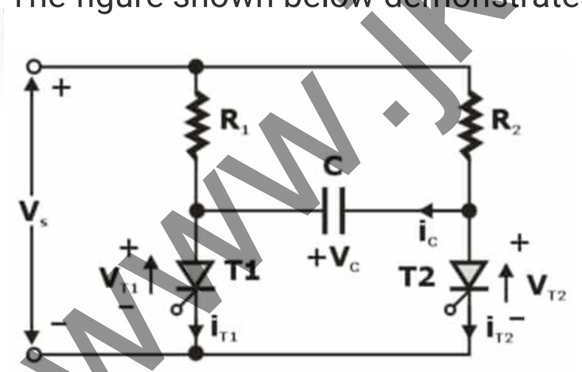
The figure shown below is circuit diagram for resonant pulse commutation. Here main Thyristor T_1 is triggered at t = 0 and auxiliary Thyristor, T_A is triggered at t = t_1. Also, $V_C(0\text{-}) = V_s$. Based on these, following analysis is done and the corresponding waveforms are shown.





6.3. Class –C or Complementary Commutation:

The figure shown below demonstrates class –C commutation.



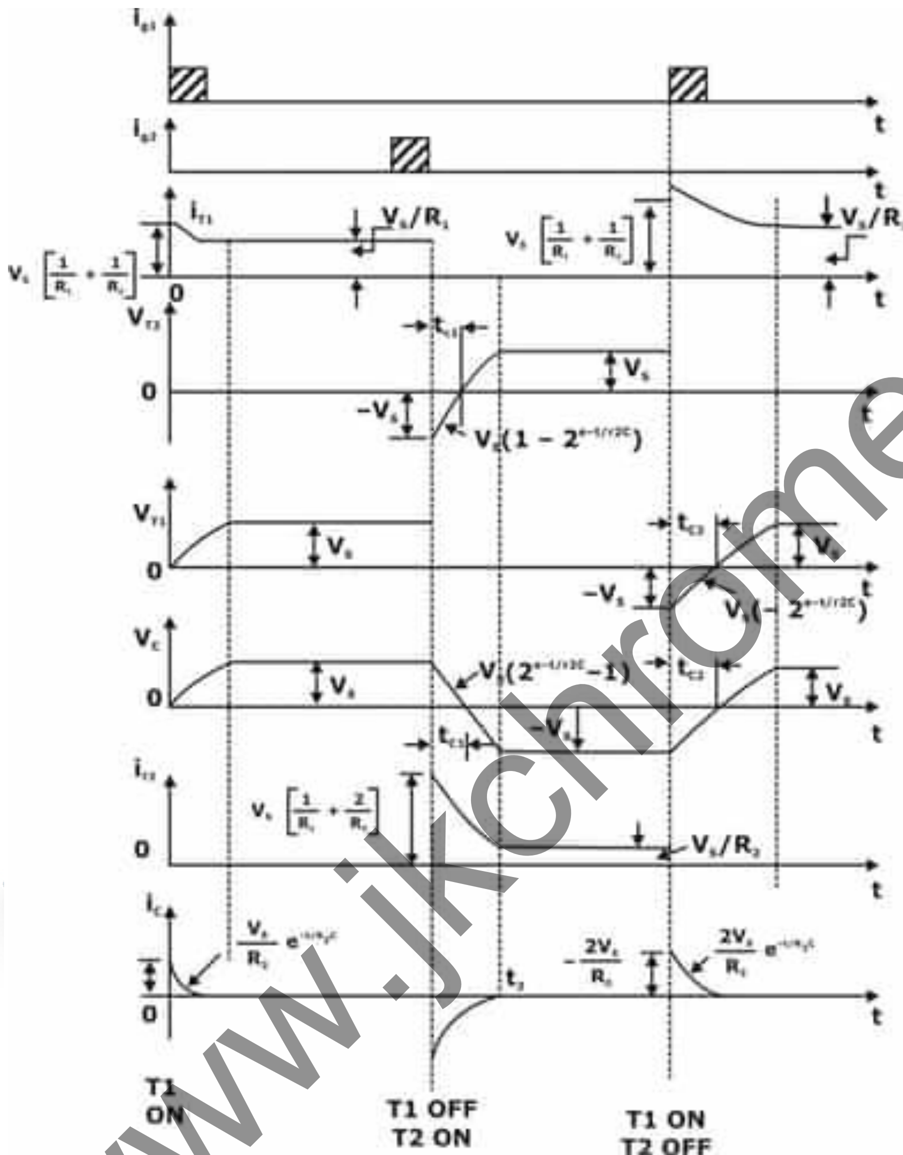
Circuit-turn-off time for T_1 is obtained by

$t_{C1}=R_1C\ln 2$

Similarly, circuit turn-off time for T_2,

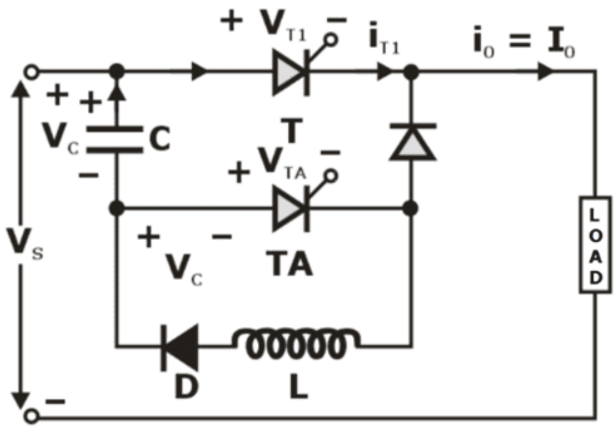
$t_{C2}=R_2C \ln 2$

Based on above analysis, the waveforms corresponding to class –C commutation are shown in figure below.



6.4. Class-D or Impulse Commutation:

Figure shown below demonstrates impulse commutation along with corresponding waveforms.


+ V
T1
−
i
T1
i0 = I0
+
+
V
C
C
−
T
+ V
TA
−
+
V
C
−
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S
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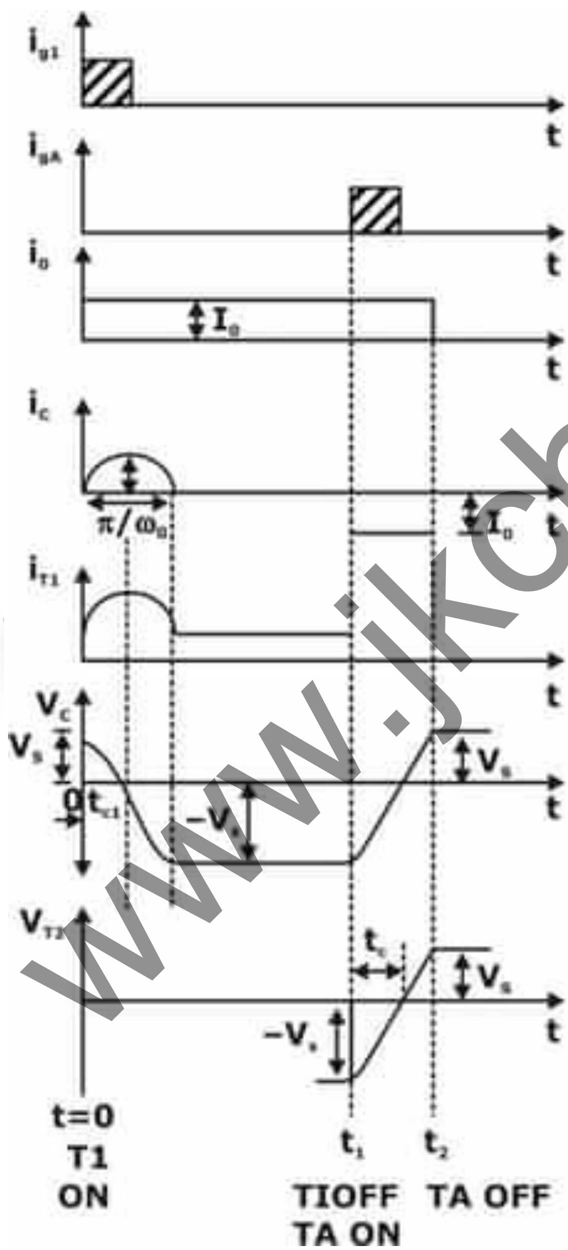
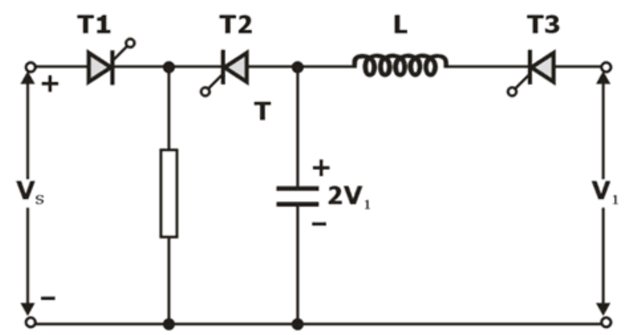
O
A
D
D
L
−


t
I0
π/ω0
I0
V
C
V
S
V
S
0
−V
S
t
C
−V
S
V
S
t=0
T1
ON
t1
t2
TIOFF
TA ON
TA OFF

6.5. Class-E or External Pulse Commutation:

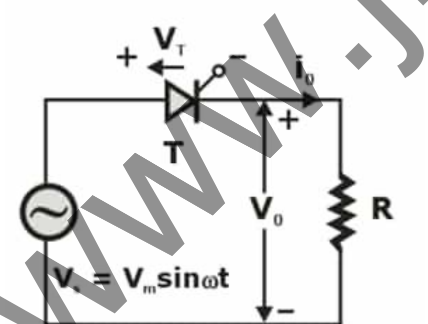
In this type of commutation, a pulse of current from a separate voltage source is used to turn-off SCR. Here the peak value of current must be more than load current for commutation. Figure shown below demonstrates external pulse commutation.



Initially, T_3 is triggered to make C to charge to $2V_1$. Later T_2 is triggered to make T_1 reverse biased with a voltage of (V_S-$2V_1<0 \Leftrightarrow V_S<2V_1$

6.6. Class –F or Line Commutation:

This type of commutation is also known as natural commutation. Here thyristor carrying load current is reverse biased by a.c. supply voltage and device is turned off hen anode current falls below holding current. This is mainly used in phase-controlled rectifiers and line-commutated inverters. Line commutation is demonstrated in the figure shown below along with corresponding waveforms.



AC to DC Converters

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Phase Control Rectifier

Phase Control Rectifiers can be classified as Single Phase Rectifier and **3 Phase Rectifier**. Further Single phase rectifier is classified as 1-Φ half-wave and 1-Φ full-wave rectifier, In a similar manner, 3 phase rectifier is classified as 3-Φ half-wave rectifier & 3-Φ full-wave rectifier.

- 1-Φ Full wave rectifier is classified as 1-Φ mid point type and 1-Φ bridge type rectifier.
- 1-Φ bridge type rectifier is classified as 1-Φ half controlled and 1-Φ full controlled rectifier.
- 3-Φ full wave rectifier is again classified as 3-Φ mid point type and 3-Φ bridge type rectifier.
- 3-Φ bridge type rectifier is again divided as 3-Φ half controlled rectifier and 3-Φ full controlled rectifier.

Important Terminologies Related to Phase Controlled Rectifiers:

There are certain terms that are frequently used in the study of **Phase Controlled rectifiers**, here we have listed the terminologies related to Phase Controlled Rectifiers. Let **"f"** be the **instantaneous value** of **any voltage or current associated with a rectifier circuit**, then the following terms, characterizing the properties of "f", can be defined.

Peak value of f $(\hat{f})$: As the name suggests $\hat{f} = |f|_{max}$ **over all time.**

Average (DC) value of f(F_{av}) : Assuming f to be periodic over the time period T

$$F_{av} = \frac{1}{T}\int_0^T f(t)dt$$

- **RMS (effective)** value of f (**f_{RMS}**) : For f , periodic over the time period T**,**

$$F_{RMS} = \sqrt{\frac{1}{T}\int_0^T f^2(t)dt}$$

- **Form factor of f (f_{FF}) :** Form factor of 'f' is defined as

$$f_{FF} = \frac{F_{RMS}}{F_{av}}$$

- **Ripple factor of f (f_{RF}):** Ripple factor of is defined as

$$f_{RF} = \frac{\sqrt{F_{RMS}^2 - F_{av}^2}}{F_{av}} = \sqrt{f_{FF}^2 - 1}$$

Note: Ripple factor can be used as a measure of the deviation of the output voltage and current of a rectifier from ideal dc.

