POWER ELECTRONICS

Power electronics is the application of solid-state electronics for the control and conversion of electric power. It also refers to a subject of research in electronic and electrical engineering which deals with design, control, computation and integration of nonlinear, time varying energy processing electronic systems with fast dynamics.

The first high power electronic devices were mercury-arc valves. In modern systems the conversion is performed with semiconductor switching devices such as diodes, thyristors and transistors. In contrast to electronic systems concerned with transmission and processing of signals and data, in power electronics substantial amounts of electrical energy are processed. An AC/DC converter (rectifier) is the most typical power electronics device found in many consumer electronic devices, e.g. television sets, personal computers, battery chargers, etc. The power range is typically from tens of watts to several hundred watts. In industry a common application is the variable speed drive (VSD) that is used to control an induction motor. The power range of VSDs start from a few hundred watts and end at tens of megawatts..

Introduction

Many different types of semiconductors have been applied in power electronics. In general, these fall into three groups:

_ **Diodes**, which are used in rectifiers, dc-dc converters, and in supporting roles.

_ **Transistors**, which in general are suitable for control of single-polarity circuits. Several types of transistors are applied to power converters. The most recent type, the insulated gate bipolar transistor (IGBT) is unique to power electronics and has good characteristics for applications such as inverters.

_ **Thyristors**, which are multi-junction semiconductor devices with latching behavior. Thyristors in general can be switched with short pulses, and then maintain their state until current is removed. They act only as switches. The characteristics are especially well-suited to controllable rectifiers, although thyristors have been applied to all power conversion applications

The Power Diode

1. Diode as a Switch

Among all the static switching devices used in power electronics (PE), the power diode is perhaps the simplest. Its circuit symbol, shown in Fig.(1), is a two terminal device, and with terminal A known as the anode and terminal K known as the cathode. If terminal A experiences a higher potential compared to terminal K, the device is said to be forward biased and a forward current (I_F) will flow through the device in the direction as shown. When a diode is, reverse biased, it does not conduct and the diode then experiences a small current flowing in the reverse direction called the leakage current. Both forward voltage drop and leakage current are ignoring in an ideal diode. In PE applications, a diode usually considered an ideal static switch.

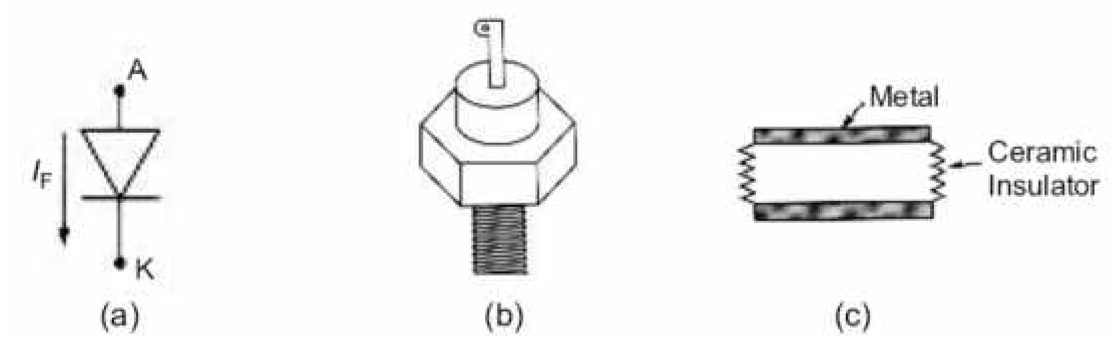


Fig.(1): Power diode: (a) symbol; (b) and (c) types of packaging.

Some Properties of PN Junction

From the forward and reverse-biased condition characteristics, one notices that when the diode is forward biased, current rises rapidly as the voltage is increased. Current in the reverse biased region is significantly small until the breakdown voltage of the diode is reached. Once the applied voltage is over this limit, the current will increase rapidly to a very high value limited only by an external resistance. The characteristics of diodes are explained as Figure (2).

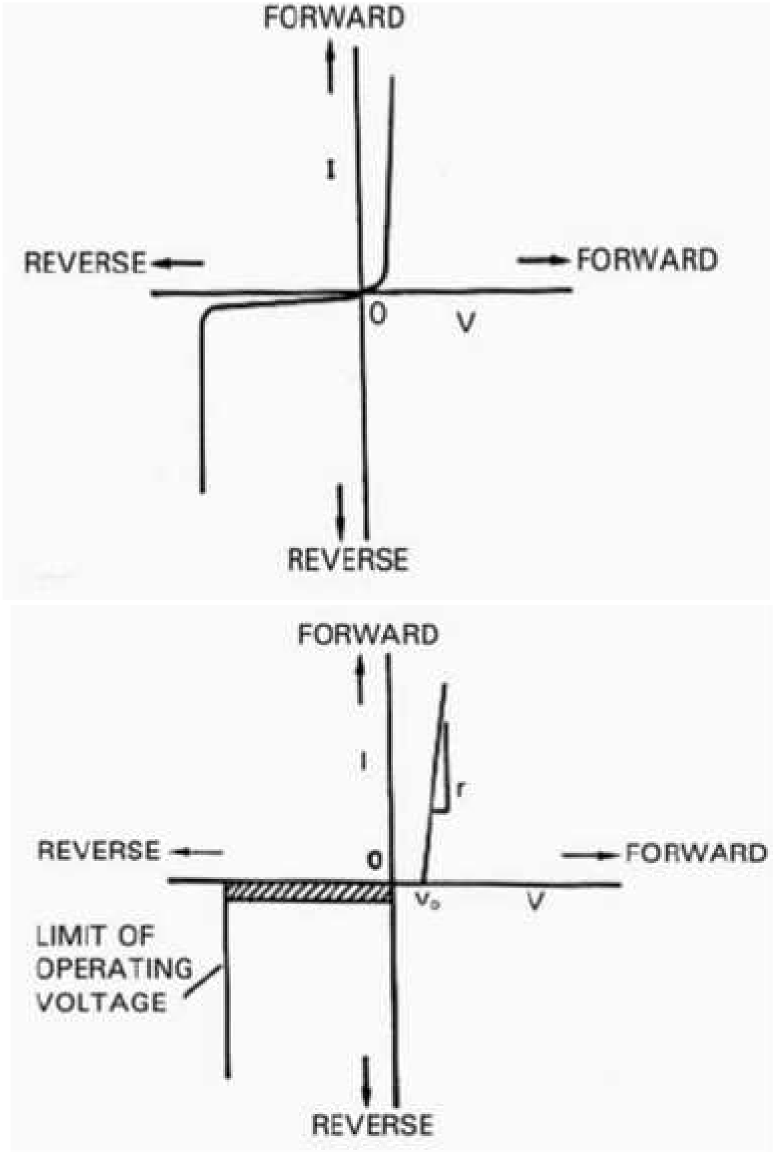


Fig. (2) : a) Typical static characteristic of a power diode.

b) Practical representation of the static characteristic of a power diode.

<u>Some Applications of Diode</u>

Diode Rectifiers:

There are two types of single-phase diode rectifier that convert a single-phase ac supply into a dc voltage, namely, single-phase half-wave rectifiers and single-phase full-wave rectifiers.. For the sake of simplicity the diodes are considered to be ideal, that is, they have zero forward voltage drop and reverse recovery time. This assumption is generally valid for the case of diode rectifiers that use the mains, a low-frequency source, as the input, and when the forward voltage drop is small compared with the peak voltage of the mains.

