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UPPSC – Polytechnic Lecturer

Electrical Engineering

Uttar Pradesh Public Service Commission (UPPSC)

Volume - 5

Power Electronics & Power System

SIERRA
INNOVATIONS

INDEX

1

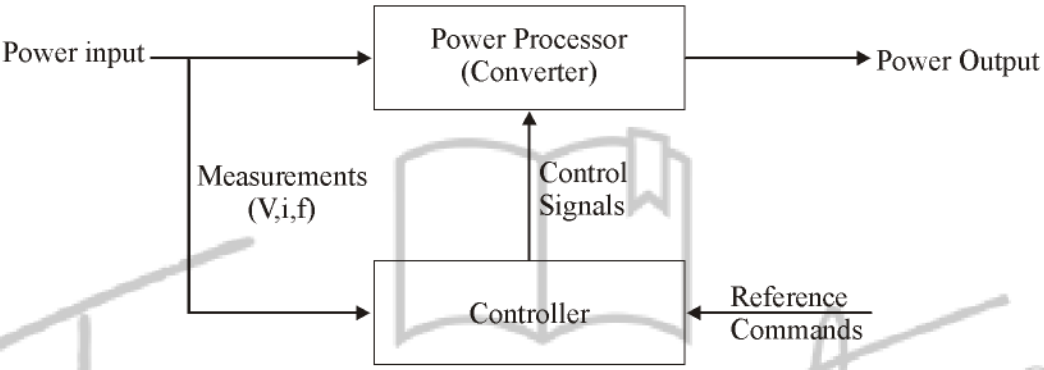
CHAPTER

Introduction to Power Electronics

THEORY

1.1 *INTRODUCTION TO POWER ELECTRONICS*

Power Electronics is used to change the characteristics (Voltage and current magnitude and frequency) of electrical power to suit a particular application. It is an interdisciplinary technology.



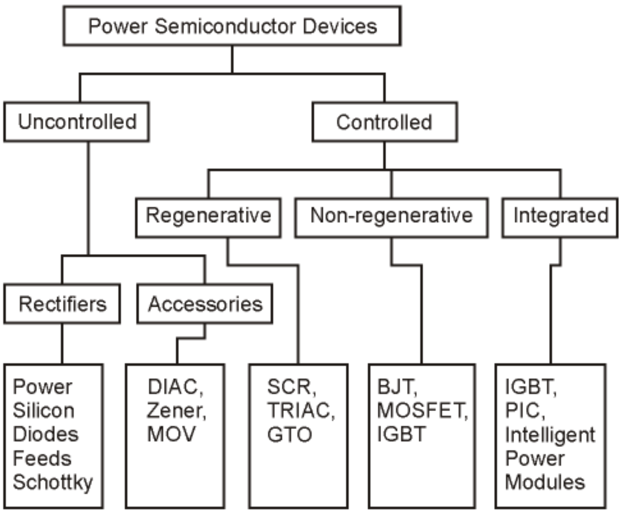
Power semiconductor devices can be categorized into three types based on their control input requirements:

(a) Current-driven devices: BJTs, GTOs.

(b) Voltage-driven devices: MOSFETs, IGBTs, MCTs.

(c) Pulse-driven devices: SCRs, TRIACs.

1.2 *POWER SECMICONDUCTOR DEVICE VARIETY*



1.3 *APPLICATIONS OF POWER ELECTRONICS*

1.3.1 Transportation

(i) Electric/Hybrid Electric Vehicles

(ii) Electric Locomotives

(ii) Electric Trucks, Buses, Construction Vehicles, Golf Carts.

1.3.2 Utilities

(i) Line transformers

(ii) Generating systems

(iii) Grid interface for alternative energy resources (Solar, wind, fuel cells, etc.) and energy storage.

(iv) FACTS

(v) HVDC

(vi) Solid state transformer

(vii)Solid state fault current limiter

(viii)Solid state circuit breaker

1.3.3 Industrial/Commercial

(i) Motor drive systems

(ii) Electric machinery and tools

(iii) Pumps/compressors

(iv) Process control

(v) Factory automation

1.3.4 Consumer Products

(i) Air conditioners/Heat pumps

(ii) Appliances

(iii) Computers

(iv) Lighting

(v) Telecommunications

(vi) Uninterruptible power supplies

(vii)Battery chargers

1.3.5 Utility Systems:

(i) High voltage DC transmission (HVDC)

(ii) Excitation Systems

(iii) VAR Compensation

(iv) Static circuit breakers

(v) Fans and boiler feed pumps

(vi) Supplementary energy systems (solar, wind)

1.3.6 Medical Equipment:

1.4 *DESIRABLE CHARACTERISTICS OF A POWER DEVICE*

(i) Small leakage current in off state.