Peak to peak ripple of (f_{pp}): By definition

$$\hat{f}_{pp} = f_{max} - f_{min} \text{ Over period T.}$$

- **Fundamental component of f (F_1):** It is the RMS value of the sinusoidal component in the Fourier series expression of f with frequency 1/T.

$$F_1 = \sqrt{\frac{1}{2}\left(f_{A1}^2 + f_{B1}^2\right)}$$

$$f_{A1} = \frac{2}{T}\int_0^T f(t)\cos 2\pi \, t/T \, dt$$

$$f_{B1} = \frac{2}{T}\int_0^T f(t)\sin 2\pi t/T \, dt$$

- **Kth harmonic component** of **f (F_K):** It is the RMS value of the sinusoidal component in the Fourier series expression of f with frequency K/T.

$$F_K = \sqrt{\frac{1}{2}\left(f_{AK}^2 + f_{BK}^2\right)}$$

$$f_{AK} = \frac{2}{T}\int_0^T f(t) \; \cos 2\pi K \, t/T \, dt$$

$$f_{BK} = \frac{2}{T}\int_0^T f(t) \; \sin 2\pi K \, t/T \, dt$$

- **Crest factor** of **f** (**C_f**): By definition

$$C_f = \frac{\hat{f}}{F_{RMS}}.$$

- **Distortion factor** of f (**$D.F_f$**): By definition ⇒ $DF_f = F_1/F_{RMS}$
- **Total Harmonic Distortion** of f (**THD_f**): The amount of distortion in the waveform of f is quantified by means of the index Total Harmonic Distortion (THD).

$$THD_f = \frac{\sqrt{1 - DF_f^2}}{DF_f}$$

- **Displacement Factor** of a Rectifier (**DPF**): If $\mathbf{v_i}$ and $\mathbf{i_i}$ are the per phase input voltage and input current of a rectifier respectively, then the Displacement Factor of a rectifier is defined as.

DPF = Cos φ_i

Where φ_i is the phase angle between the fundamental components of v_i and i_i.

- **Power factor of a rectifier (PF)**: As for any other equipment, the definition of the power factor of a rectifier is

$$PF = \frac{\text{Actual power input to the Rectifier}}{\text{Apparent power input to the Rectifier}}$$

if the per phase input voltage and current of a rectifier are $\mathbf{v_i}$ and $\mathbf{i_i}$ respectively then

$$PF = \frac{V_{i1} I_{i1} \cos\varphi_i}{V_{iRMS} I_{iRMS}}$$

If the rectifier is supplied from an ideal sinusoidal voltage source then ⇒ $V_{i1} = V_{iRMS}$

$$PF = \frac{I_{i1}}{I_{iRMS}} \cos\varphi_i = DF_{i1} \times DPF$$

In terms of THD_{ii}

$$PF = \frac{DPF}{\sqrt{1 + THD_{ii}^2}}$$

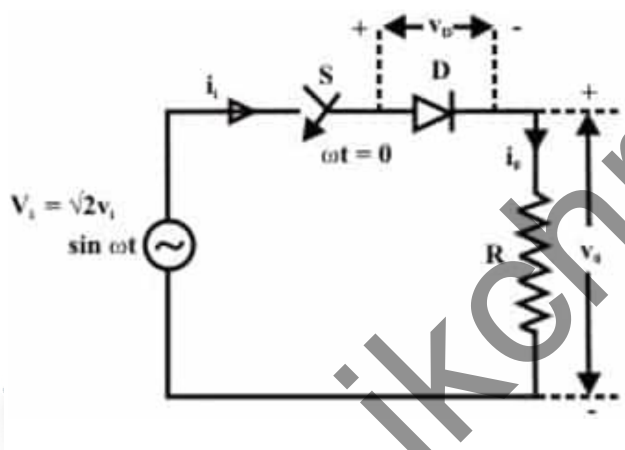
- **Firing angle of a rectifier (α)**: Used in connection with a controlled rectifier using thyristors. It refers to the time interval from the instant a thyristor is forward biased to the instant when a gate pulse is actually applied to it.
- **Extinction angle of a rectifier (γ)**: Also used in connection with a controlled rectifier. It refers to the time interval from the instant when the current through an outgoing thyristor becomes zero (and a negative voltage

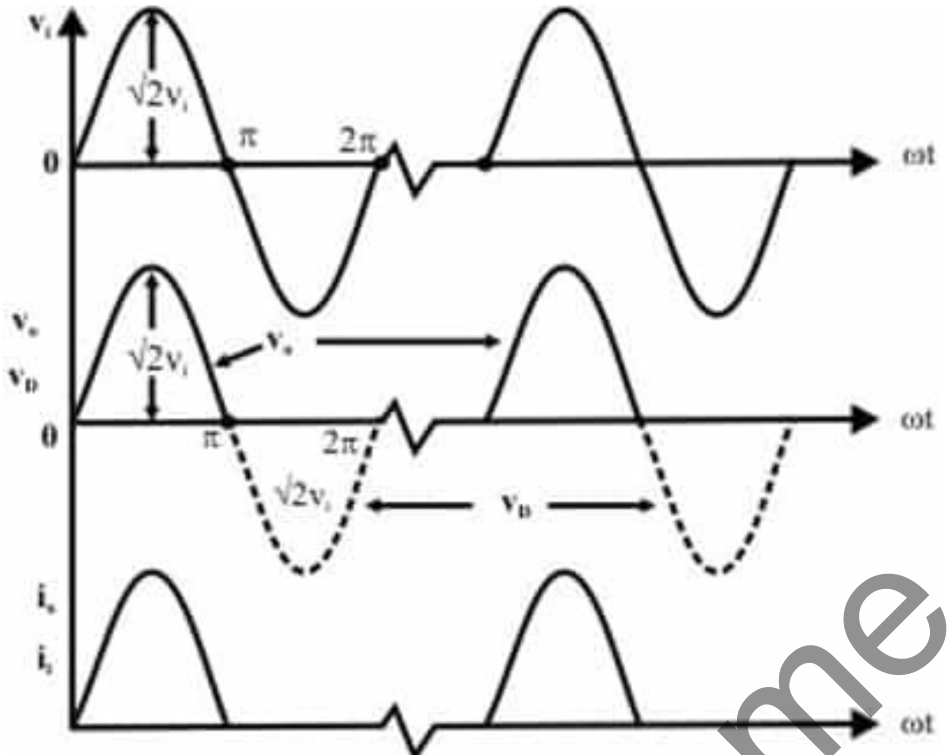
applied across it) to the instant when a positive voltage is reapplied. It is expressed in radians by multiplying the time interval with the input supply frequency (ω) in rad/sec. The extinction time (γ/ω) should be larger than the turn off time of the thyristor to avoid commutation failure.

- **Overlap angle of a rectifier (μ)**: The commutation process in a practical rectifier is not instantaneous. During the period of commutation, both the incoming and the outgoing devices conduct current simultaneously. This period, expressed in radians, is called the overlap angle "μ" of a rectifier. It is easily verified that $\alpha + \mu + \gamma = \pi$ radian.

Single phase uncontrolled half wave rectifier

This is the simplest and probably the most widely used rectifier circuit albeit at relatively small power levels. The output voltage and current of this rectifier are strongly influenced by the type of the load. In this section, operation of this rectifier with resistive, inductive and capacitive loads will be discussed.





Circuit diagram and the waveforms of a single phase uncontrolled half wave rectifier are shown above in the figure. If the switch S is closed at t = 0, the diode D becomes forward biased in the interval $0 < \omega t \le \pi$. If the diode is assumed to be ideal then

For $0 < \omega t \le \pi$

$v_o = v_i = \sqrt{2}\, V_i \sin \omega t$ & $v_D = v_i - v_o = 0$

Since the load is resistive

$$i_0 = v_0/R = \frac{\sqrt{2}V_0}{R}\sin\omega t$$

For **$\omega t > \pi$**, v_i becomes negative and D becomes reverse biased. So in the interval **$\pi < \omega t \le 2\pi$**

$i_1 = i_o = 0$

$v_0 = i_0 R = 0$

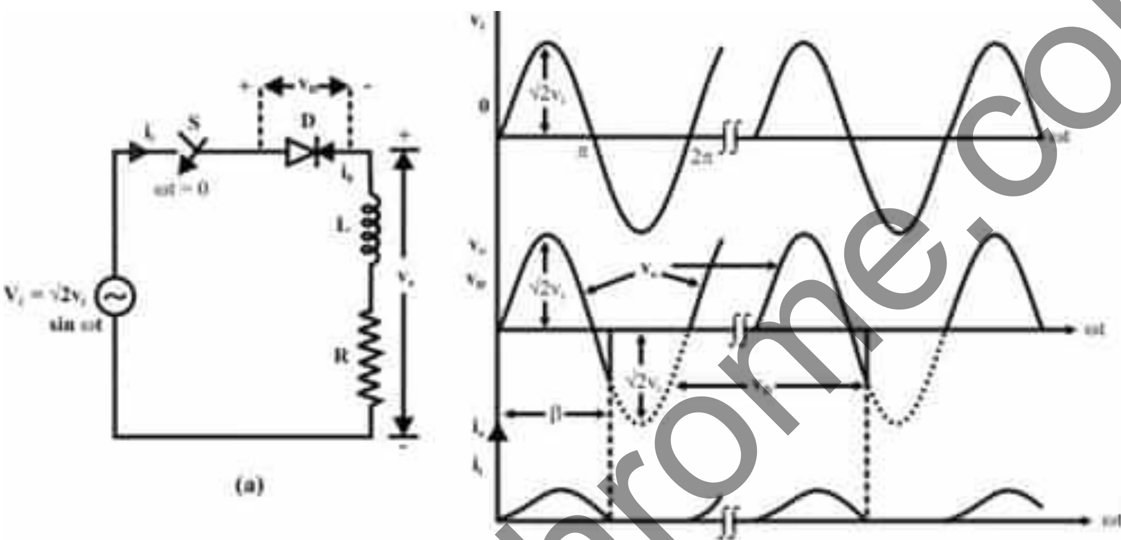
$v_D = v_i - v_o = v_i = \sqrt{2}\, V_i \sin wt$

From these relationships

$$V_{0AV} = \frac{1}{2\pi}\int_0^{2\pi} v_0 d\omega t = \frac{1}{2\pi}\int_0^{\pi} \sqrt{2}V_i \sin\omega t d\omega t = \frac{\sqrt{2}V_i}{\pi}$$

$$V_{DRMS} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} 2V_i^2 \sin^2\omega t d\omega t} = \frac{V_i}{\sqrt{2}}$$

Single Phase Uncontrolled Half Wave Rectifier with R-L load



From the preceding discussion

For $0 \le \omega t \le \beta$

$v_D = 0$

$v_o = v_i.\ i_o = i_i$

For $\beta \le \omega t \le 2\pi$

$v_o = 0$

$i_o = i_i = 0$

$v_D = v_i - v_o = v_i$

$$V_{0AV} = \frac{1}{2\pi}\int_0^{2\pi} v_0 d\omega t = \frac{1}{2\pi}\int_0^{\beta} \sqrt{2}V_i \sin\omega t d\omega t$$

$$V_{0AV} = \frac{\sqrt{2}V_i}{\pi}\left(\frac{1-\cos\beta}{2}\right)$$

$$V_{0RMS} = \sqrt{\frac{1}{2\pi}\int_0^{\beta} 2V_i^2 \sin^2\omega t d\omega t}$$

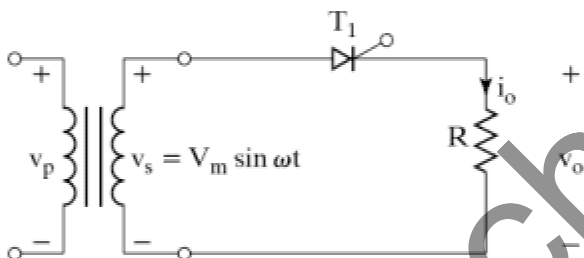
$$= \sqrt{\frac{V_i^2}{2\pi}\left(\beta - \frac{1}{2}\sin 2\beta\right)} = \frac{V_i}{\sqrt{2}}\sqrt{\frac{2\beta - \sin 2\beta}{2\pi}}$$

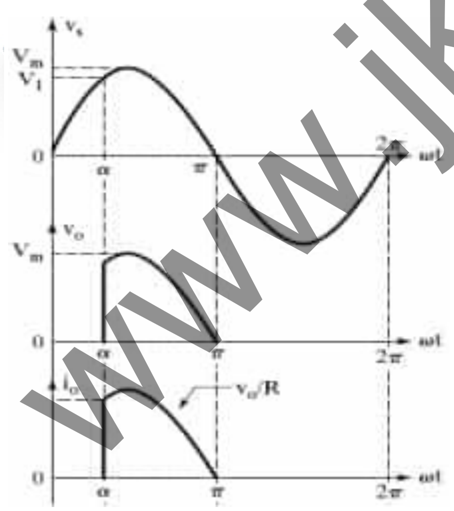
$$i_0 = \frac{\sqrt{2}V_i}{Z}\left| \sin\varphi e^{-\frac{\omega t}{\tan\varphi}} + \sin(\omega t - \varphi) \right|$$

$$i_0(\omega t = \beta) = \frac{\sqrt{2}V_i}{Z}\left[\sin\varphi e^{-\frac{\beta}{\tan\varphi}} + \sin(\beta - \varphi) \right] = 0$$

$$\text{or } \sin\varphi e^{-\frac{\beta}{\tan\varphi}} = \sin(\varphi - \beta)$$

Single phase half wave Controlled Rectifier with R-L load





$v_s = V_m \sin \omega t =$ i/p ac supply voltage

$V_m =$ max. value of i/p ac supply voltage

$V_S = \frac{V_m}{\sqrt{2}} =$ RMS value of i/p ac supply voltage

$v_O = v_L =$ output voltage across the load

When the thyristor is triggered at $\omega t = \alpha$

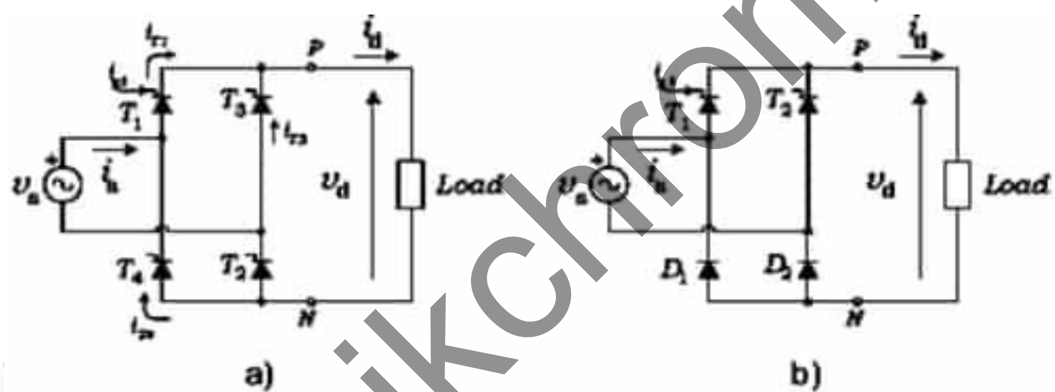
$v_O = v_L = V_m \sin \omega t;\ \omega t = \alpha$ to π

$i_O = i_L = \frac{v_O}{R} =$ Load current; $\omega t = \alpha$ to π

$i_O = i_L = \frac{V_m \sin \omega t}{R} = I_m \sin \omega t; \omega t = \alpha$ to π

Where $I_m = \frac{V_m}{R} =$ max. value of load current

Single Phase-Controlled Rectifier (firing angle α)



Single-phase bridge rectifier: (a) fully controlled; and (b) semi-controlled.