Single-Phase Half-Wave Rectifiers(R Load)

The simplest single-phase diode rectifier is the single-phase half-wave rectifier. A single-phase half-wave rectifier with resistive load is shown in Figure below. The circuit consists of only one diode that is usually fed with a transformer secondary as shown. During the positive half-cycle of the transformer secondary voltage, diode D conducts. During the negative half-cycle, diode D stops conducting. Assuming that the transformer has zero internal impedance and provides perfect sinusoidal voltage on its secondary winding, the voltage and current waveforms of resistive load R and the voltage waveform of diode D are shown in Figure (3) below.

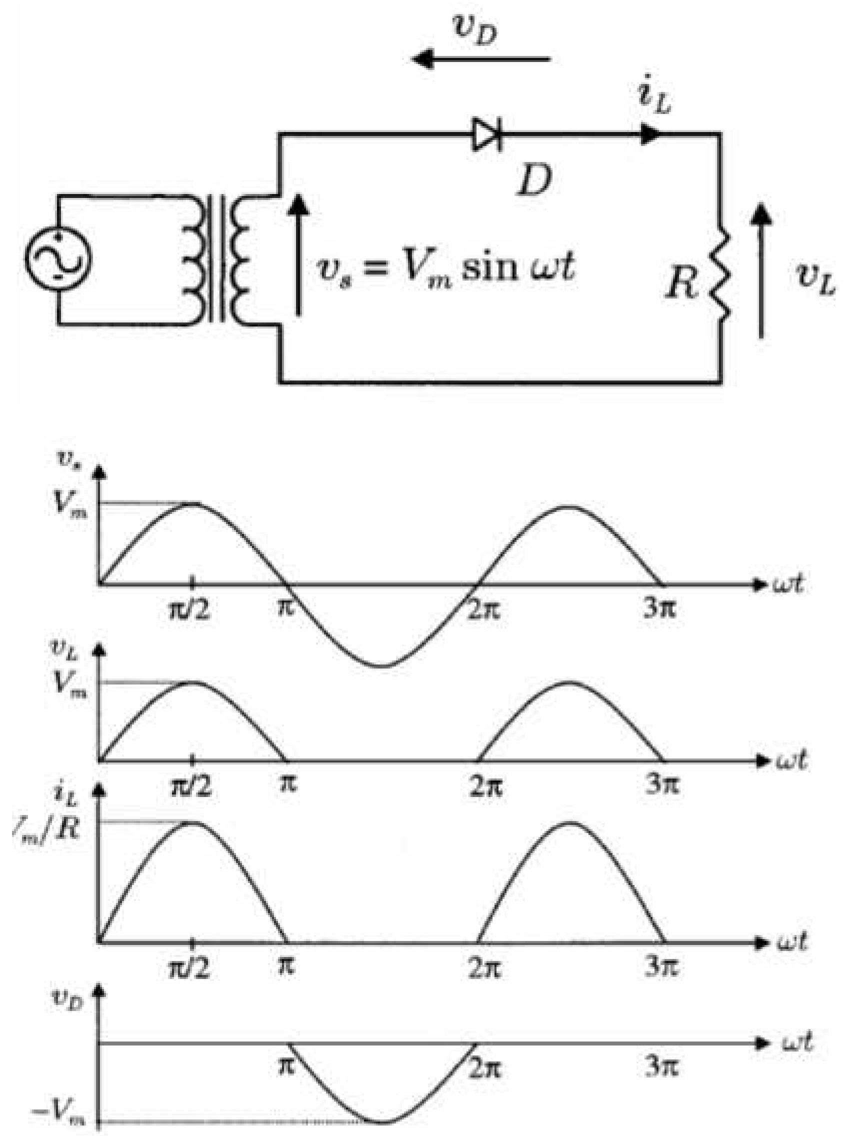


Fig.(3): a) half-wave rectifier circuit

b) the output of half-wave rectifiers

The average value of the load voltage vL is Vdc and it is defined as:

$$V_{dc} = \frac{1}{T}\int_0^T v_L(t)dt$$

That load voltage $V_L(t)=0$, for the negative half-cycle. Note that the angular frequency of the source $\omega=2\pi/T$. Then:

$$V_{dc} = \frac{1}{2\pi}\int_0^\pi V_m \sin \omega t d(\omega t)$$

Therefore,

$$V_{dc} = \frac{V_m}{\pi} = 0.318\ V_m$$

The root-mean-square (rms) value of load voltage v_L is V_L, which is defined as:

$$V_L = \left[\frac{1}{T}\int_0^T v_L^2(t)dt\right]^{1/2}$$

In the case of a half-wave rectifier, $V_L(t)=0$ for the negative half-cycle, therefore,

$$V_L = \sqrt{\frac{1}{2\pi}\int_0^\pi (V_m \sin \omega t)^2 d(\omega t)}$$

or

$$\text{Half-wave } V_L = \frac{V_m}{2} = 0.5\ V_m$$

The average value of load current i_L is I_{dc} and because load R is purely resistive it can be found as:

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

The root-mean-square (rms) value of load current i_L is I_L and it can be found as:

$$I_L = \frac{V_L}{R}$$

In the case of a half-wave rectifier,

$$I_{dc} = \frac{0.318\ V_m}{R}$$

And

$$I_L = \frac{0.5\ V_m}{R}$$

→The rectification ratio, which is a figure of merit for comparing the effectiveness of rectification, is defined as:

$$\frac{\mathbf{P_{dc}}}{\mathbf{P_L}} = \frac{\mathbf{V_{dc} I_{dc}}}{\mathbf{V_L I_L}}$$

In the case of a half-wave diode rectifier, the rectification ratio can be determined by:

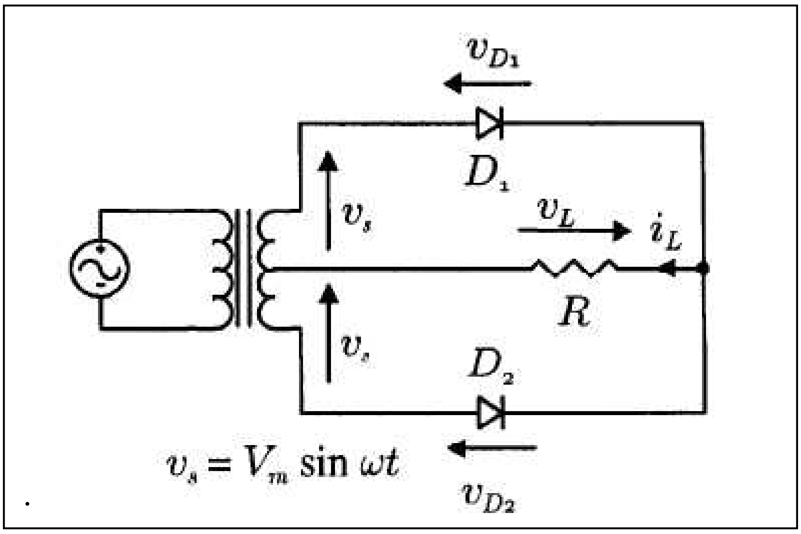
$$= \frac{(0.318\ V_m)^2}{(0.5\ V_m)^2} = 40.5\%$$

<u>Single-Phase Full-Wave Rectifiers</u>

There are two types of single-phase full-wave rectifier, namely, full-wave rectifiers with center-tapped transformer and bridge rectifiers.

|***1. full-wave rectifier with a center-tapped transformer***:

It is clear that each diode, together with the associated half of the transformer, acts as a half-wave rectifier. The outputs of the two half-wave rectifiers are combining to produce full-wave rectification in the load.