(ii) Small on-state voltage drop to minimize conductive losses.

(iii) Short turn-on and turn-off times (high switching frequency.)

(iv) Large forward and reverse voltage blocking capability so, minimizes need to series several devices to enhance a blocking capability.

(v) High on-state current rating minimizes need to parallel devices.

1.5 *TYPES OF POWER CONVERSION*

(a) AC-DC converter (Rectifier) :

Converts input AC to variable magnitude DC, e.g. battery chargers, computer power supplies.

(b) AC-AC Converter (Cycloconverter and AC voltage Controller) :

Converts input AC to variable magnitude variable frequency AC, e.g. ship propulsion systems.

(c) DC-AC Converter (Inverter) :

Converts input DC to variable magnitude variable frequency AC, e.g. electric/hybrid electric traction drives.

(d) DC-DC converter (DC Chopper-Buck/Boost/Buck-Boost Converter)

Converts input DC to variable magnitude DC, e.g. voltage regulators.

(e) DC-DC converters (Switched Mode Power Supplies (SMPS))

Make up about 75% of power electronics industry.

(i) Power Supplies for Electronic Equipment
(ii) Robotics
(iii) Automotive/Transportation
(iv) Switching Power Amplifiers
(v) Photovoltaic Systems

(f) DC-AC-Inverter

(i) AC Machine Drive (permanent magnet, switched reluctance, or induction machine)
(ii) Uninterruptible Power Supply (UPS)
(iii) Machine Tools
(iv) Induction Heating-Steel Mills
(v) Locomotive Traction
(vi) Static Var Generation (Power Factor Correction)
(vii) Photovoltaic or Fuel Cell Interface with Utility

(g) AC-DC-rectifier

(i) DC Machine Drive
(ii) Input Stage to DC/DC or DC/AC Converter
(iii) Energy Storage Systems
(iv) Battery Chargers
(v) Aerospace Power Systems
(vi) Subways, Trolleys
(vii) High Voltage DC (HVDC) Transmission

(h) AC-AC Converters-Voltage Controller 1-ϕ to 3-ϕ Converters.

(i) Lighting/Heating Controls
(ii) Large Machine Drives

1.6 *POWER TRANSISTORS*

1. BJT
2. MOSFET
3. IGBT

1.6.1 *BJT*

- Bipolar device i.e. holes & electrons.
- Current controlled device.
- Low input impedance.
- Low ON-state voltage drop and lower conduction loss.
- Higher switching power losses.
- Secondary breakdown occur.
- Negative temperature coefficient because of negative temperature coefficient BJT are not advisable for parallel operation.
- Low conduction losses.
- Lower operating frequency (10 kHz).
- ON-state in saturation region.
- Controlled turn-on & turn-off device.
- Turn-on & Turn-off time depend on junction capacitances.
- Control signal requirement continuously.
- Ratings : 1400V, 400A, 10 kHz
- Switching period, $t_s = 50\mu$ sec-100μsec

1.6.2 *MOSFET*

- Unipolar device i.e. majority carrier device.
- Voltage controlled device.
- High input impedance.
- High-ON state voltage drop and higher conduction losses.
- Lower-switching power losses.
- Free from secondary breakdown.
- Positive temperature coefficient.
- Because of positive temperature coefficient, MOSFET are advisable for parallel operation.
- Higher conduction losses.
- Higher operating frequency (100 kHz).
- ON-operating in ohmic region.
- Control turn-on & turn-off device.
- Smaller turn-off time because it does not have minority carrier storage.
- Control signal requirement continuously.
- Ratings : 1000V; 50A, 100 kHz
- Switching period, $t_s = 1\mu$ sec