- So with a phase controlled converter, we can regulate the output voltage by varying **firing angle α**. We can even cause power flow from dc-side to ac-side as long as $I_d>0$ (e.g., pull power out of inductor and put into line).
- In a semi-controlled rectifier, control is affected only for positive output voltage, and no control is possible when its output voltage tends to become negative since it is clamped at zero volts.
- For a Resistive load the output of the semiconverter

$$V_{d\alpha} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_{max} \sin \omega t d(\omega t) = \frac{V_{max}}{\pi}(1 + \cos \alpha)$$

- The Output of Full Wave Rectifier with R-L-E load

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\beta} V_m \sin(\omega t)\, d(\omega t)$$

$$= \frac{2V_m}{\pi}\cos\alpha$$

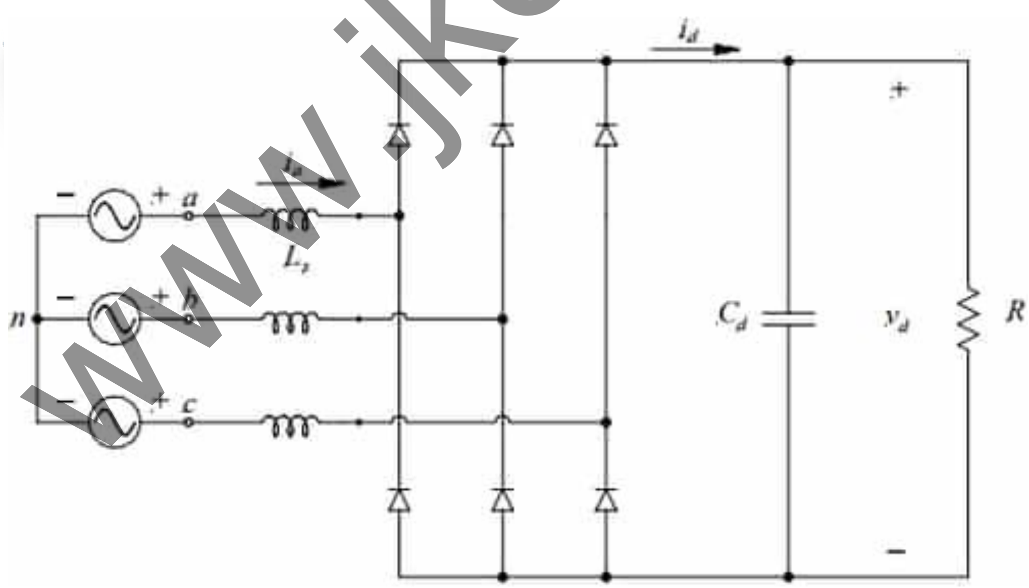
Three-Phase Rectifier

As the application Point of view **Three-phase controlled rectifiers** have a wide range of applications, from small rectifiers to large High Voltage Direct Current (HVDC) transmission systems. They are used for electro-chemical process, many kinds of motor drives, traction equipment, controlled power supplies, and many other applications.

From the point of view of the commutation process, they can be classified in two important categories: Line Commutated Controlled Rectifiers (Thyristor Rectifiers), and Force Commutated PWM Rectifiers.

- The 3-Phase Controlled rectifier provide a maximum dc output of "$V_{dc(max)} = 2V_{m/\Pi}$" the output ripple frequency is equal to the twice the ac supply frequency.

Three-Phase Diode Rectifier



The circuit shown in the given figure by using 6 diodes Named as three phase Rectifier. It shows the AC side currents and DC side voltage for the case of high load inductance.

$$V_{do} = \frac{3}{\pi}\sqrt{2}V_{l-l} = 1.35V_{l-l}$$

we see that on the AC side, the RMS current, $\mathbf{I_s}$ will be

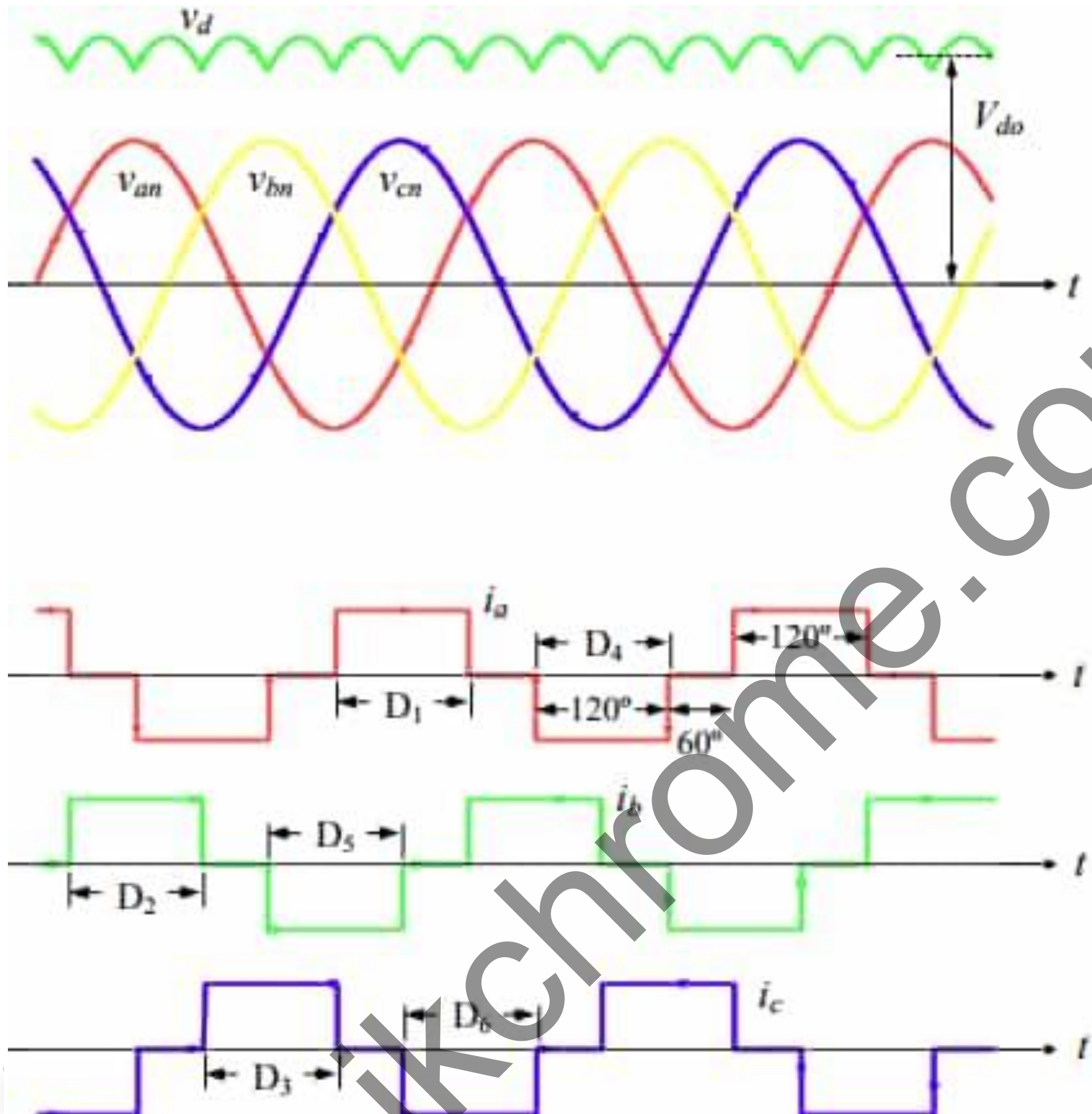
$$I_s = \sqrt{\frac{2}{3}}I_d = 0.816I_d$$

while the fundamental current, i.e. the current at power frequency is:

$$I_{s1} = \frac{1}{\pi}\sqrt{6}I_d = 0.78I_d$$

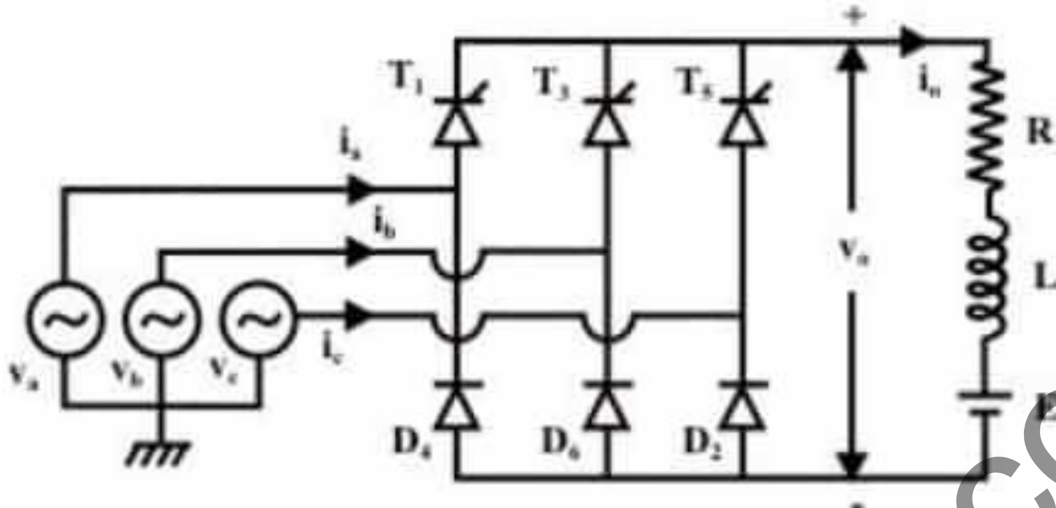
Again, inductance on the AC side will delay commutation, causing a voltage loss, i.e. the DC voltage will be less than that predicted by equation Vd_o.