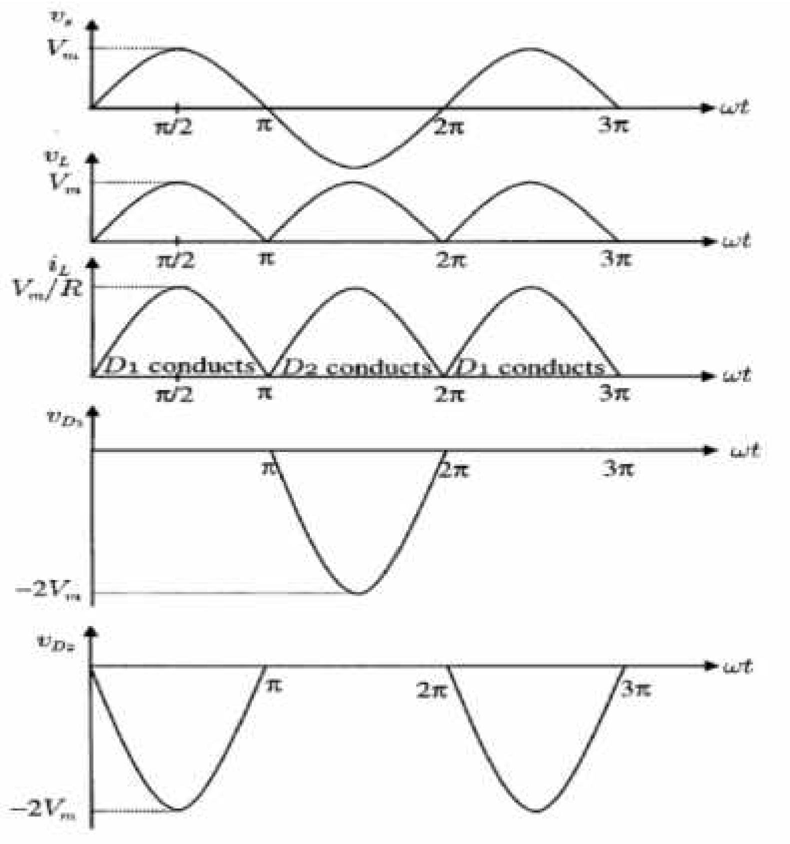


Fig. (4): a) full-wave rectifier with center-tapped transformer.

b) the output of full wave rectifier with center- tapped transform

- ✓ It is clear that the peak inverse voltage (PIV) of the diodes is equal to $2V_m$ during their blocking state. Hence, the Peak Repetitive Reverse Voltage (V_{RRM}) rating of the diodes must be chose to be higher than $2V_m$ to avoid reverse breakdown.
- ✓ During its conducting state, each diode has a forward current that is equal to the load current and, therefore, the Peak Repetitive Forward Current (I_{FRM}) rating of these diodes must be chosen to be higher than the peak load current V_m/R in practice

***2. Bridge rectifier*:**

It can provide full-wave rectification without using a center-tapped transformer. During the positive half cycle of the transformer secondary voltage, the current flows to the load through diodes D_1 and D_2. During the negative half cycle, D_3 and D_4 conduct.

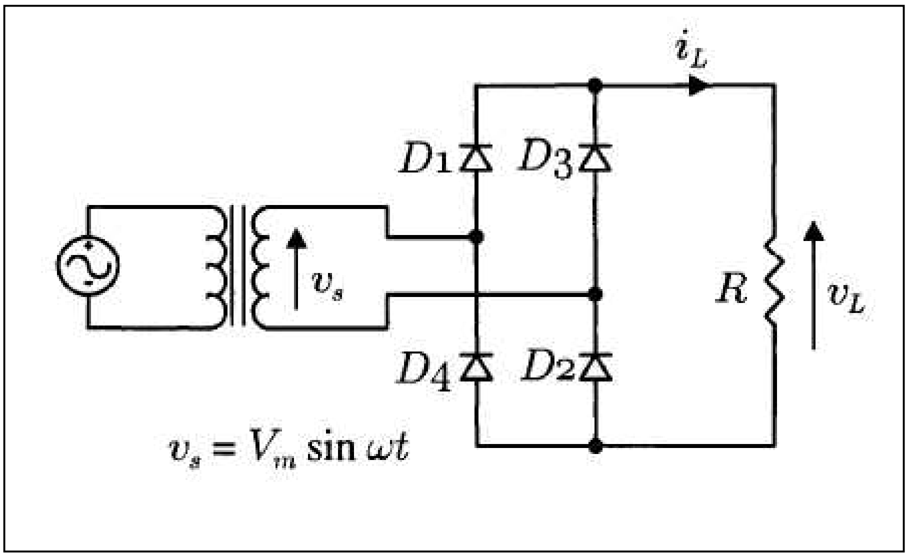


Fig. (5): full- wave rectifier (bridge rectifier)

- ✓ As with the full-wave rectifier with center-tapped transformer, the Peak Repetitive Forward Current (I_{FRM}) rating of the employed diodes must be chosen to be higher than the peak load current $V_m = I_m \times R$
- ✓ → However, the peak inverse voltage (PIV) of the diodes is reduced from $2V_m$ to V_m during their blocking state.

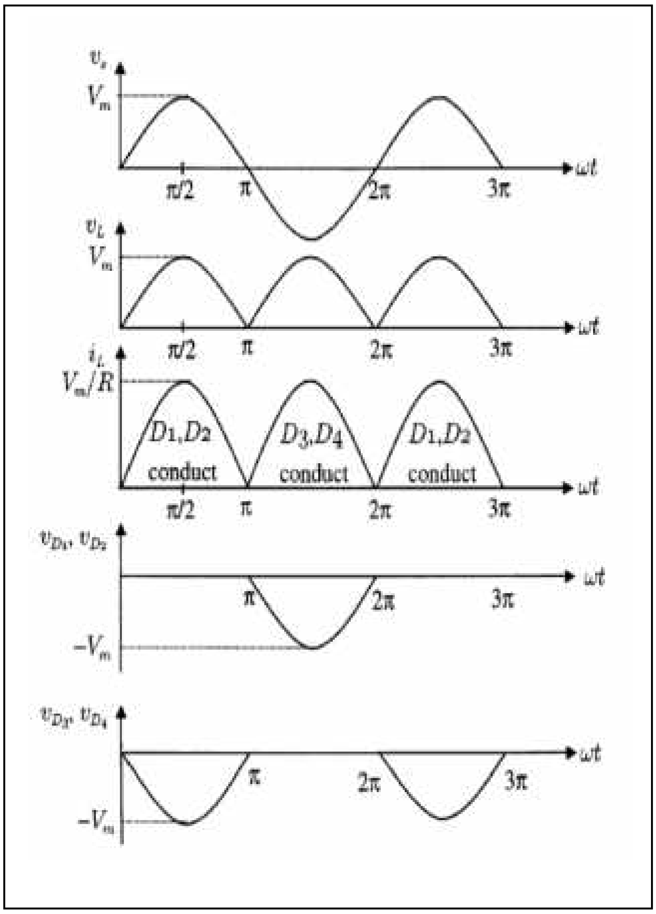
In the case of a full-wave rectifier, $v_L(t)=V_m |\sin\omega t|$ for both the positive and negative half-cycles. Hence;

$$V_{dc} = \frac{1}{\pi}\int_0^{\pi} V_m \sin \omega t \, d(\omega t)$$

Therefore;

$$\text{Full-wave } V_{dc} = \frac{2V_m}{\pi} = 0.636\, V_m$$

The root-mean-square (rms) value of load voltage v_L is V_L, which is defined as:



$$V_L = \left[\frac{1}{T} \int_0^T v_L^2(t) dt \right]^{1/2}$$

Hence, the equation can be rewritten as:

$$V_L = \sqrt{\frac{1}{\pi} \int_0^{\pi} (V_m \sin \omega t)^2 d(\omega t)}$$

OR

$$\text{Full-wave } V_L = \frac{V_m}{\sqrt{2}} = 0.707\ V_m$$

Therefore; the average and the rms value load current is:

$$I_{\text{dc}} = \frac{0.636\ V_m}{R}$$

$$I_L = \frac{0.707\ V_m}{R}$$

The rectification ratio is:

$$\frac{P_{\text{dc}}}{P_L} = \frac{V_{\text{dc}} I_{\text{dc}}}{V_L I_L}$$

$$= \frac{(0.636\ V_m)^2}{(0.707\ V_m)^2} = 81\%$$

Lecture two

Thyristor abistable

1. Introduction

It is one of the most important type power electronics devices. It operate as a bistable switches operating form non-conducting to conducting state, and can assumed as an ideal switching for some application. The thyristor are manufactured by diffusion method. Thyristors are usually three-terminal devices with four layers of alternating p- and n-type material (i.e. three p-n junctions) in their main power handling section. The control terminal of the thyristor, called the gate (G) electrode, may be connected to an integrated and complex structure as part of the device. The other two terminals, anode (A) and cathode (K), handle the large applied potentials and conduct the major current through the thyristor. The anode and cathode terminals are connected in series with the load to which power is to be controlled