1.6.3 *IGBT*

- Bipolar device.
- Voltage controlled device.
- Three terminal device : Emitter, collector and gate.
- Low forward voltage drop.
- Low on-state power loss than MOSFET.
- Low conduction loss than MOSFET.
- Having characteristics of BJT & MOSFET.
- Controlled turned-on & turned-off devices.
- Control signal requirement continuously.
- High input impedances.
- Positive temperature coefficient.
- Secondary breakdown not occur.
- Used for parallel operation.
- Ratings : 1200V, 500A, 50 kHz.
- Switching period, $t_s = 20\mu$ sec.
- Two terminal, three layer device : power diode, DIAC.
- Majority carrier device : MOSFET, SIT.
- Bipolar device : Diode, BJT, IGBT, MCT.
- Unidirectional device : Diode, SCR, LASCR.
- Bidirectional device : TRIAC, DIAC, BJT.
- Negative pulse turn-on device : MCT.
- Negative pulse turn-off device : GTO.
- Controlled turn-on & off device : BJT, MOSFET, IGBT, SIT MCT.
- Continuous control signal : BJT, MOSFET, IGBT, SITH.
- Uncontrolled device : Diode, DIAC.
- Bistable switch : SCR.
- Bidirectional current device : TRIAC, RCT.
- Unidirectional current device : Diode, SCR, GTO, BJT, MOSFET, IGBT, SITH and MCT.

❍❍❍

2

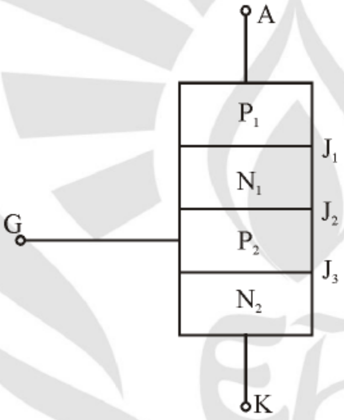
CHAPTER

SCR

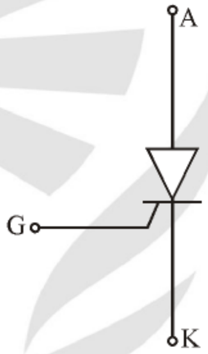
THEORY

2.1 *INTRODUCTION*

Thyristor (SCR) is 4 layer, 3 p-n junction, charge controlled semi conductor device. It has three terminals called Gate(G), Anode (A) and Cathode (K).Inner two layers of SCR are lightly doped so that the strength of junction J_2 is more than the strength of junctions of J_1 and J_3. SCRs are used up to 3000 A and Voltage up to 10 kV.



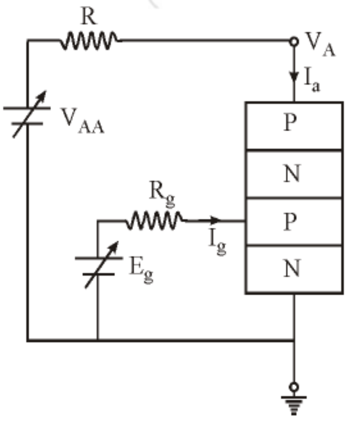
Layer Diagram

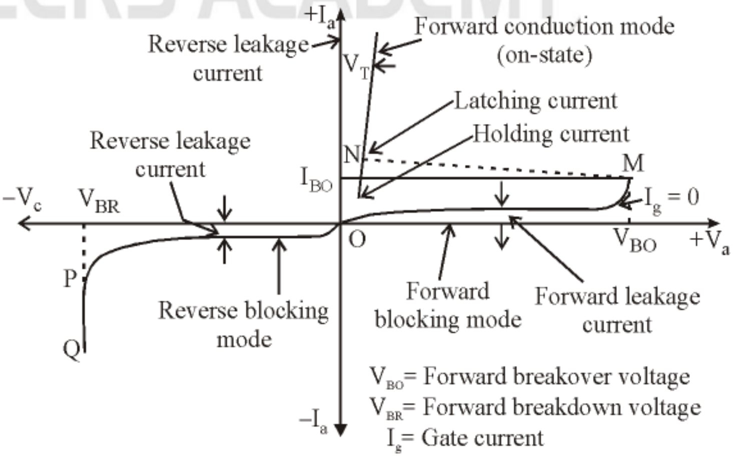


Symbol

Outer layers are heavily doped as Compared to inner layers.