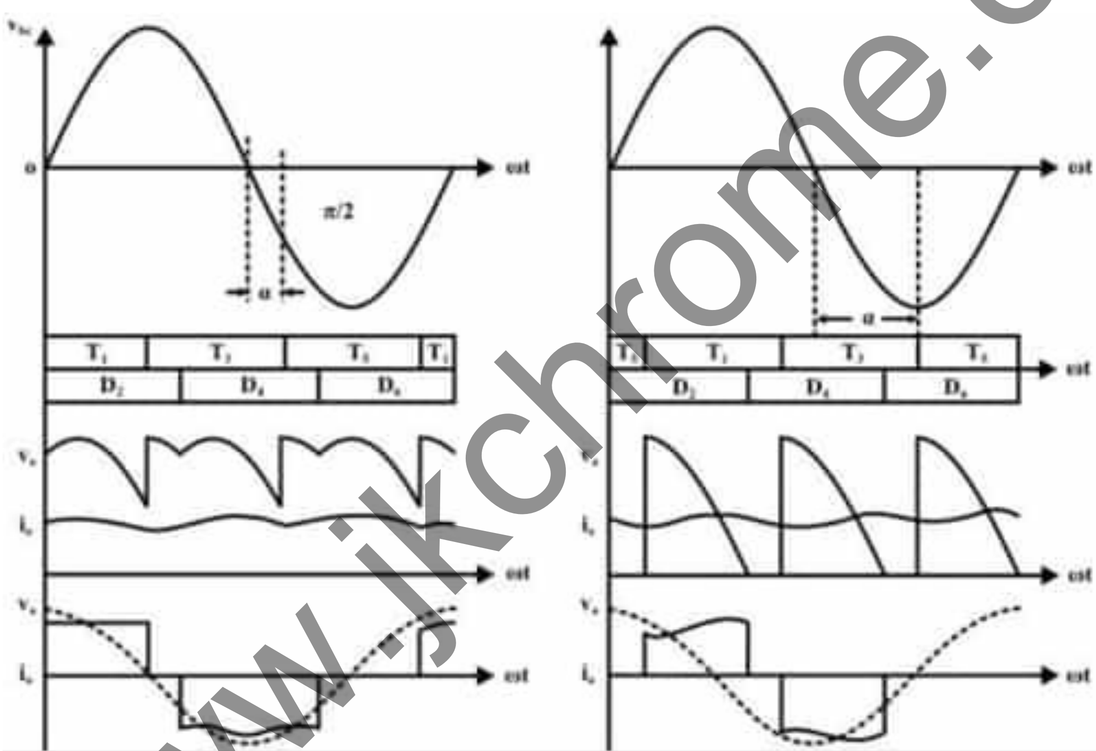
Waveforms of a three-phase full-wave rectifier with diodes and inductive load



Three Phase Half Controlled Rectifier

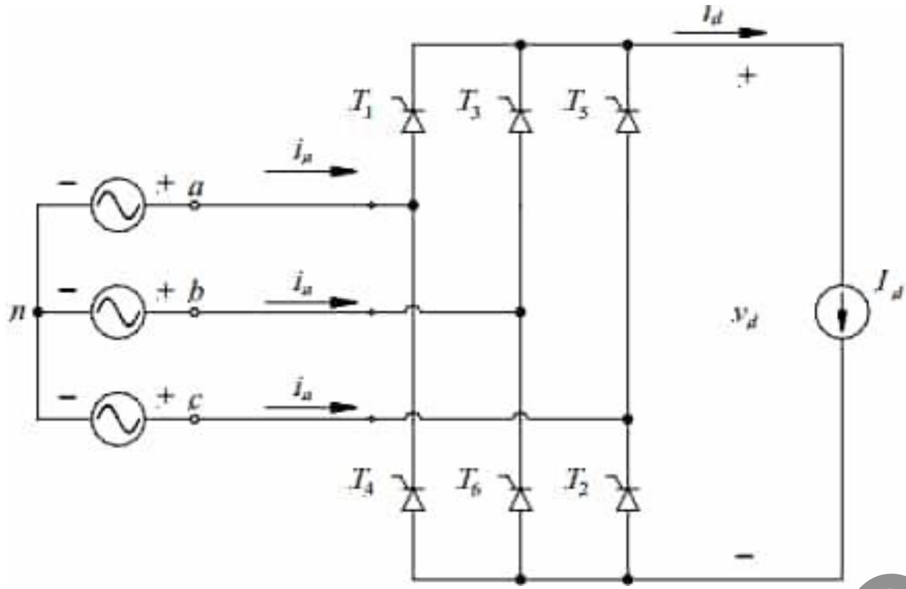
In the given figure below shows the circuit diagram of three phase half controlled converter supplying an **R-L-E load**. In the continuous conduction mode only one thyristor from top group and only one diode from the bottom group conduct at a time. However, unlike fully controlled converter here both devices from the same phase leg can conduct at the same time. Hence, there are nine conducting modes as shown in Figure.



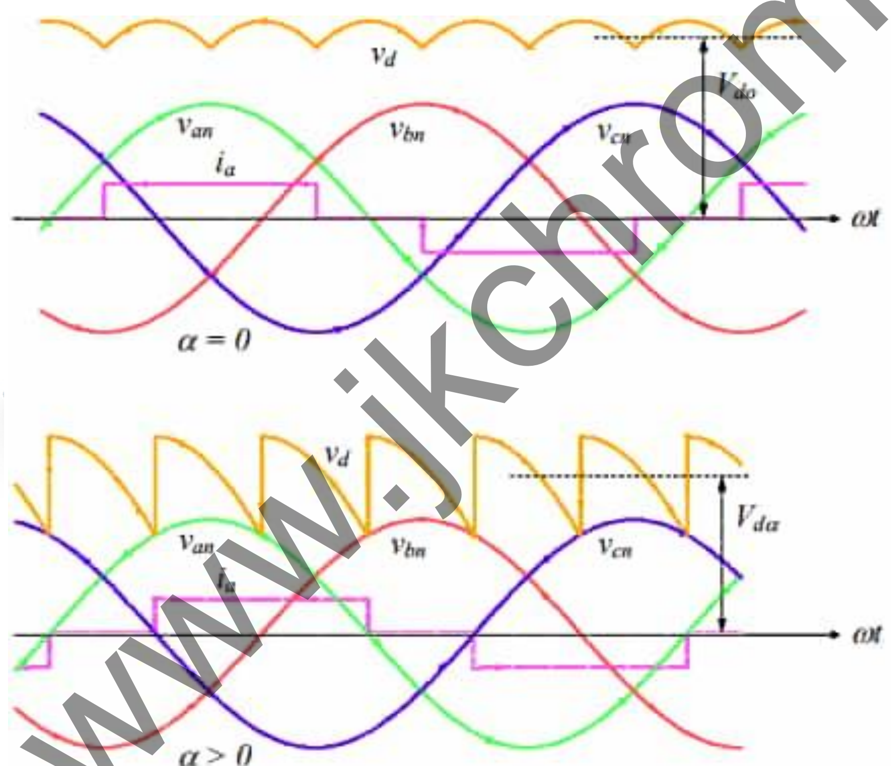


3- Phase Full Controlled Rectifier

In **3-phase full controlled rectifier 6 thyristors** are needed to accommodate three phases. In the given figure below shows the schematic of the system, and Figureshows the output voltage waveforms.



Output Waveform for 3-Phase Full Controlled Rectifier



- The delay angle α is again measured from the point that a thyristor becomes forward biased, but in this case the point is at the intersection of the voltage waveforms of two different phases. The voltage on the DC side is then (the subscript o here again meaning Ls = 0).

$$V_{do} = \frac{3}{\pi}\sqrt{2}V_{l-l}\cos(\alpha) = 1.35V_{l-l}\cos(\alpha)$$

while the power for both the AC and DC side is

$$P = V_{do}I_d = 1.35V_{l-l}I_d\cos(\alpha) = \sqrt{3}\cdot V_{l-l}\cdot I_{s1}\cos(\alpha)$$

which leads to

$I_{s1} = 0.78\ I_d$

and the relationship between V_{do} and $V_{d\alpha}$

$V_{d\alpha} = V_{do}$ Cos(α)

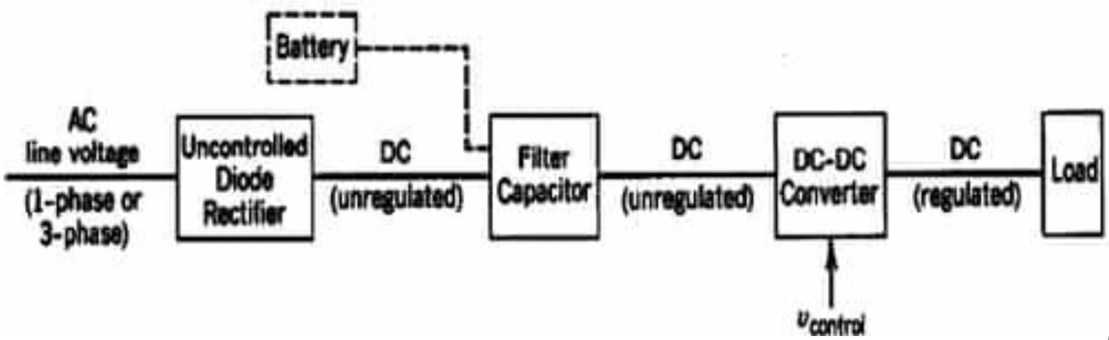
- Again, if the delay angle α is extended beyond 90°,the converter transfers power from the DC side to the AC side, becoming an inverter. We should keep in mind, though that even in this case the converter is drawing reactive power from the AC side.
- For both 1-phase and 3-phase controlled rectifiers, a delay in α creates a phase displacement of the phase current with respect to the phase voltage, equal to α. The cosine of this angle is the power factor of the fundamental harmonic.

DC to DC Converters

"Power Electronics & Drives : DC to DC Converters

A **Chopper or DC-to-DC Converter** is a static device which is used to obtain a variable variable dc voltage voltage from a constant constant dc voltage voltage source.

- The thyristor converter offers greater efficiency, faster response, lower maintenance, smaller size and smooth control control. Choppers Choppers are widely used in trolley trolley cars, battery operated vehicles, traction motor control, control of large number of dc motors, etc.
- They are also used in regenerative braking of dc motors to return energy back to supply and also as dc voltage voltage regulators regulators.



- Power conversion deals with the process of converting electric power from one form to another.
- The power electronic devices performing the power conversion are called power converters.
- The power conversion is achieved using power semiconductor devices, which are used as switches.
- The power devices used are SCRs (silicon controlled rectifiers, or thyristors), triacs, power transistors, power MOSFETs, insulated gate bipolar transistors (IGBTs), and MCTs (MOS-controlled thyristors).

DC to DC Conversion:

- DC-dc converters are used to convert unregulated dc voltage to regulated or variable dc voltage at the output.
- They are widely used in switch-mode dc power supplies and in dc motor drive applications.
- In dc motor control applications, they are called chopper-controlled drives.
- The input voltage source is usually a battery or derived from an ac power supply using a diode bridge rectifier.

Choppers are of two types

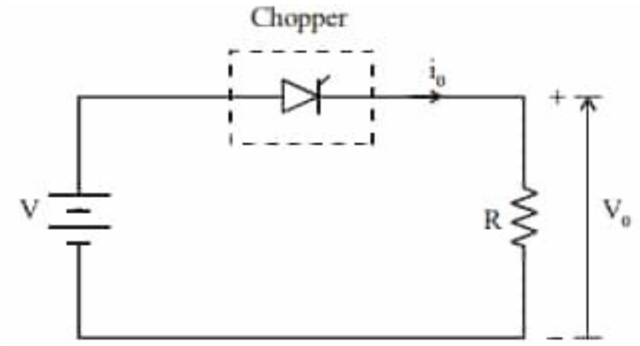
- Step-down choppers
- Step-up choppers

Note: In step-down choppers, the output voltage will be less than the input voltage whereas in step-up choppers output voltage will be more than the input voltage.

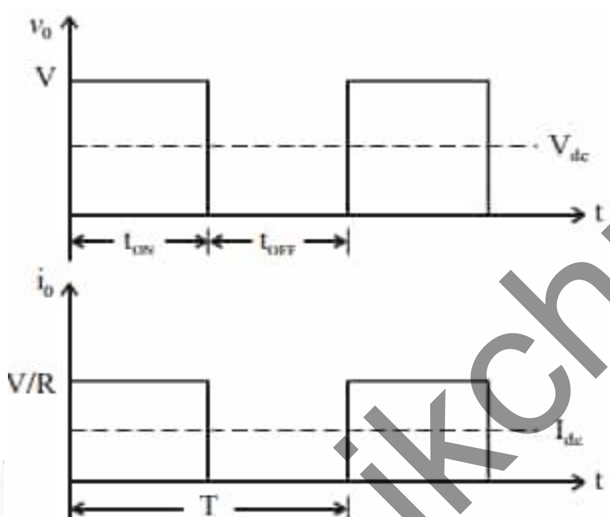
Principle of Step Down Chopper

- Figure shows a step-down chopper with resistive load.
- The thyristor in the circuit acts as a switch.

- When thyristor is ON,supply voltage appears across the load and when thyristor is OFF, the voltage across the load will be zero.
- It is also called **Buck- Converter.**



Output Voltage Waveform of Step Down Chopper



Where

- **V_{dc} =** Average value of Output or Load Voltage.
- **I_{dc} =** Average value of output or Load Current.
- **T_{ON} =** Time interval for which SCR IS ON.
- **T_{OFF} =** Time interval for which SCR is OFF.
- **$T = T_{ON} + T_{OFF}$ =** Period of Switching or Chopping Period.
- **f =** Frequency of Chopper Switching or Chopping Frequency.
- **$D = T_{ON}/T$**

Average Output Voltage

$$V_{dc} = V\left(\frac{t_{ON}}{t_{ON} + t_{OFF}}\right)$$

$V_{dc} = V(T_{on}/T) = V.D$

Average output current,

$$I_{dc} = \frac{V_{dc}}{R}$$

$$I_{dc} = \frac{V}{R}\left(\frac{t_{ON}}{T}\right) = \frac{V}{R}d$$

RMS value of output voltage

$$V_O = \sqrt{\frac{1}{T}\int_0^{t_{ON}} v_o^2 dt}$$

But during t_{ON}, $v_o = V$

Therefore RMS output voltage

$$V_O = \sqrt{\frac{1}{T}\int_0^{t_{ON}} V^2 dt}$$

$$V_O = \sqrt{\frac{V^2}{T}t_{ON}} = \sqrt{\frac{t_{ON}}{T}}.V$$

$$V_o = \sqrt{d}.V$$

Output power $P_O = V_O I_O$

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

Therefore output power $P_O = \frac{V_O^2}{R}$

$$P_O = \frac{dV^2}{R}$$

Effective input resistance of chopper

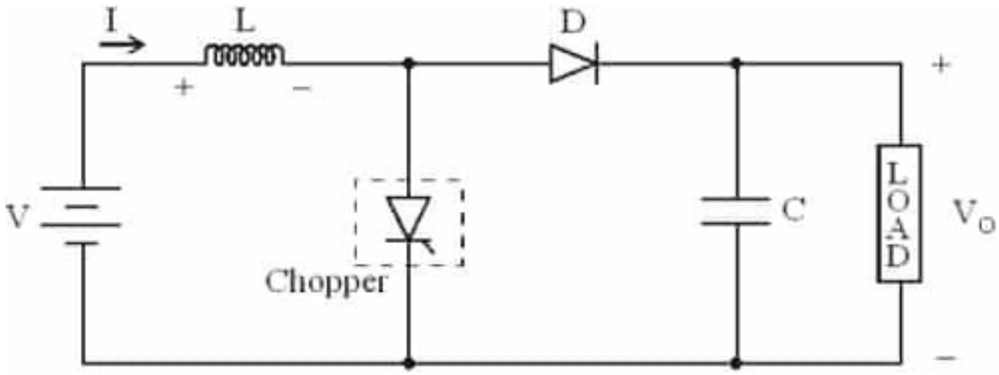
$$R_i = \frac{V}{I_{dc}}$$

$$R_i = \frac{R}{d}$$

The Output Voltage can be varied by varying the output voltage.