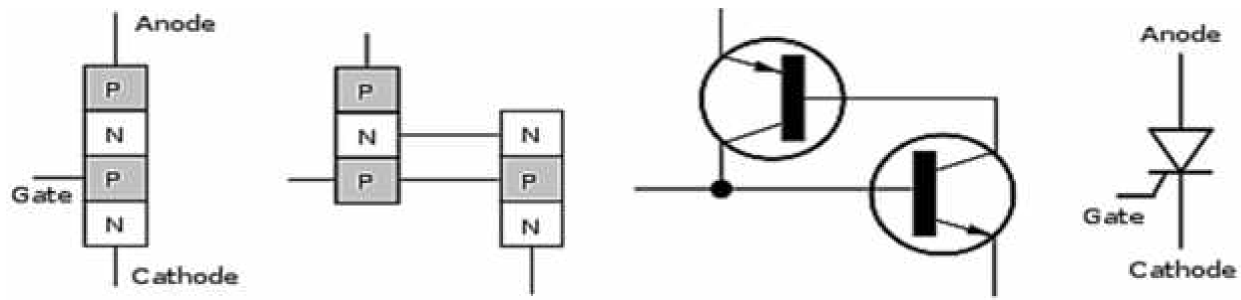


Fig. (6) symbol and structure of thyristor

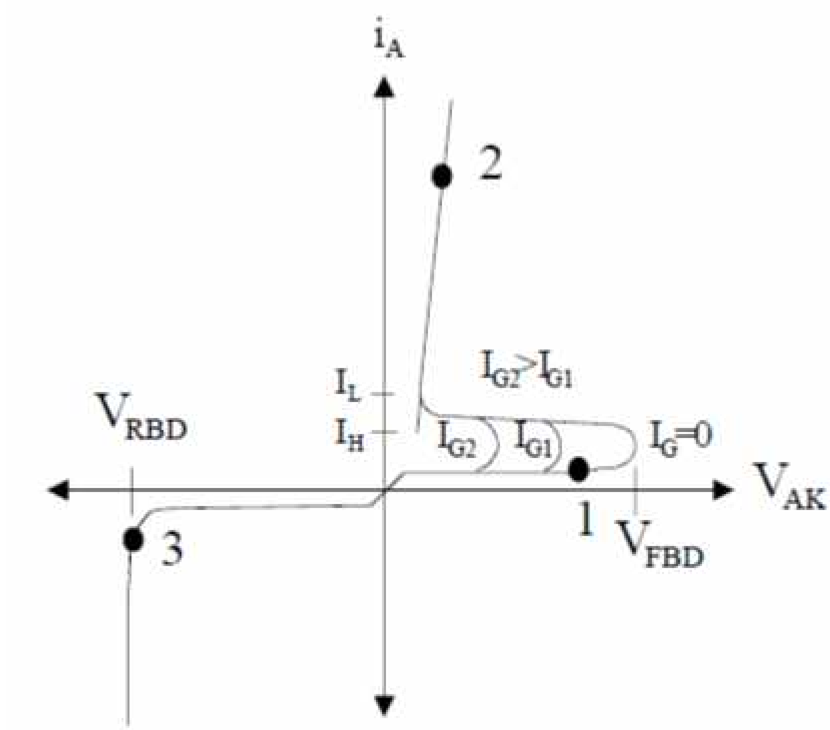
The operation of thyristors is as follows. When a positive voltage is applied to the anode (with respect to a cathode), the thyristor is in its forward-blocking state. The center junction J_2 is reverse-biased. In this condition only thermally generated leakage current flows through the device and can often be approximate as zero in value. When a positive gate current is injected into the device J_3 becomes forward-biased and electrons are injected from the n-emitter into the p-base. The thyristor is latched in its on state (forward-conduction). In other words, when the anode voltage is positive with respect to the cathode the junctions J_1 and J_3 are forward biasing. The junction J_2 will be reverse biasing and only a small leakage current pass from anode to cathode. The thyristor t this case called "forward blocking" or "off state" condition and leakage current called state current, "I_D".

If the anode to cathode voltage V_{AK} is increased to sufficiently large value, the reverse biased junction J_2 will break and this called "avalanche breakdown" and corresponding voltage called " forward breakdown V_{BO}".

Since other junctions J_1 and J_3 are already forward biased a free movement of carriers across all three junctions this will result large forward anode to cathode current this called " ON state" or "conducting state. The current at ON state is limited by the external resistance or impedance and the anode current must be large than value called "Latching current I_L" in order to maintain the required current or carrier to flow a cross the junctions otherwise the thyristor back to block condition.

At conducting state the thyristor behave like conducting diode and there is no current over the device because there is no depilate region on the junction $J_{2.}$

If the current reduced below such value called "holding current I_H" a depilation region will develop a round junction J_2 due to reduce of the number of the carrier and then thyristor will be in blocking state. When the cathode voltage is positive with respect to anode the J_2 will forward and J_1 and J_3 will be reverse biased, the thyristor called "reverse blocking" and current called "reverse current I_R".



Static characteristic i-n curve typical of thyristors.

As the thyristor moves from forward-blocking to forward conduction, the external circuit must allow sufficient anode current to flow to keep the device latched. If the thyristor is already in forward conduction and the anode current is reduced, the device can move its operating mode from forward-conduction back to forward-blocking. The minimum value of anode current necessary to keep the device in forward-conduction after it has been operating at a high anode current value by the holding current I_H. The holding current value is lower than the latching current value.

Thyristor Equivalent Circuit

$I_C = \alpha I_E + I_{CBO}$ 1

I_C: collector current

I_E: emitter current

I_{CBO}: leakage current of collector-base junction

α: common base current gain

$$\alpha = \frac{I_C}{I_E}$$

$I_{C1} = \alpha_1 I_A + I_{CBO1}$

$I_{C2} = \alpha_2 I_K + I_{CBO2}$

$I_A = I_{C1} + I_{C2}$

$I_A = \alpha_1 I_A + I_{CBO} + \alpha_2 I_K + I_{CBO2}$…………..2

$I_K = I_A + I_G$………….3

Sub equ 3 in 2 to obtain

$$I_A = \frac{I_G + I_{CBO1} + I_{CBO2}}{1 - [\alpha_1 + \alpha_2]}$$

Triggering (Turn on) Methods of Thyristor:

The main idea of triggering thyristor is to applied positive signal at gate terminal of the thyristor, there are many type of circuit to do that like:.

The various thyristor triggering methods are

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

(a) Forward Voltage Triggering:-

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

(b) Thermal (or) Temperature Triggering:-

- The width of depletion layer of SCR decreases with increase in junction temperature.
- Therefore in SCR when V_{AR} is very near its breakdown voltage, the device is triggered by increasing the junction temperature.
- By increasing the junction temperature the reverse biased junction collapses thus the device starts to conduct.