2.2 *I-V CHARACTERISTICS*





2.2.1 Forward Blocking Mode :

In this mode of operation SCR is applied with positive anode voltage. The junctions J_1 and J_3 are in forward bias and J_2 is reverse bias and the device is in off state. The device remains in this mode until the anode voltage reaches a critical value called forward break over voltage (V_{FBO}).

2.2.2 Forward Conducting Mode :

When the anode voltage is greater than the forward break over voltage then avalanche break down occurs at Junction J_2 and the device starts conducting.In forward conduction mode SCR behaves like a closed switch. SCR start conducting only if the current through the device is greater than a minimum current called latching current during the turning ON process.

3.2.3 Reverse Blocking State :

When the anode voltage is negative, the junctions J_1 and J_3 are in reverse bias and junction J_2 is in forward bias, the device is in off state and this region of characteristic curve is called reverse blocking state. When the reverse voltage becomes more than V_{RBO} then avalanche break down occurs at reverse bias junctions J_1 and J_3 and the device start conducting in reverse direction.

2.2.4 Latching Current :

It is the minimum anode current required to turn on the SCR during turning on process. Latch current is related to turn on process where as the holding current is related to turn off process because when the junction J_2 breaks down then large number of carriers are generated. So, the large current starts flowing, this current is latch current.

2.2.5 Holding Current :

When the device is already in conducting state and if the anode current is reduced below a minimum level, the device gets turn off. This minimum current required to turn off device is called holding current. The holding current is therefore related to the turn off process. The holding current is always less than the latch current because current continues to flow even below latch current due to charges stored in layers.

Now to turn off the device the current has to be reduced till all the carriers are after re-combination anode current will be less than holding current.

Note: $\boxed{\begin{array}{c} V_{RBO} > V_{FBO} \\ I_L > I_H \end{array}}$ $\boxed{\frac{I_L}{I_H} \approx 3}$

2.2.6 Forward Break Over Voltage :

It is the critical voltage required for breakdown of junction J_2 under forward biased condition. It is minimum voltage to be applied across the device for turn ON the device cut out gate signal.

When anode voltage becomes equal to forward break over voltage the junction J_2 breaks down due to Avalanche multiplication and the device start conducting.The forward break over voltage can be reduced by applying a positive pulse at gate terminals. When the gate current increases, the forward break over voltage decreases.

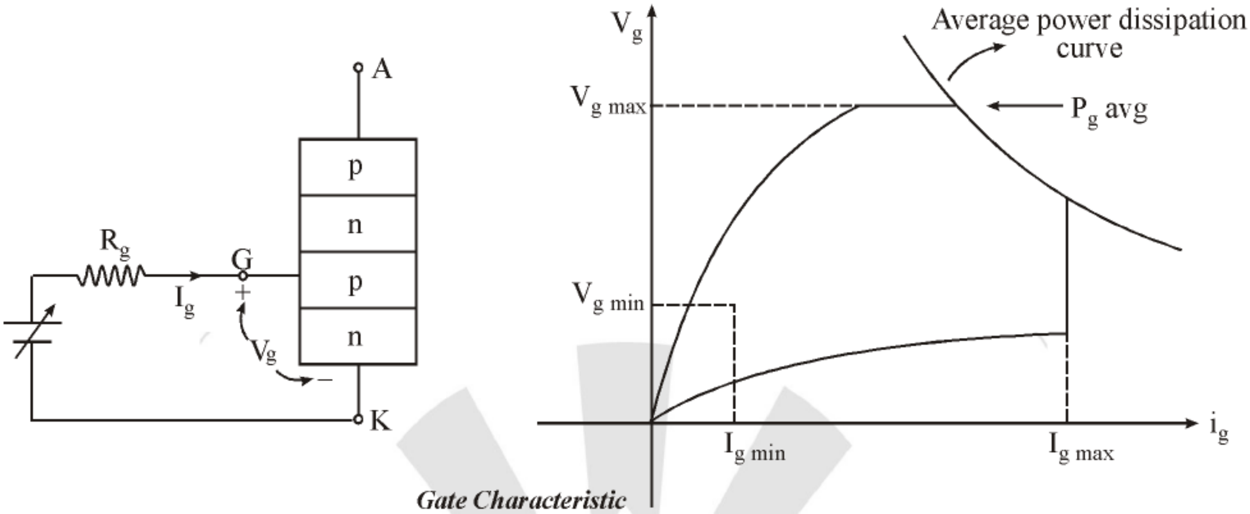
2.2.7 Zener Break Down :

Depends on voltage and dopping level. both layers must be highly dopped, small voltage is required for break down. It is electrostatic breakdown.