Principle of Step-Up Chopper

- This converter is used to produce higher voltage at the load than the supply voltage.
- When the power switch is on, the inductor is connected to the dc source and the energy from the supply is stored in it.
- When the device is off, the inductor current is forced to flow through the diode and the load.
- The induced voltage across the inductor is negative.
- The inductor adds to the source voltage to force the inductor current into the load.
- It is also called as **Boost Converter**.



- The output voltage is given by: $V_{out} = V_{in} / (1 - D)$
- Thus for variation of D in the range $0 < D < 1$, the load voltage V_{out} will vary in the range $V_{in} < V_{out} < \infty$.

EXPRESSION FOR OUTPUT VOLTAGE

Assume the average inductor current to be *I* during *ON* and *OFF* time of Chopper

When Chopper is ON

Voltage across inductor $L = V$

Therefore energy stored in inductor = $V\,I\,t_{ON}$

where $t_{ON} = ON$ period of chopper.

When Chopper is OFF (energy is supplied by inductor to load)

Voltage across $L = V_O - V$

Energy supplied by inductor $L = (V_O - V) I t_{OFF}$, where $t_{OFF} = OFF$ period of Chopper.

Neglecting losses, energy stored in inductor *L* = energy supplied by inductor L

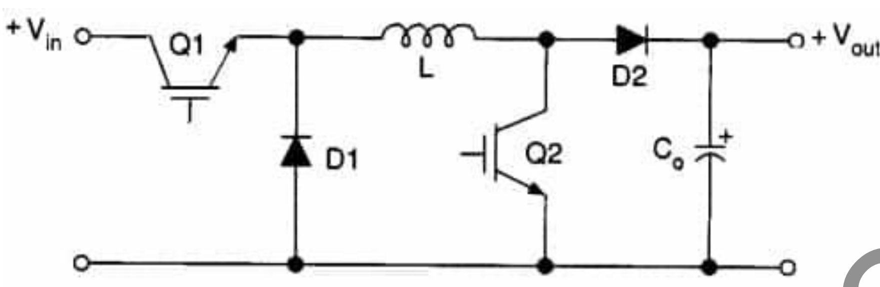
Therefore $V I t_{ON} = (V_O - V) I t_{OFF}$

$$V_O = \frac{V\left[t_{ON} + t_{OFF}\right]}{t_{OFF}}$$

Buck-Boost Converter

- A buck-boost converter can be obtained by the cascade connection of the buck and the boost converter which is shown in the following figure.
- When the power device is turned on, the input provides energy to the inductor and the diode is reverse biased.

- When the device is turned off, the energy stored in the inductor is transferred to the output.
- No energy is supplied by the input during this interval.
- In dc power supplies, the output capacitor is assumed to be very large, which results in a constant output voltage.
- In dc drive systems, the chopper is operated in step-down mode during motoring and in step-up mode during regeneration operation.



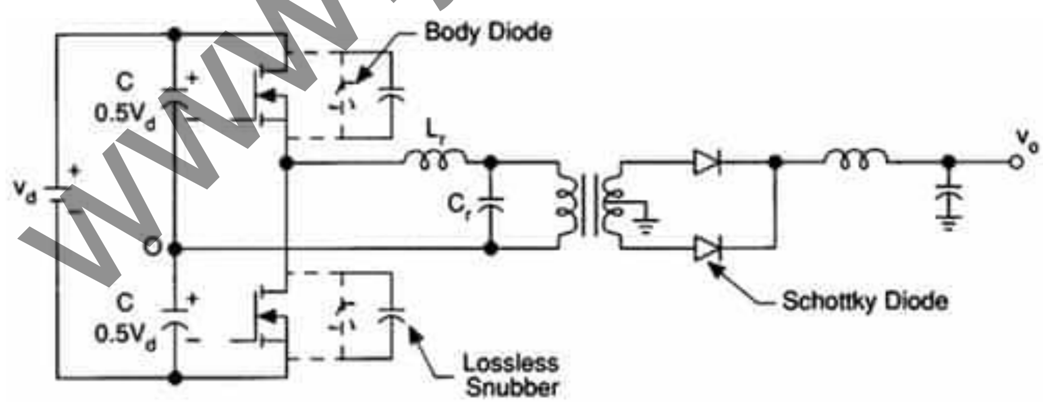
The steady-state output voltage V_{out} is given by: $V_{out} = V_{in} D / (1 - D)$

This allows the output voltage to be higher or lower than the input voltage, based on the duty cycle D.

Resonant-Link DC-DC Converters

The use of resonant converter topologies would help to reduce the switching losses in dc-dc converters and enable the operation at switching frequencies in the megahertz range.

By operating at high frequencies, the size of the power supplies could be reduced.



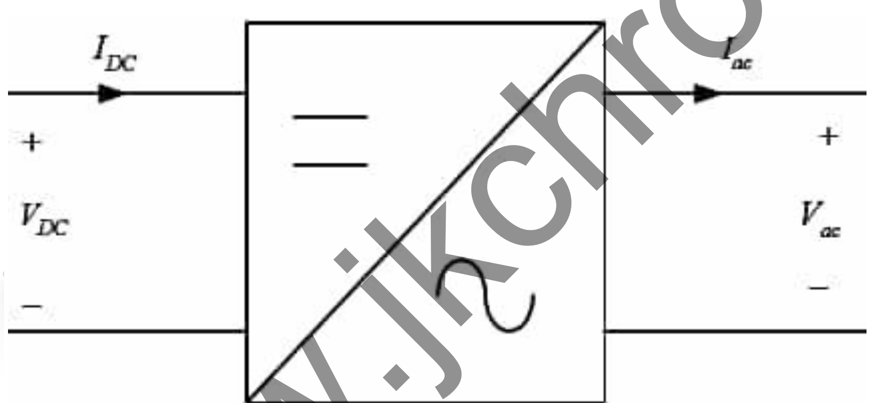
- The dc power is converted to high-frequency alternating power using the MOSFET half-bridge inverter.

- The resonant capacitor voltage is transformer-coupled, rectified using the two Schottky diodes, and then filtered to get output dc voltage.
- The output voltage is regulated by control of the inverter switching frequency.
- Instead of parallel loading as in the above figure, the resonant circuit can be series-loaded; that is, the transformer in the output circuit can be placed in series with the tuned circuit.
- The series resonant circuit provides short-circuit limiting feature.

DC to AC Converters

Power Electronics & Drives: DC to AC Converters

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



- Output voltage of the inverter may be a square wave, quasi-square wave or low distorted sine wave.
- Output Voltage of the inverter is controlled by the drives of the switches.
- Another technique to control the output of the Inverter is Pulse Width Modulation Technique,In this case the Inverter are called Pulse Width Modulated Inverter.
- Since for the inverter operation input DC is converted to AC output which may contain some harmonics,these harmonics can be reduced by using proper control schemes.

TYPICAL APPLICATIONS – Un-interruptible power supply (UPS), Industrial (induction motor) drives, Traction, HVDC.

Types of inverter

Inverters can be broadly classified into two types. They are

1. Voltage Source Inverter (VSI)

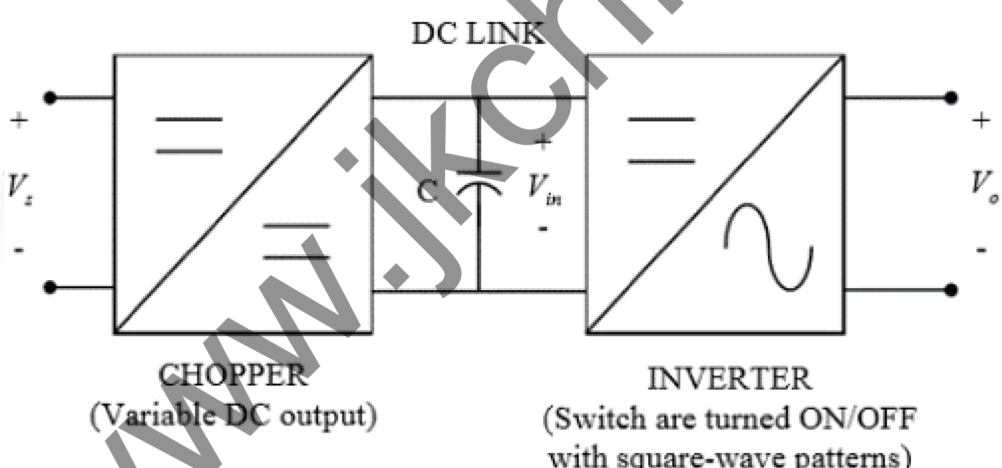
When the DC voltage remains constant, then it is called *Voltage Source Inverter(VSI*) or Voltage Fed Inverter (VFI).

2. Current Source Inverter (CSI)

When the input current is maintained constant, then it is called *Current Source Inverter (CSI)* or Current Fed Inverter (CFI).

Voltage source inverter (VSI) with variable DC link

Sometimes, the DC input voltage to the inverter is controlled to adjust the output. Such inverters are called *Variable DC Link Inverters*. The inverters can have a single phase or three-phase output.

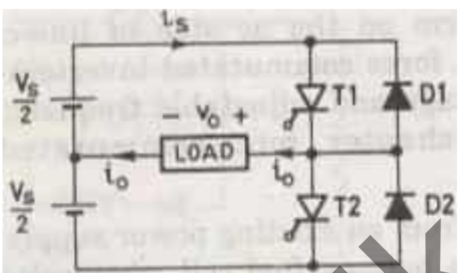


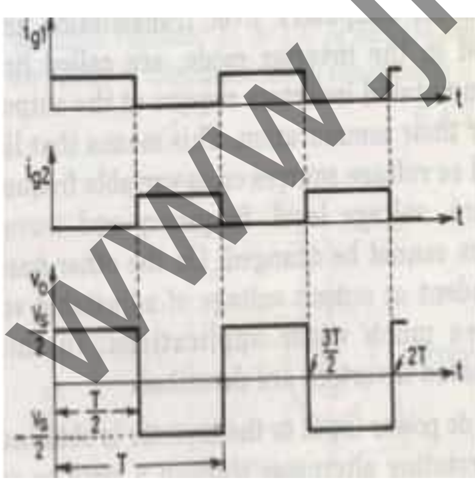
- DC link voltage is varied by a DC-to DC converter or controlled rectifier.
- Generate “square wave” output voltage.
- Output voltage amplitude is varied as DC link is varied.
- Frequency of output voltage is varied by changing the frequency of the square wave pulses.

VSI	CSI

VSI is fed from a DC voltage source having small or negligible impedance.	CSI is fed with adjustable current from a DC voltage source of high impedance.
Input voltage is maintained constant	The input current is constant but adjustable.
Output voltage does not dependent on the load	The amplitude of output current is independent of the load.
The waveform of the load current as well as its magnitude depends upon the nature of load impedance.	The magnitude of output voltage and its waveform depends upon the nature of the load impedance.
VSI requires feedback diodes	The CSI does not require any feedback diodes.
The commutation circuit is complicated	Commutation circuit is simple as it contains only capacitors.
Power BJT, Power MOSFET, IGBT, GTO with self commutation can be used in the circuit.	They cannot be used as these devices have to withstand reverse voltage

Single phase voltage source inverters





$$V_0 = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos(n\omega t) + b_n \sin(n\omega t))$$

$V_o(rms) = \frac{1}{T_0/2}\int_0^{T_0/2} \frac{V_S^2}{4}\, dt = \frac{V_S}{2}$

Due to symmetry along x-axis

a_o = 0 , a_n = 0

b_n = 4Vs/nπ

The instantaneous output voltage

$v_0 = \sum_{n=1,3,5...}^{\infty} \frac{2V_S}{n\pi} \sin(nwt)$

& =0, For n=2,4.....