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

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

(d) dv/dt Triggering:-

- When the device is forward biased, J1 and J3 are forward biased, J2 is reverse biased.
- Junction J2 behaves as a capacitor, due to the charges existing across the junction.
- If voltage across the device is V, the charge by Q and capacitance by C then,
  $i_c = dQ/dt$
  $Q = CV$
  $i_c = d(CV)/dt$
  $i_c = C.dV/dt + V.dC/dt$
  as $dC/dt = 0$
  $i_c = C.dV/dt$
- Therefore when the rate of change of voltage across the device becomes large, the device may turn ON, even if the voltage across the device is small.

(e) Gate Triggering:-

- Applying a positive voltage between gate and cathode can Turn ON a forward biased thyristor.
- When a positive voltage is applied at the gate terminal, charge carriers are injected in the inner P-layer, thereby reducing the depletion layer thickness.
- As the applied voltage increases, the carrier injection increases, therefore the voltage at which forward break-over occur decrease

The total switching period being much smaller compared to the cycle time, i_A and V_{AK}. There are a transition time 't_{ON}' from forward off state to forward on state. This transition time is called the thyristor turn ON time and can be divided into three separate intervals namely as like

- **Delay time(t_d)**: After witching ON, the gate current of thyristor will start to conduct over the portion of the cathode which is closest to the gate. This conducting area starts spreading at a finite speed until the entire cathode region become conductive.
- **Rise time (t_r):** is the time taken by the anode current to rise from 10% of its final value to 90% of its final value for inductive load the voltage falls faster than the current. While for a capacitive load V_{AK} fall rapidly in the beginning.

- **Spread time (t_p):** It is the time taken by the anode current to rise from 90% of it's a final value to 100%. During this time conduction spreads over the entire cross section of the cathode of the thyristor.

Thyristor Gate Triggering Technique

Three types of signals are used for gate triggering.

1. DC gate triggering:-

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

2. AC Gate Triggering:-

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

3. Pulse Gate Triggering:-

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

- **Gate current to triggering (IGT):** Minimum value of a gate current below which reliable turn on of the thyristor can not be guaranteed. Usually specified at the same break over voltage as IGT.
- **Gate voltage to triggering(VGT):** Minimum value of the gate cathode forward below which the thyristor can be guaranteed to remain OFF. All spurious noise voltage in the gate drive circuit must be below this level.
- **Peak reverse gate voltage (VGRM):** Maximum reverse voltage that can appear between the gate and the cathode terminals without damaging the junction.
- **Average gate power dissipation(PGAR):** Average power dissipated in the gate-cathode junction should not exceed this value for gate current pulses wider than 100µs.
- **Peak forward gate current (IGRM):** The forward gate current should not exceed this limit even on instantaneous basis.

Some points should be taken at design of gate current:

- Gate signal should be removed after the turn-ON of thyristor.
- While the thyristor at the reverse biased NO gate signal should be applied. Otherwise the thyristor will explode.
- The width of gate pulse signal must longer than the time required for the current to reach the holding current I_H. Practically $t_G > t_{ON}$ of the thyristor.

Each thyristor has maximum gate voltage limit(V_{gmax}), gate current limit (I_{gmax}) and maximum average gate power dissipation limit($P_{gav.Max}$), these limit should not be exceed in order to avoid permanent damage to the gate cathode junction. There are also minimum limit of V_g(V_{gmin}) and I_g (I_{min}) for reliable turn on the thyristor. A gate non triggering voltage (V_{ng}) is also specified by the manufacturers of thyristor. All spurious noise signals should be less than this voltage V_{ng} in order to prevent unwanted turn on of the thyristor. Maximum power dissipation for pulsed operation (P_{gm}) allows higher gate current to flow which reduces the turn-on time of the thyristor.

$\delta P_{gm}=P_{gav.Max}$

δ =duly ratio=$T_{ON} f_P$

f_P= pulse frequency

$T_{ON}= \delta T_s$

$P_{gm}=I_g V_g$

$E_s=R_s I_g+ V_g$

Where E=triggering source voltage

R_s= gate- source resistance

I_g= gate current

V_g= gate-cathode voltage

This figure shows the waveforms of the gate current (i_g), anode current (i_A) and anode cathode voltage (V_{AK}) in an expanded time scale during turn on.

Thyristor turn-OFF

Once the thyristor is on, and its anode current is above the latching current level the gate loses control. It can be turned off only by reducing the anode current below holding current. The turn off time t_q (t_{OFF}) of a thyristor is defined as the time between the instant anode current becomes zero and the instant the thyristor regains forward blocking capability. If forward voltage is applied across the device during this period the thyristor turns on again.