2.2.8 Avalanche Break Down :

It occurs due to thermal effect or temperature. It occurs in lightly doped semiconductor junctions.

2.2.9 Gate Characteristic :



Gate Characteristic

Where I_{gmax} = Maximum gate current allowed

V_{gmax} = Maximum gate voltage

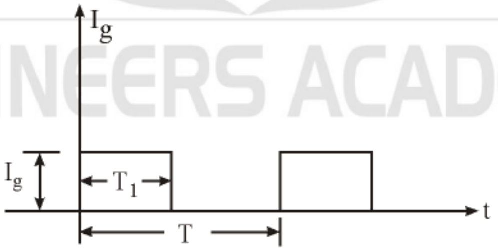
V_{gmin} = Minimum gate voltage

I_{gmin} = Minimum gate current

V_{gmin} and I_{gmin} are decided by satisfactory turning off of the device.

For the satisfactory turning on, the operating point of gate characteristic should always lie nearest to P_{avg} curve.

The turn on time of the thyristor can be reduced by increasing the amplitude of gate current and power dissipation can be reduced by reducing the period of gate pulse in pulse triggering the thyristor remains in on state even if gate current is reduced to zero once it turned ON by pulse triggering.

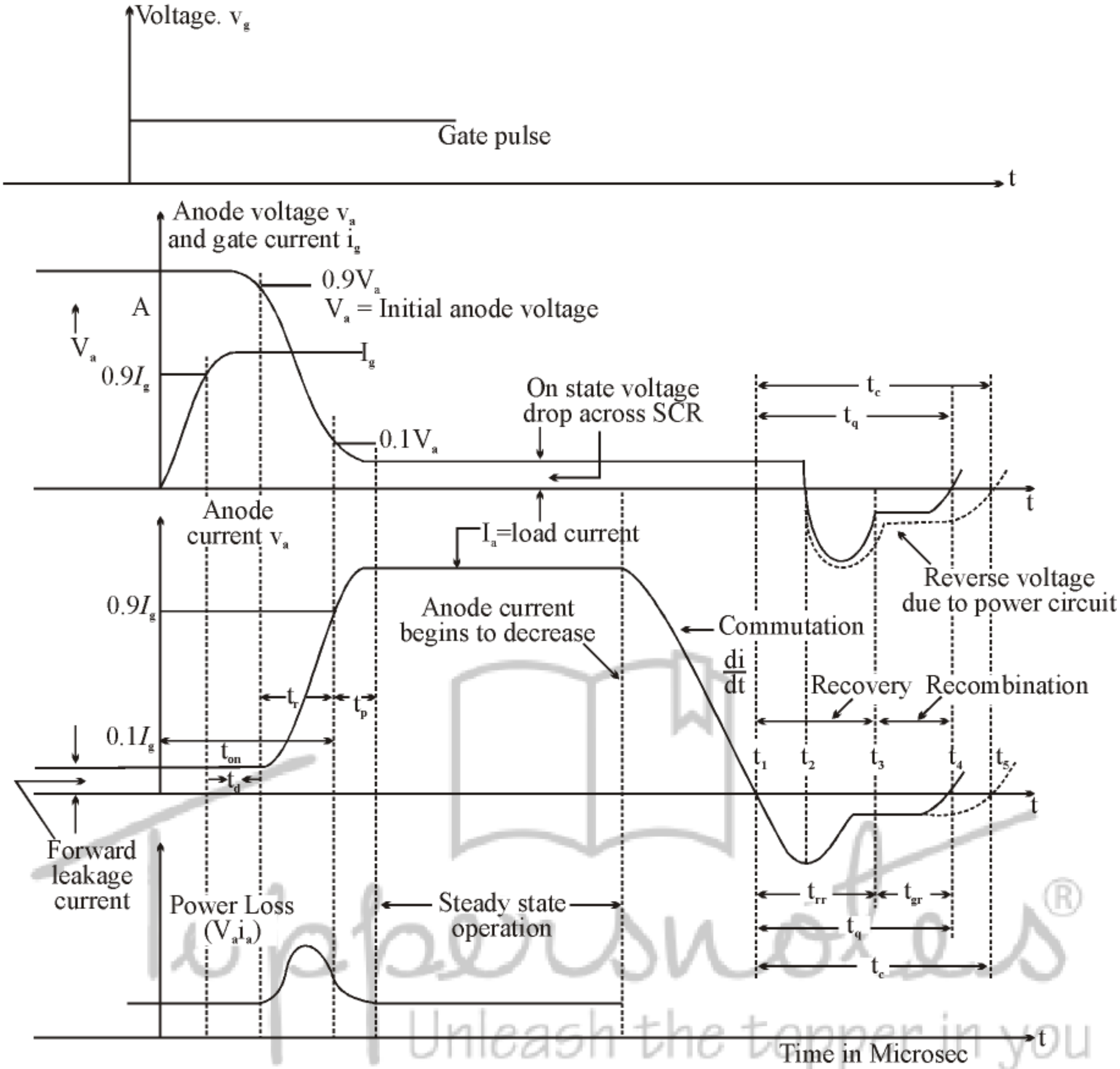


$$d = \text{duty cycle} = \frac{T_1}{T}$$

$$\frac{I_{g\ avg}}{\delta} \le I_{gm} \qquad \text{(more power dissipation in gate)}$$