The rms value of the fundamental output voltage

$V_{01} = \frac{2V_S}{\sqrt{2}\pi} = 0.45V_S$

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

So if $V_0 = \sum_{n=1,3,5...}^{\infty} \frac{2V_S}{n\pi} \sin(nwt)$

$P_{01} = (I_{01})^2 R = [\frac{2V_S}{\sqrt{2}\pi\sqrt{R^2+(\omega L)^2}}]^2 R$

DC Supply Current

Assuming a lossless inverter, the ac power absorbed by the load must be equal to the average power supplied by the dc source.

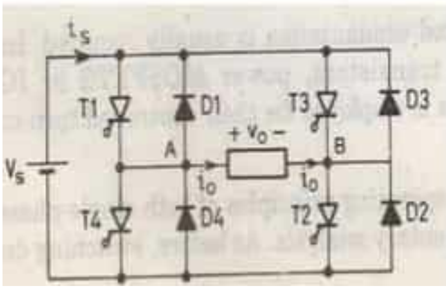
$$\int_0^T i_s(t)dt = \frac{1}{V_s}\int_0^T \sqrt{2}V_{01}\sin(\omega t)\sqrt{2}I_0\sin(\omega t - \theta_1)\, dt = I_S$$

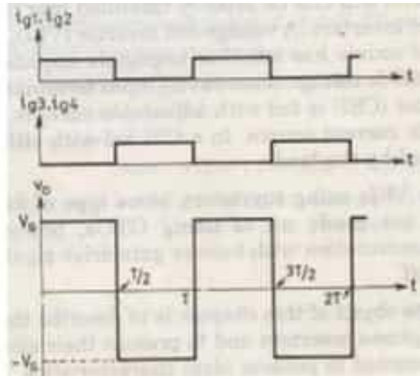
V_{01} =Fundamental rms output output voltage

I_0=rms load current

θ_1=the load angle at the fundamental frequency

Single phase full bridge inverter





For n=1, $V_1 = \frac{4V_S}{\sqrt{2}V_S}$=$0.9V_S$ (The rms of fundamental)

Instantaneous load current $i0$ for an RL load

$$i_0 = \sum_{n=1,3,5...}^{\infty} \frac{4V_S}{n\pi\sqrt{R^2+(n\omega L)^2}}\sin(n\omega t - \theta_n)$$

Where θn = $\tan^{-1}$(nwL/R)

The rms output voltage is

$$V_0=\left(\frac{2}{T_0}\int_0^{T/2} V_S^2\right)^{1/2} = V_S$$

The instantaneous output voltage in a Fourier series

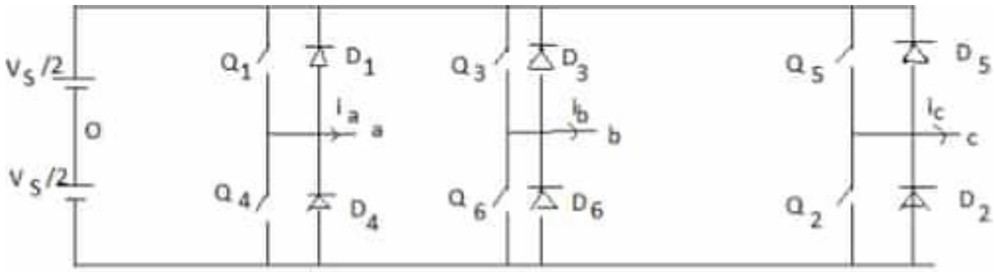
$$v_0 = \sum_{n=1,3,5...}^{\infty} \frac{4V_S}{n\pi}\sin(n\omega t)$$

Three Phase Voltage Source Inverter

When three single-phase inverters are connected in parallel a three phase inverter is formed.

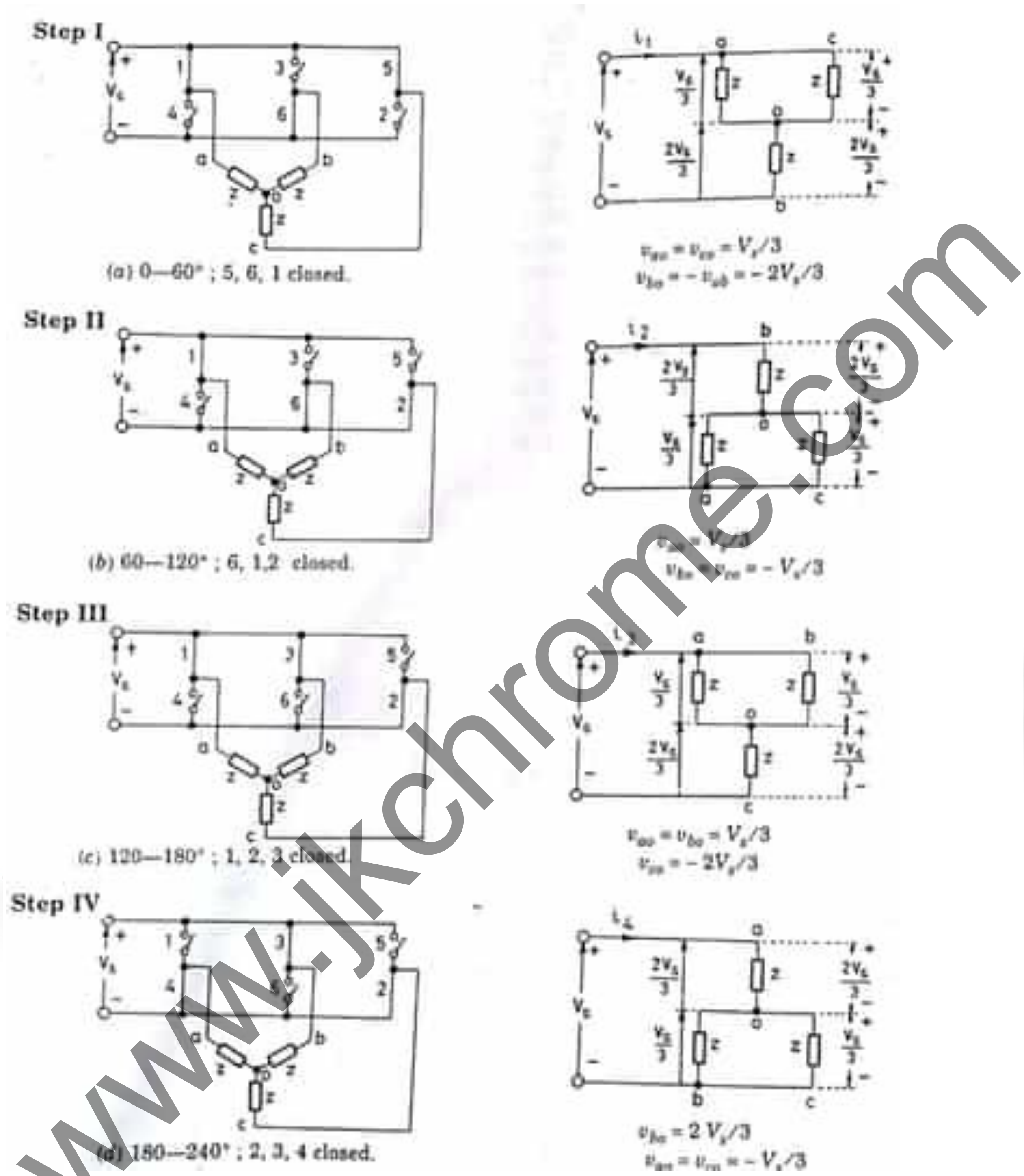
The gating signal has to be displaced by 120^0 with respect to each other so as achieve three phase balanced voltages.

A 3-phase output can be achieved from a configuration of six transistors and six diodes.

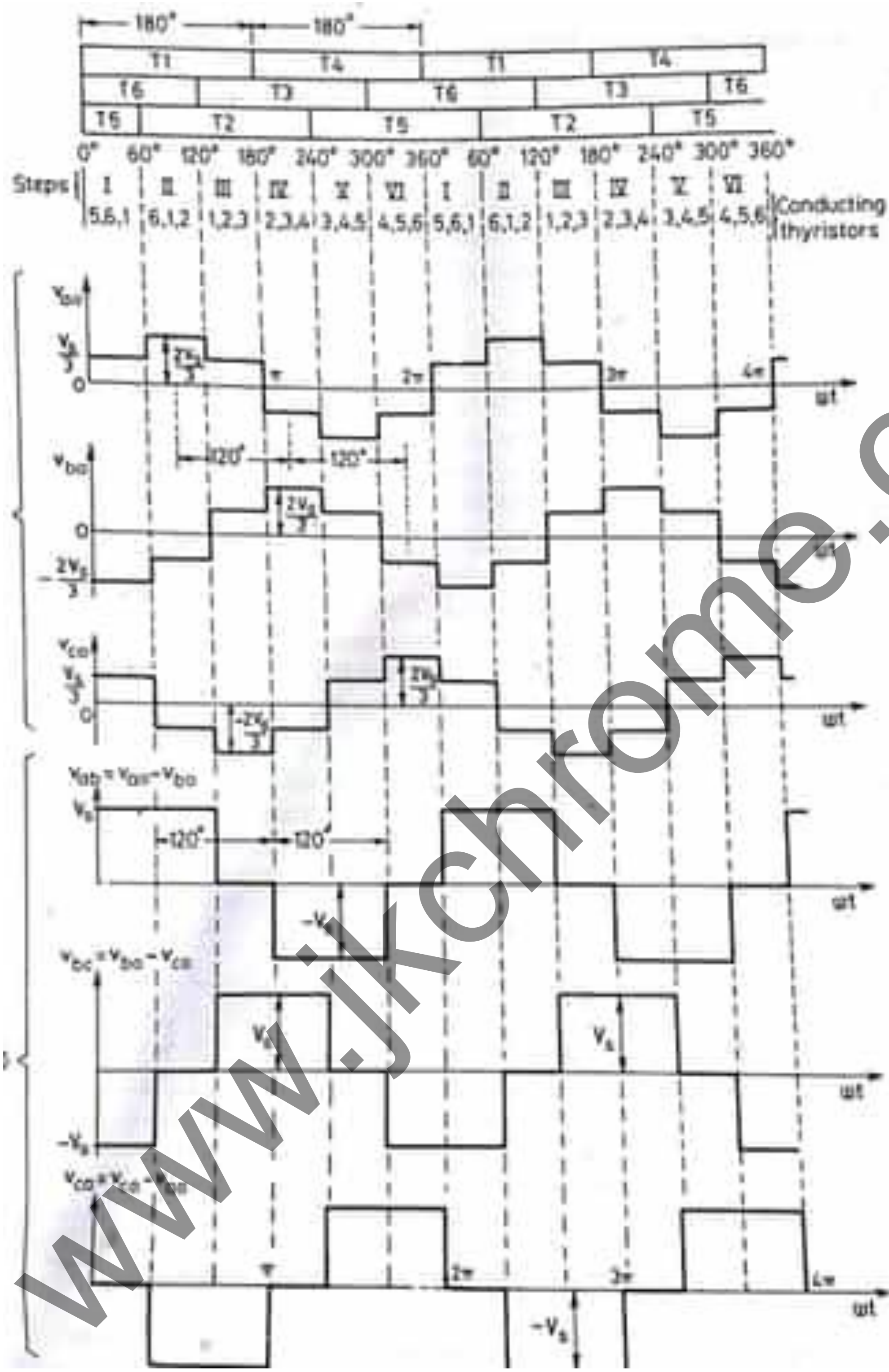


Two type of control can be applied to transistors, they are such as 180º & 120ºconduction

180-degree conduction.



Here $Q_1Q_2Q_3Q_4Q_5$ & Q_6 are the positions of thyristor When Q_1 is switched on, terminal a is connected to the positive terminal of dc input voltage.