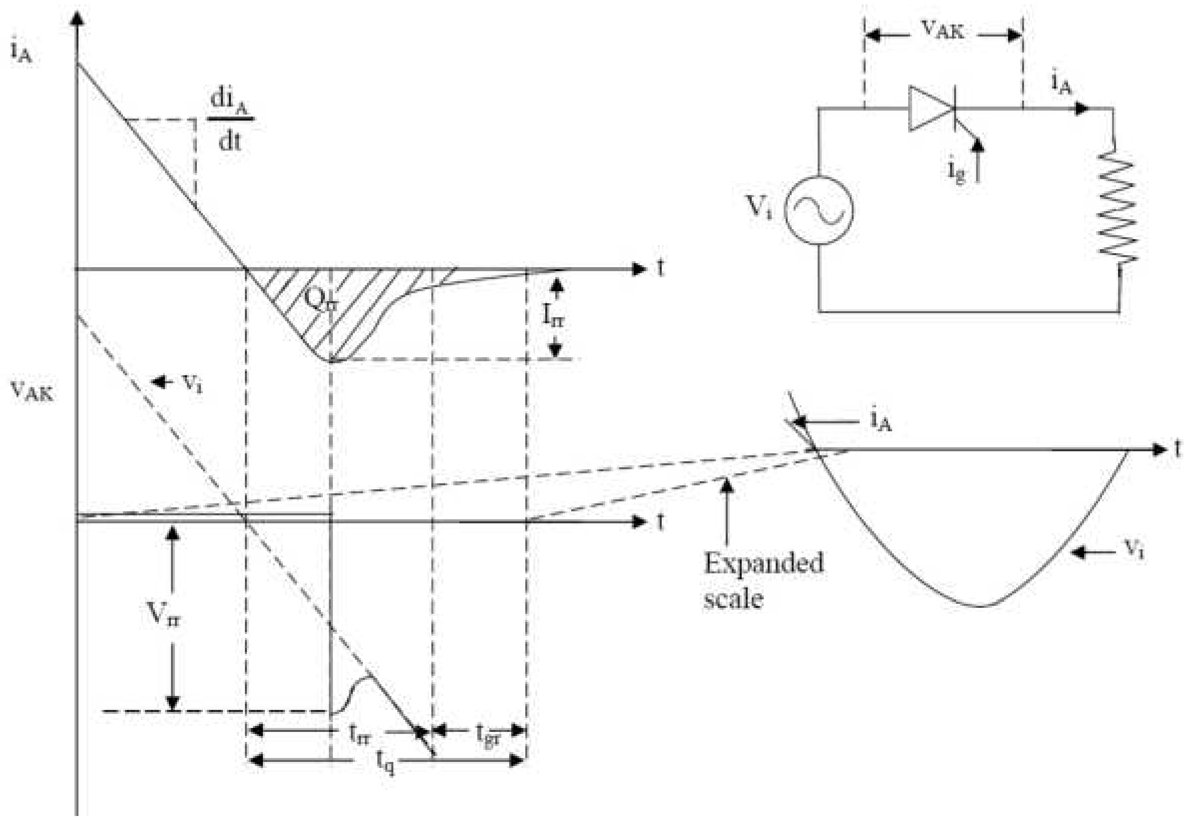


Fig. (8) Turn OFF characteristics of the thyristor

The anode current becomes zero at time t_1 and starts growing in the negative direction with the same di_A/dt till time t_2. This negative current removes excess carriers from junctions J_1 & J_3. At time t_2 excess carriers densities at these junctions are not sufficient to maintain the reverse current and the anode current starts decreasing. The value of the anode current at time t_2 is called the reverse recovery current (I_{rr}). The reverse anode current reduces to the level of reverse saturation current by t_3. Total charge removed from the junctions between t_1 & t_3 is called the reverse recovery charge (Q_{rr}). Fast decaying reverse current during the interval t_2 t_3 coupled with the di/dt limiting inductor may cause a large reverse voltage spike (V_{rr}) to appear across the device.. Up to time t_2 the voltage across the device (V_{AK}) does not change substantially from its on state value. However, after the reverse recovery time, the thyristor regains reverse blocking capacity and V_{AK} starts following supply voltage v_i. At the end of the reverse recovery period (t_{rr}) trapped charges still exist at the junction J_2 which prevents the device from blocking forward voltage just after t_{rr}. These trapped charges are removed only by the process of recombination. The time taken for this recombination process to complete (between t_3 & t_4) is called the gate recovery time (t_{gr}). The time interval $t_q = t_{rr} + t_{gr}$ is called "device turn off time" of the thyristor.

No forward voltage should appear across the device before the time t_q to avoid its inadvertent turn on. A circuit designer must provide a time interval t_c ($t_c > t_q$) during which a reverse voltage is applied across the device. t_c is called the "circuit turn off time".

Thyristor Triggering Circuits

The triggering process of the thyristor done by applying a positive voltage between gate and cathode, and due to that changing of the biasing of the junction J_2 and then the thyristor conduct. The design, type and feature of triggering circuit depend on the application of thyristor. So, there is not triggering circuit that suitable for all types of thyristor application circuit.

Type of Triggering

There are three basic types of the gate firing signals

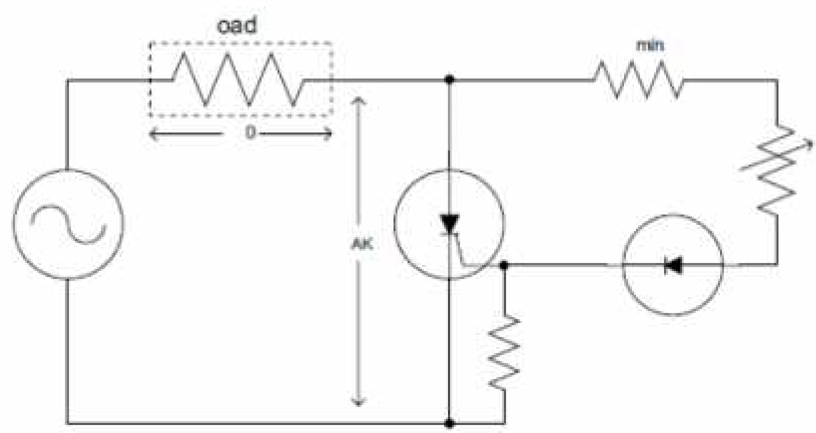
D.C signal triggering

The D.C triggering used at the case when the temperature change and current rate (di/dt) not considered. This type do by many techniques as:

1-Resistance Trigger Circuits

A step dc voltage, a slow rising dc signal, or a rectified positive half-wave signal can be used to trigger thyristors. When the voltage applied to the gate terminal exceeds the V_{GT} level, triggering takes place. As soon as V_G reaches the V_{GT} level and supplies the required gate current, conduction of SCR takes place. The voltage V_{AK} collapses and therefore V_G also reduces to almost zero level, and v appears across the load. Now, R1 can be increased to reduce V_{R2} and thus to increase α. However, with a larger R1, eventually the circuit fails to trigger the device the control of a is restricted to 90 only

$$V_G = \frac{R_{GK}}{R_1 + R_{GK} + R_{\min}} v$$



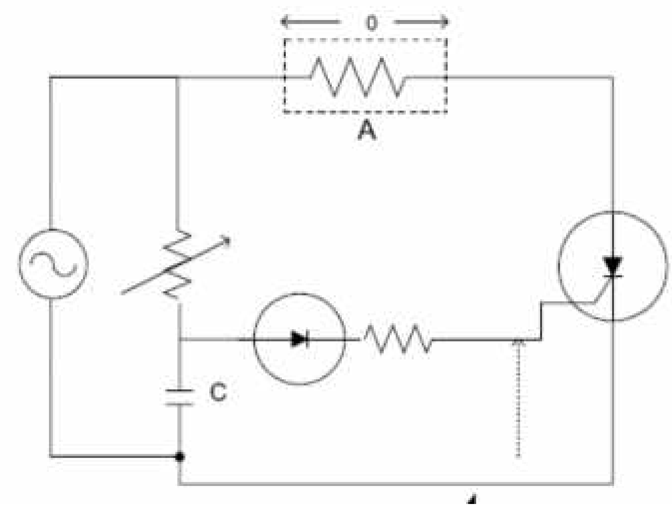
D.C triggering circuit

2-RC Trigger Circuits

A phase-shifted signal in an ac circuit and a slow rising signal in a dc circuit generated by an RC network are used to trigger the thyristors. In these cases the range of a is extendable beyond 90.

A.C signal Tiggering

During the positive half-cycle when V_c hence V_G exceeds the V_{GT} level, conduction of the thyristor takes place. In fact V_G is the rectified capacitor voltage. Thus, a can be controlled over wide range beyond 90. By variation of R. the magnitude of vG can also be controlled by gate current limiting resistance R2, as in the case of a resistance-trigger circuit.

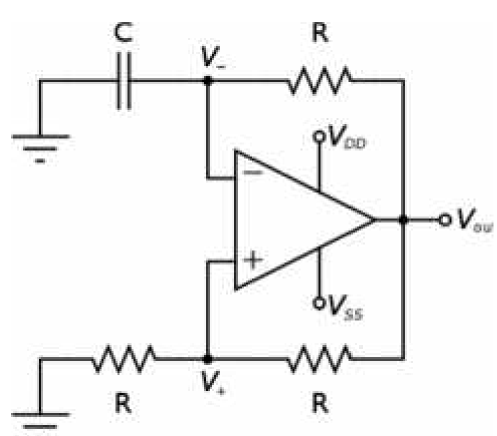


A.C triggering circuit

Pulse gate triggering

1-A **relaxation oscillator**

is an oscillator based upon the behavior of a physical system's return to equilibrium after being disturbed. That is, a dynamical system within the oscillator continuously dissipates its internal energy. Normally the system would return to its natural equilibrium; however, each time the system reaches some threshold sufficiently close to its equilibrium, a mechanism disturbs it with additional energy. Hence, the oscillator's behavior is characterized by long periods of dissipation followed by short impulses. The period of the oscillations is set by the time it takes for the system to relax from each disturbed state to the threshold that triggers the next disturbance.



Relaxation Oscillator

2- Zero- crossing detector (Integeral Cycle Control)

The zero-crossing is important for systems which send digital data over AC circuits, such as modems, X10 home automation control systems, and Digital Command Control type systems for Lionel and other AC model trains. In alternating current, the zero-crossing is the instantaneous point at which there is no voltage present. In a sine wave or other simple waveform, this normally occurs twice during each cycle.