$\delta = f\ T_1$ There *f* is the frequency of firing or triggering pulse

2.3 *SWITCHING CHARACTERISTICS OF SCR*



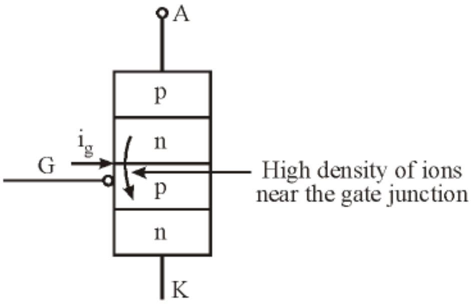
SCR Voltage and current waveforms during turn-on and turn-off processes.

2.3.1 *TURN ON TIME*

Delay time (t_d) : Time taken to rise the i_a from 0% to 10% of full load current, when the gate pulse is applied.

Rise time (t_r) : Time taken to rise the i_a from 10% to 90% of full load current.

Spread time (t_p) : Time taken to rise the i_a from 90% to full load current or it is time taken to spread the conducting channel (conduction) through out the junction.Once the device has turn on.



2.3.2 TURN OFF TIME

$\mathbf{t_{rr}}$ = reverse recovery time

$\mathbf{t_{gr}}$ = gate recovery time

$\mathbf{t_q}$ = turn off time

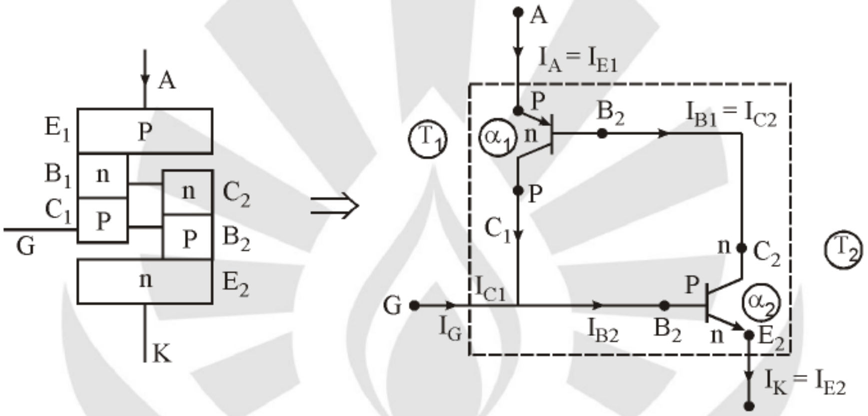
$$\mathbf{t_q} = t_{rr} + t_{gr}$$

Turn off time is the time taken by the SCR to regain its forward blocking capability after the anode current is reduced to zero.

Losses in the SCR are maximum during turning on and turning off process.