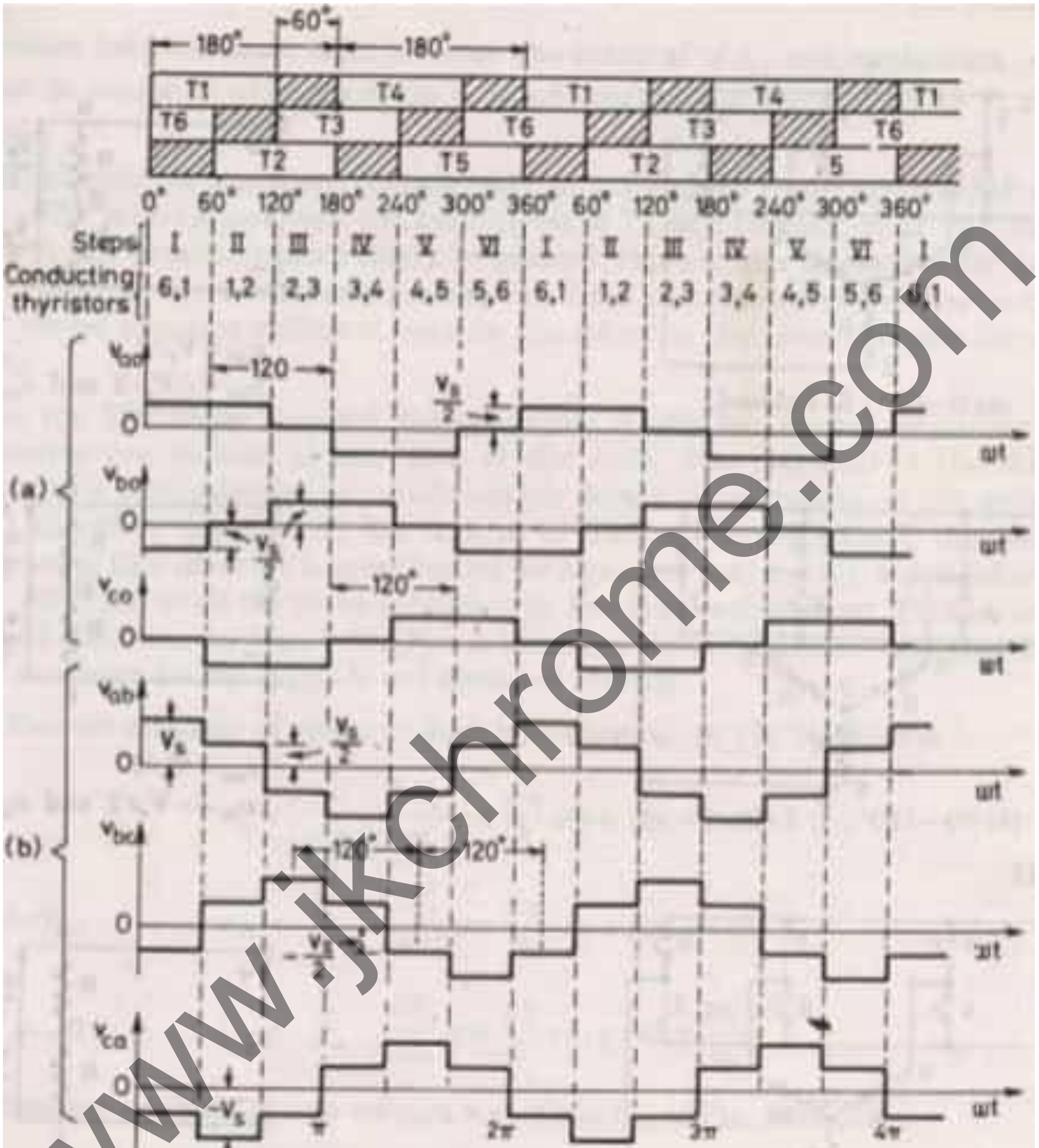


When Q_4 is switched on terminal a is brought to negative terminal of the dc source. There are 6 modes of operation is a cycle and the duration of each mode is 60^o.

The conduction sequence of thyristor or if we replace 123,234,345,456,561,612. The gating signals are shifted from each other by 60° to get 3-φ balanced voltages.

V_{RN}	V_{YN}	V_{BN}	V_{RY}	V_{YB}	V_{BR}	V_1
$\frac{V}{3}$	$\frac{-2V}{3}$	$\frac{V}{3}$	V_{dc}	$-V_{dc}$	0	$\frac{2}{\sqrt{3}}(330^0)$
$\frac{2V}{3}$	$\frac{-V}{3}$	$\frac{-V}{3}$	V_{dc}	0	$-V_{dc}$	$\frac{2}{\sqrt{3}}(30^0)$
$\frac{V}{3}$	$\frac{V}{3}$	$\frac{-2V}{3}$	0	V	-V	$\frac{2}{\sqrt{3}}(90^0)$
$\frac{-V}{3}$	$\frac{2V}{3}$	$\frac{-V}{3}$	-V	V	0	$\frac{2}{\sqrt{3}}(150^0)$
$\frac{-2V}{3}$	$\frac{V}{3}$	$\frac{V}{3}$	-V	0	0	$\frac{2}{\sqrt{3}}(210^0)$
$\frac{-V}{3}$	$\frac{-V}{3}$	$\frac{2V}{3}$	0	-V	0	$\frac{2}{\sqrt{3}}(270^0)$

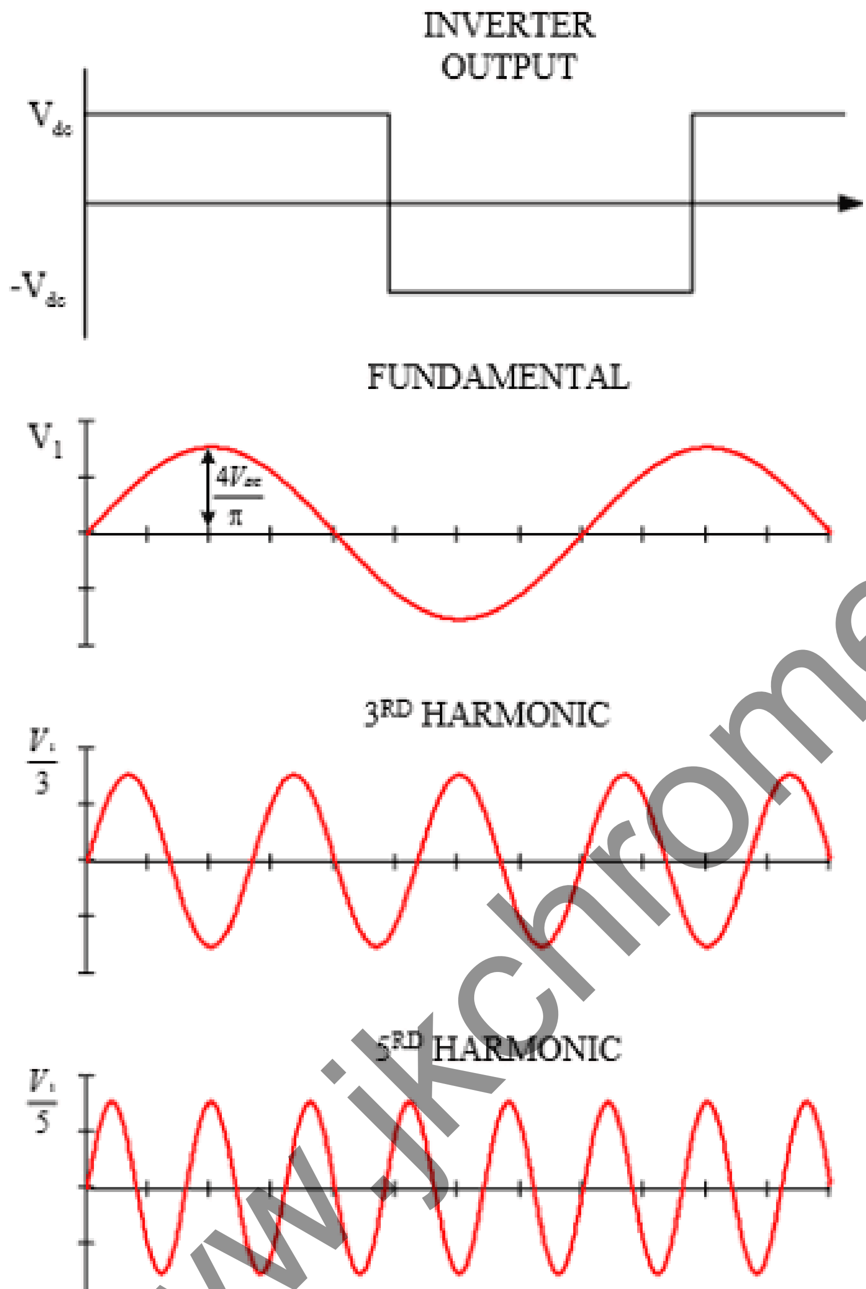
Three phase 120° mode VSI



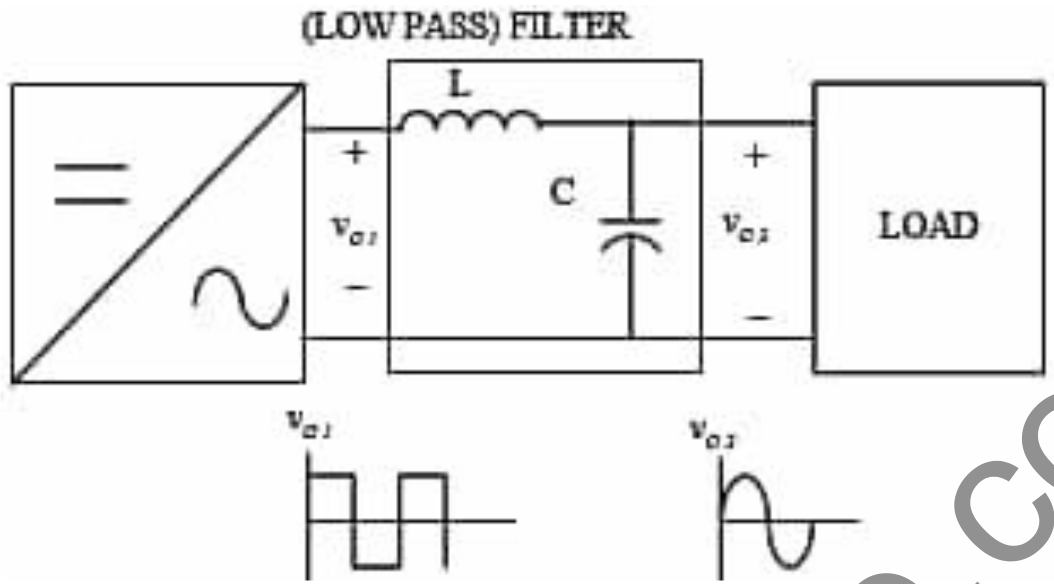
The circuit diagram is same as that for 180° mode of conduction.

Here each thyristor conducts for 120°.There are 6 steps each of 60° duration, for completing one cycle of ac output voltage.

Waveform & Harmonics of Square Wave Inverter


INVERTER
OUTPUT
Vdc
-Vdc
FUNDAMENTAL
V1
4Vdc/π
3RD HARMONIC
V1/3
5RD HARMONIC
V1/5

Filtering



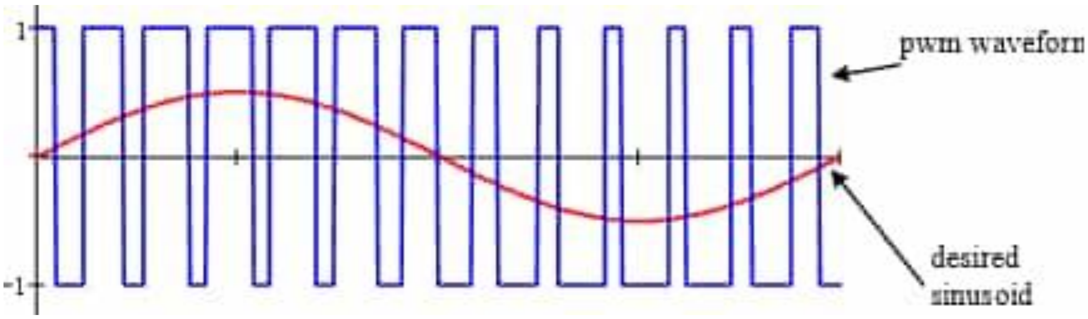
- Output of the inverter is “chopped AC voltage with zero DC component”. In some, applications such as UPS, “high purity” sine wave output is required.
- An LC section low-pass filter is normally fitted at the inverter output to reduce the high frequency harmonics.
- In some applications such as AC motor drive, filtering is not required.

In square wave inverters, maximum output voltage is achievable. However there in NO control in harmonics and output voltage magnitude.

- The harmonics are always at three, five, seven etc times the fundamental frequency.
- Hence the cut-off frequency of the low pass filter is somewhat fixed. The filter size is dictated by the VA ratings of the inverter.
- To reduce filter size, the PWM switching scheme can be utilised.
- In this technique, the harmonics are “pushed” to higher frequencies. Thus the cut-off frequency of the filter is increased. Hence the filter components (I.e. L and C) sizes are reduced.
- The trade off for this flexibility is complexity in the switching waveforms.

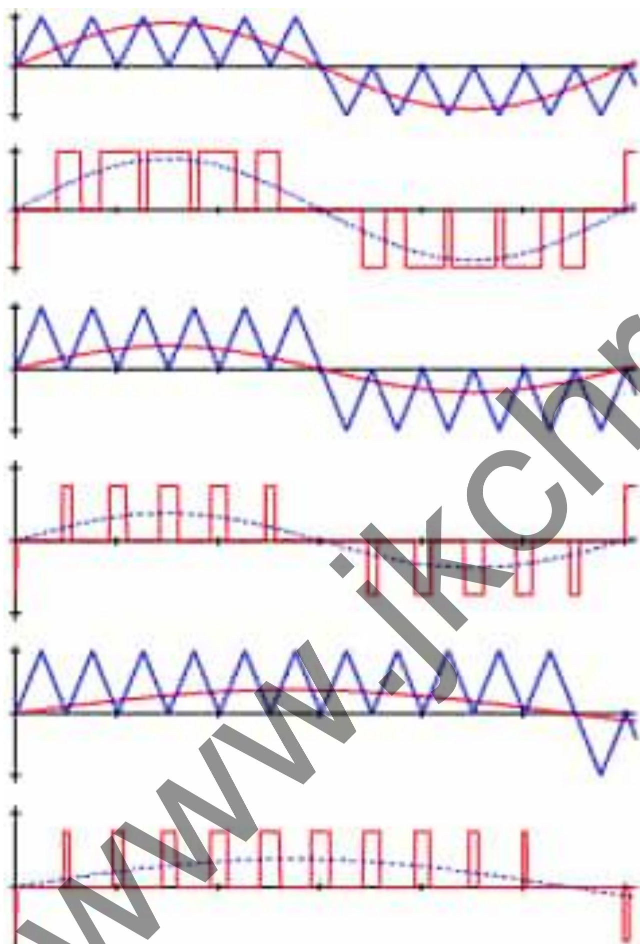
Pulse-width modulation (PWM)

A better square wave notching is shown below -this is known as PWM technique.