Zero-crossing is a commonly used term in electronics, mathematics, sound, and image processing. In mathematical terms, a "zero-crossing" is a point where the sign of a function changes (e.g. from positive to negative), represented by a crossing of the axis (zero value) in the graph of the function

3-Short pulse and long pulse:

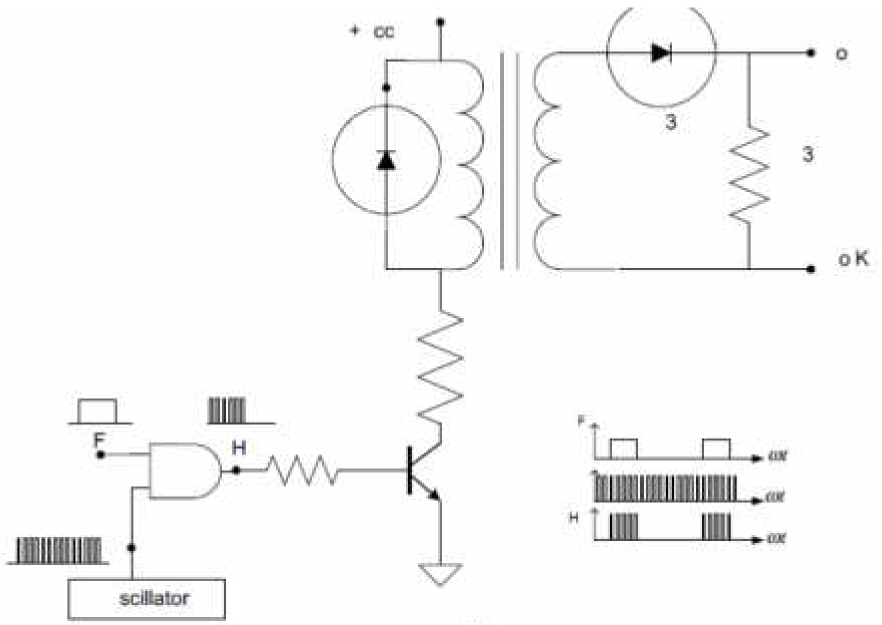
Pulse generators are available for generating output pulses having widths (duration) ranging from minutes down to under 1 picosecond. Pulse generators are generally voltage sources, with true current pulse generators being available only from a few suppliers. Pulse generators may use digital techniques, analog techniques, or a combination of both techniques to form the output pulses. Gate trigger current varies inversely with gate pulse width

4- pulses train generator

In this type is used transformer to obtain on the train of pulses, connect the transformer directly between gate and cathode, use a series resistor to either reduce the holding current or balance gate current, or use a series diode to reduce holding current of thyistor. In some cases where high noise levels are present, it may be necessary to load the secondary of the transformer with a resistor to prevent false triggering.

5- pulses train generator and AND logic gate

The pulses are generated by a differentiator circuit (R_1C_1), which converts a step input signal into sharp positive and negative pulses. The positive pulse is then amplified by a transistor amplifier circuit positive pulse (or square-wave signal) from an oscillator is applied to an AND gate continuously. These pulses are allowed to reach the base of transistor only when the input drive control signal is high. The transistor basically acts as a switch to energize the primary winding of the pulse transformer corresponding to each pulse. Moreover, these pulses also are amplified. A negative pulse is also generated in the secondary winding. This pulse is blocked by the diode D_2. Thus amplified positive pulses become available between G and K terminals of the thyristor.



Pulse train generator with AND logic gate

Thyristor Commutation circuits

In a conventional thyristor, once it has been switched on by the gate terminal, the device remains latched in the on-state (*i.e.* does not need a continuous supply of gate current to remain in the on state), providing the anode current has exceeded the latching current (I_L). As long as the anode remains positively biased, it cannot be switched off until the anode current falls below the holding current (I_H). There are several techniques used for that called " commutation circuits".

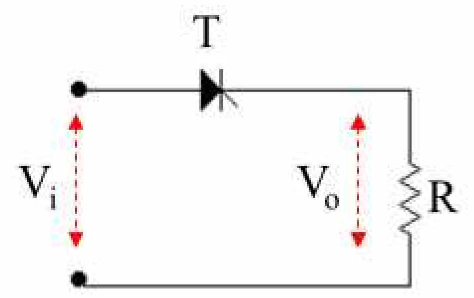
The commutation is the process of the turn OFF thyristor and it is normally cause transfer of current flow to other parts of the circuit.

The main techniques of the turn OFF thyristor

1- Natural commutation
2- Forced commutation, which divided in to:
    a- Self commutation
    b- Resonant pulse commutation
    c- Complementary commutation
    d- External pulse commutation
    e- Load side commutation
    f- Line commutation

1-Natural commutation

If the source voltage is A.C then the input signal will reach zero at every cycle, this could turn OFF thyristor due to natural behavior of the source voltage. This is called natural. In practice the thyristor is triggering synchronously with zero crossing in every cycle in order to provide continuous control.



2-Fored commutation

In some thyristor circuit, the input voltage is D.C and the forward current of the thyristor is forced to zero by additional circuit called " forced commutation circuit" to turn OFF thyristor. It normally used in D.C to D.C convertor and D.C to A.C converter.

a- Self commutation

In this type of commutation the tyristor is turn OFF due to characteristics of the circuit. As shown in figure below when the capacitor is initially uncharged, when the thyristor T_1 is ON the capacitor charging current i as:

$$V_{s=} V_L + V_C = L\frac{di}{dt} + \frac{1}{C}\int i\,dt + V_{co}\ (t=0)$$

With initial condition i=0 (t=0), V_c=0 (t=0), the solution of last equation is:

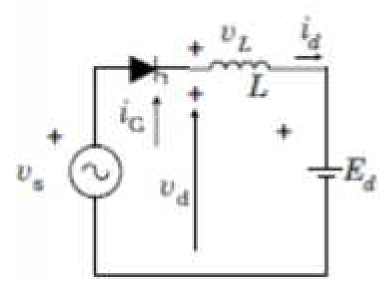
i(t)= $V_s\sqrt{\frac{L}{C}}\sin(wt)$

$$\omega = \frac{1}{\sqrt{LC}}$$

The capacitor voltage is:

$V_c(t) = V_s(1\text{-}\cos(wt))$

After time $t = \pi\sqrt{LC}$ the charging current becomes zero and T_i is OFF itself, this called commutation time.

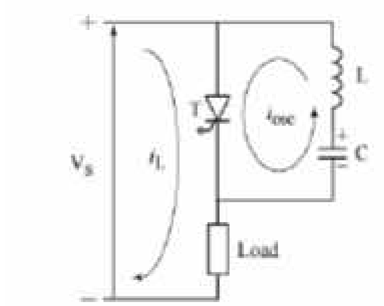


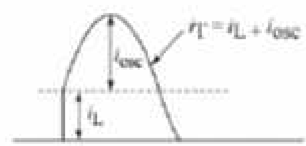
b- Resonant pulse commutation

When the SCR is triggered, anode current flows and charges up C with the dot as positive. The L-C-R form a second order under-damped circuit. The current through the SCR builds up and completes a half cycle. The inductor current will then attempt to flow through the SCR in the reverse direction and the SCR will be turned off.