Note : *for the proper operation of SCR the circuit turn off time must be greater than the thyristor turn off time.*

2.4 *TWO TRANSISTOR MODEL*



When Devices is conducting then :

$$I_{C1} = \alpha_1 I_{E1} + I_{CBO1}$$

$$\Rightarrow \quad I_{C1} = \alpha_1 I_A + I_{CBO1} \qquad \ldots(i)$$

$$I_{C2} = \alpha_2 I_{E2} + I_{CBO2}$$

$$\Rightarrow \quad I_{C2} = \alpha_2 I_k + I_{CBO2} = I_{B1} \qquad \ldots(ii)$$

$$I_{B1} + I_{C1} = I_{E1}$$

$$I_{B1} = I_{E1} - I_{C1} \qquad \text{[From (ii)]}$$

$$I_{B1} = I_A - [\alpha_2 I_A + I_{CBO1}]$$

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

$$\Rightarrow \quad I_A - [\alpha_2 I_A + I_{CBO1}] = \alpha_2 I_k + I_{CBO2}$$

$$I_A - \alpha_2 I_A - \alpha_2 I_k = I_{CBO1} + I_{CBO2} \qquad \ldots(iii)$$

also $\qquad I_k = I_A + I_G$

Putting I_A in equation (iii),

$$\Rightarrow \qquad I_A - \alpha_1 I_A - \alpha_2(I_A + I_G) = I_{CBO1} + I_{CBO2}$$

$$\Rightarrow \qquad I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1-(\alpha_1 - \alpha_2)}$$

As I_E increases then current gain α increase due to this $I_A \uparrow$. This effect is cummulative effect, So, the anode current rieses to full load current.

Difference Between Two Transistor Mode and Thyristor

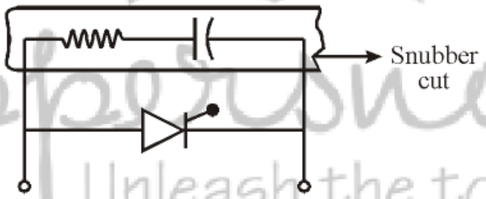
(i) The two transistor model required the continuous base current for the transistor therefore the base current not reduce to zero but in case of SCR, the gate current is reduce to zero, once the SCR is in conduction mode

(ii) In order to switch off the thyristor, a reverse voltage must be applied while in case of transistor, the base current must be reduce to zero for turning off the device.

2.5 METHOD OF TRIGGERING OF SCR

2.5.1 $\frac{dv}{dt}$ Triggering

When the rate of change of forward voltage across the thyristor is large the current $C\frac{dv}{dt}$ flows in reverse biased junction J_2. This may cross the latch current and device may be turned on. $\frac{dv}{dt}$ triggering is not preferred because the voltage transient in the circuit may causes false triggering of the device. This false triggering can be avoided by using a circuit called **snubber** circuit. Snubber circuit contains series RC circuit connected across the thyristor.



2.5.2 Forward Voltage Triggering

In this method the forward voltage is greater than V_{FB} is applied across the device. This voltage results in avalanche break down of reverse bias junction J_2 and hence the device is turn on. losses in the device is maximum during turn on process therefore, the large anode voltage in forward voltage triggering may damage the device. Hence this method of triggering is not preferred.

2.5.3 Gate Triggering

This is the most commonly used method of triggering of SCR, the injection of carriers at reversed biased junction through gate results in reduction of the forward break over voltage (V_{FB}) and thus the device can be turn on by injecting the charge carrier through gate at a particular forward voltage which is always less than the forward break over voltage V_{FB} when gate current is zero. Magnitude of gate current = 20 to 200 mA. For reducing the turn on time of SCR, the pulse of small width and large amplitude should be applied at gate terminal .The pulse width of gate current must be greater that turn on time of SCR. When the amplitude of gate pulse is large than the minimum gate current required for turning on of SCR, the device is called Hard driven or driven.