Both amplitude and frequency can be controlled independently. Very flexible.

PWM-output voltage and frequency control



Output voltage harmonics

Total Harmonic Distortion (THD) is a measure to determine the “quality” of a given waveform.

$$THDv = \frac{\sqrt{\sum_{n=2}^{\infty}\left(V_{n,RMS}\right)^2}}{V_{1,RMS}} = \frac{\sqrt{\sum_{n=2}^{\infty}\left(V_{RMS}\right)^2 - \left(V_{1,RMS}\right)^2}}{V_{1,RMS}}$$

Study of harmonics requires understanding of wave shapes. Fourier Series is a tool to analyse wave shapes.

Harmonics of square-wave

$$b_n = \frac{V_{dc}}{n\pi}\left[-\cos(n\theta)\Big|_0^{\pi} + \cos(n\theta)\Big|_{\pi}^{2\pi}\right]$$
$$= \frac{V_{dc}}{n\pi}\left[(\cos 0 - \cos n\pi) + (\cos 2n\pi - \cos n\pi)\right]$$
$$= \frac{V_{dc}}{n\pi}\left[(1 - \cos n\pi) + (1 - \cos n\pi)\right]$$
$$= \frac{2V_{dc}}{n\pi}\left[(1 - \cos n\pi)\right]$$

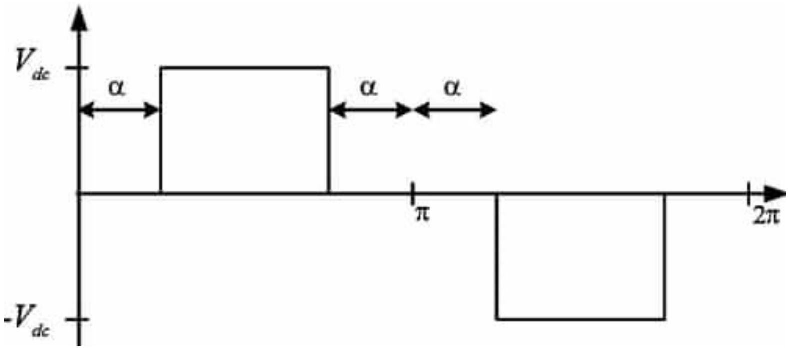
When n is even cos nπ =1

When n is odd cos nπ = -1

bn = 4 V_{dc}/ nπ

- Harmonic decreases as n increases. It decreases with a factor of (1/n).
- Even harmonics are absent – Nearest harmonics is the 3rd. If fundamental is 50Hz, then nearest harmonic is 150Hz.
- Due to the small separation between the fundamental an harmonics, output low-pass filter design can be quite difficult.

Quasi-square wave



a_n = 0 Due to half wave symmetry.

$$b_n = \frac{2V_{dc}}{n\pi}\left[\cos(n\alpha) - \cos n\pi \cos n\alpha\right]$$

If n is even then bn = 0

If n is odd then

$$b_n = \frac{4V_{dc}}{n\pi}\cos(n\alpha)$$

In particular, amplitude of the fundamental

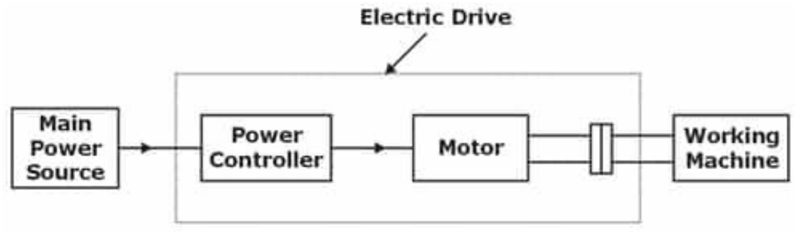
$$b_1 = \frac{4V_{dc}}{\pi}\cos(\alpha)$$

In General, n^{th} Harmonics will be eliminated if ⇒ **α = 90°/n**

Electric Drives

"Power Electronics & Drives: Electric Drives

In many applications, electric motors supply power to a load, hence, require a variable voltage or variable frequency control. The same can be achieved through power electronic converters. Figure below shows block diagram of an electric drive system.



Electric drives are typically of two types: AC Drives & DC Drives. These two mainly differ by the motor type (DC or AC) which supply power. Figure below shows block diagram of a modern electric drive system using power electronic converter.

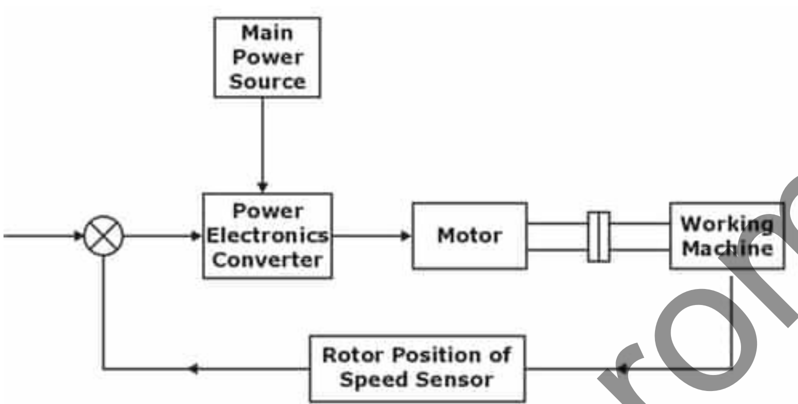


Fig. Block diagram of a modern electric drive system using power electronic converter

DC DRIVES

DC Drives consists of a DC Motor, Power Electronic Converter. i.e. Rectifier (or) chopper. Speed Sensing Mechanism-Tachometer, Feedback circuit and intelligent device (Micro controller).

The following dc motors are suitable for speed control applications.

1. Series motor
2. Separately excited dc motor

In the speed control application, load remains same i.e., output current is continuous and assumed to be constant.

$$E_a = \frac{Z\phi NP}{60A} = Z\phi n\left(\frac{P}{A}\right) \qquad \omega_m = 2\pi n$$

$$E_a = Z\phi\left(\frac{\omega_m}{2\pi}\right)\left(\frac{P}{A}\right) = \left(\frac{Z}{2\pi}\cdot\frac{P}{A}\right)\phi\omega_m \qquad \Rightarrow \boxed{E_a = K_a\phi\omega_m}$$

Where, $\boxed{K_a = \frac{Z}{2\pi}\left(\frac{P}{A}\right)}$

$E_a I_a$ (Electrical power) = $T_e\omega_m$ (Mechanical power)

$$T_e = \frac{E_a I_a}{\omega_m} \qquad \Rightarrow \boxed{T_e = K_a\phi I_a}$$

Single phase half wave converter drive:

The figure shown below shows single phase half wave converter supplying power to a DC motor. It is assumed that armature draws a constant current, I_a.

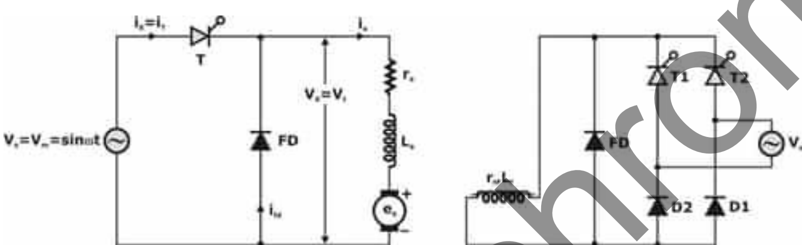


Fig. Single phase half wave converter drive

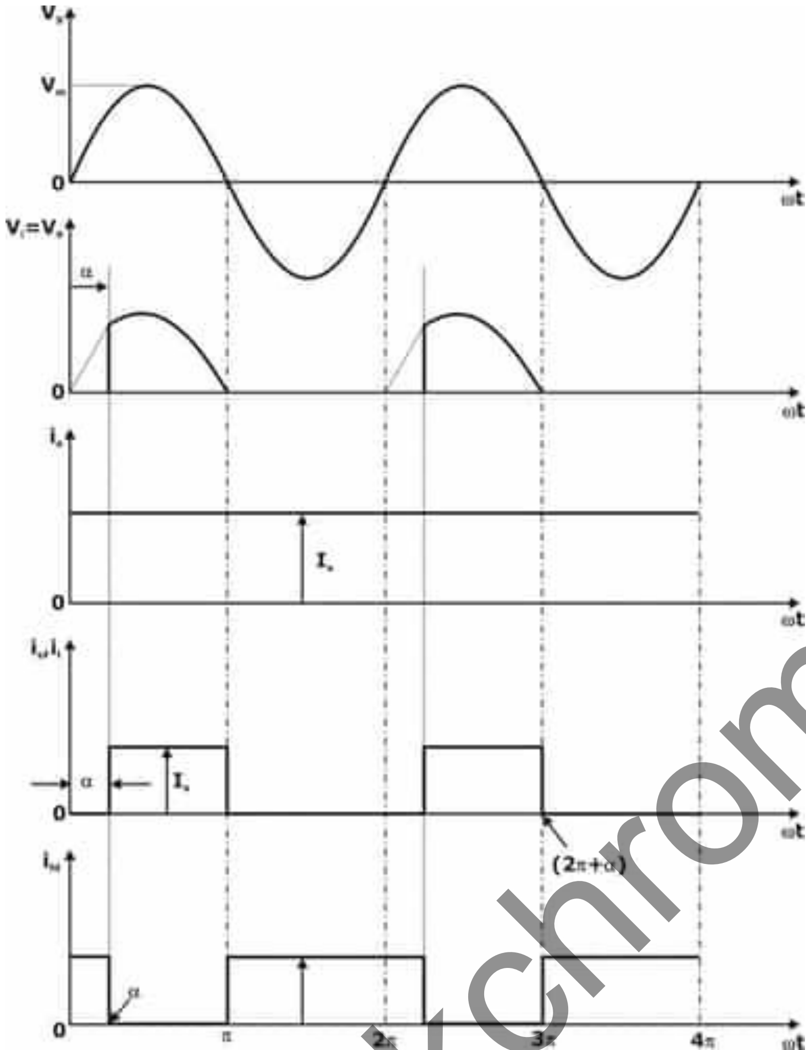


Fig. Waveforms for Single phase half wave converter drive

Average output voltage,

$$V_0 = V_t = \frac{V_m}{2\pi}(1+\cos\alpha_1) \qquad ; 0 < \alpha_1 < \pi$$

Rms value of source current,

$$I_{s(rms)} = I_t\sqrt{\left(\frac{\pi-\alpha_1}{2\pi}\right)}$$

Rms value of current through freewheeling diode,

$$I_{fd(rms)} = I_a \sqrt{\left(\frac{\pi + \alpha_1}{2\pi}\right)}$$

Input power factor,

$$p.f. = \frac{E_a I_a + I_a^2 r_a}{V_s I_{sr}} = \frac{I_a (E_a + I_a r_a)}{V_s I_{sr}}$$

THREE-PHASE DRIVES:

Larger DC motors are fed through three-phase converters for their speed control. For speeds below base speed, three-phase controlled converter feeds power to armature circuit and for speeds above base speed, the same is connected to field circuit. The output ripple frequency of three-phase converter is higher than that of single-phase converter. Hence for reducing armature current ripple, inductance required in three-phase dc drive is lower than of single-phase dc drive. Also, the motor performance in three-phase dc drive is superior to that of single-phase dc drive.

The three-phase dc drives may be subdivided as,

- Three phase half wave converter drive
- Three phase semiconductor drive
- Three phase full converter drive
- Three phase dual converter drive

The operation of three phase DC drives is similar to single phase DC drives except that output voltage equation should be used accordingly.

Three Phase half wave Converter Drive:

Average output voltage,

$$V_0 = V_t = \frac{3\sqrt{6}}{2\pi} V_{ph} \cos\alpha$$

Rms value of source current,

$$I_{sr} = I_{Trms} = I_a \sqrt{\frac{1}{3}}$$

AC DRIVES

When AC voltage of frequency control of input voltage of an AC motor is required. The same can be achieved through AC voltage regulators or cycloconverter.

- AC drives have many advantages over DC drives like lighter weight for the same rating and low maintenance.
- Whereas the disadvantages are, ac drives are more complex and generate harmonics in supply system.
- Also, AC drives can be classified as induction motor and synchronous motor drives.
- Induction motors are the one generally used in AC drives.

Various methods of Speed Control of Induction Motors:

- Pole changing method
- Cascade method of speed control
- Stator voltage control
- Stator frequency control
- Stator v/f control