Resonant commutation is divided to two types as:

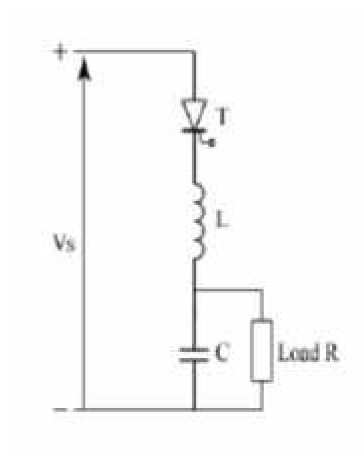
- Parallel resonant commutation





- Series resonant commutation

$$t_{on} = \frac{T_0}{2} = \frac{1}{2f_0} = \pi\sqrt{LC}$$

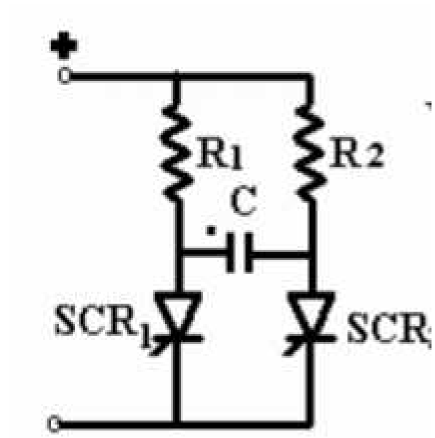


c-Complementary commutation circuit

This configuration has two SCRs. One of them may be the main SCR and the other auxiliary. Both may be load current carrying main SCRs. The configuration may have four SCRs with the load across the capacitor, with the integral converter supplied from a current source. Assume SCR_2 is conducting. C then charges up in the polarity shown. When SCR_1 is triggered, C is switched across SCR_2 via SCR_1 and the discharge current of C opposes the flow of load current in SCR_2.

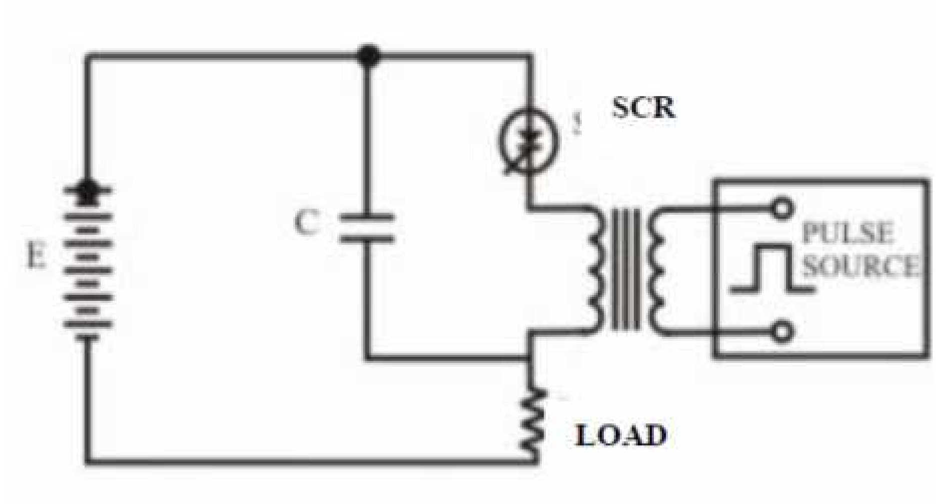
t_{OFF}=RC ln(2)

R=R_1=R_2



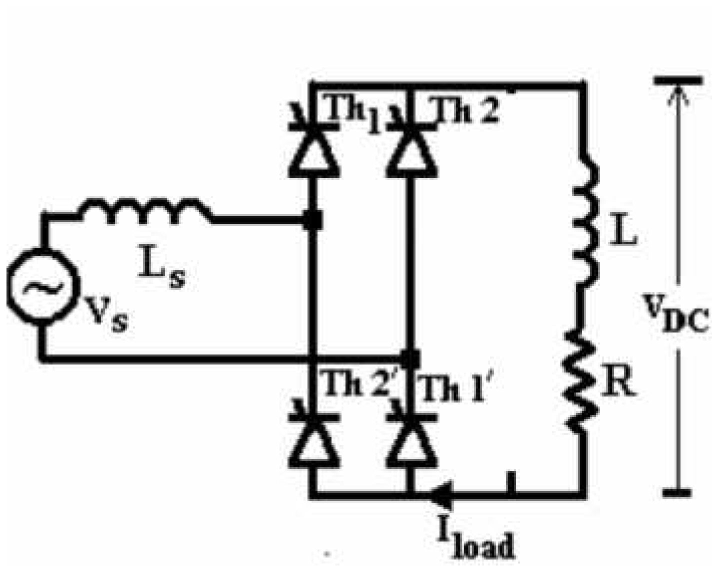
d-External pulse source for commutation

The transformer is designed with sufficient iron and air gap so as not to saturate. It is capable of carrying the load current with a small voltage drop compared with the supply voltage. When SCR1 is triggered, current flows through the load and pulse transformer. To turn SCR_1 off positive pulse is applied to the cathode of the SCR from an external pulse generator via the pulse transformer. The capacitor C is only charged to about 1 volt and for the duration of the turn-off pulse it can be considered to have zero impedance. Thus the pulse from the transformer reverses the voltage across the SCR, and it supplies the reverse recovery current and holds the voltage negative for the required turn-off time.



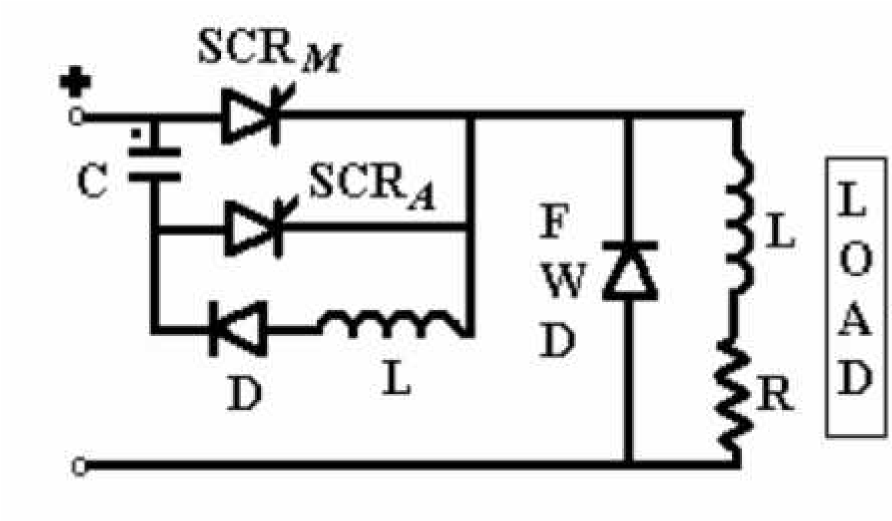
e-line commutated

If the supply is an alternating voltage, load current will flow during the positive half cycle. With a highly inductive load, the current may remain continuous for some time till the energy trapped in the load inductance is dissipated. During the negative half cycle, therefore, the SCR will turn off when the load current becomes zero 'naturally'. The negative polarity of the voltage appearing across the outgoing SCR turns it off if the voltage persists for the rated turn-off period of the device. The duration of the half cycle must be definitely longer than the turn-off time of the SCR.



f-Load commutation circuit

The circuit shown in Figure below (complementary commutation) can be converted to load commutation if the load current is carried by only one of the SCR's, the other acting as an auxiliary turn-off SCR. The auxiliary SCR would have a resistor in its anode lead of say ten times the load resistance.



Power Losses in Thyristor

During the switching cycle of the thyristor the power losses come from the following source :

1- ON-state power losses
2- OFF- state power losses
3- Forward condition power losses
4- Gate –trigger power losses
5- Forward and Reverse blocking power losses

When the thyristor is blocking in either direction, the Off- state power losses and triggering losses is small enough to be ignored. For low operation frequencies the switching losses is small. The main source of the power losses is the ON- state power losses. These losses given by:

ON- state power losses=I_{rms} * V_{th} (ON- state voltage)

OFF- state power losses = leakage current I_D * blocking voltage