2.5.4 Light Triggering

In this method, the reversed biased junction is irradiated through a window which results in generation of electron holes pair and due to this current increases and then ultimately junction break down occurs. The *SCR employing light triggering are called LASCR (Light activated SCR). LASCR is used in HVDC transmission system.*

2.5.5 Temperature Triggering

During the forward blocking, the reverse saturation current flows through the reverse biased junction the current causes the heating which rises the temperature. Due to increase in temperature electron hole pair are generated. Which further increases the reverse saturation current and hence the heating of the junction increase and thus the effects become cummulative which ultimately results in the breakdown of reverse bias junction and the device is turned on. *Temperature triggering can damage the device due to heating so it is not used.*

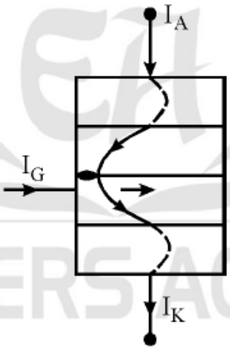
2.6 *RATING OF THYRISTOR*

2.6.1 $\frac{dv}{dt}$ rating

It is the maximum rate of change of anode voltage above which the device is turned on.

2.6.2 $\frac{di}{dt}$ rating

When the device is turned on then the current through the reverse bias junction J_2starts flowing through the part of the junction nearest to gate and if the rate of increase in anode current is larger than the spread rate of conduction channel then more current will flow through the small area of conduction channel. This result the heat up of junction J_2 which can damage the device.



2.6.3 Surge Current Rating

This rating indicates the maximum possible non (only one time) repetitive surge current which the device can with stand without getting damage .*The surge current rating (I_s)*

$$I_s = I\sqrt{\frac{T}{t}}$$

Where, I_s = Surge current passed for time 't'.

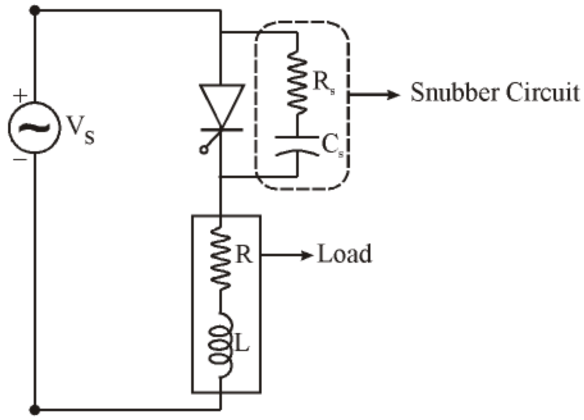
I = Surge current passed for time T

T= Half cycle of the wave.

2.7 *PROTECTION OF SCR*

2.7.1 $\frac{dv}{dt}$ Protection

When large dv/dt is applied across the thyristor under forward blocking state the current through reverse biased junction may cross the latching current which may result in false triggering of SCR. The device is protected against large dv/dt by connecting a series RC circuit known as snubber circuit across the thyristor.



$$\left.\frac{dv}{dt}\right|_{max} = \frac{V_s R_s}{L}$$

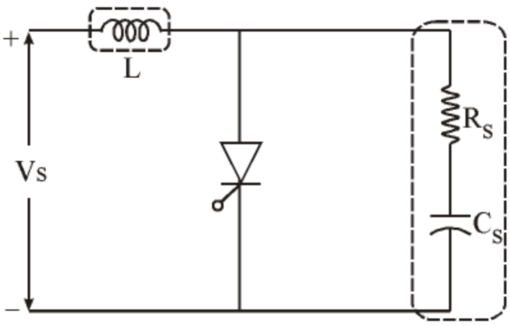
$$\left.\frac{dv}{dt}\right|_{max} = R_s\left(\frac{di}{dt}\right)_{max}$$

$$R_s = 2\xi\sqrt{\frac{L}{C_s}}$$

ξ = Damping ratio

2.7.2 $\frac{di}{dt}$ Protection

Large di/dt may cause thermal damage to the Thyristor. The device is protected against the di/dt by connecting the inductor in series with the SCR.



2.7.3 Over Voltage Protection

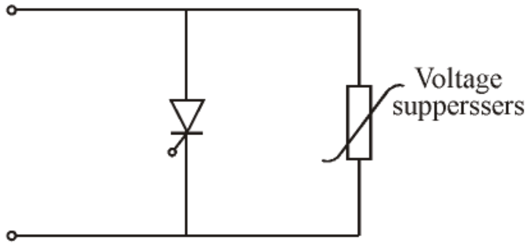
The over voltage may result in maloperation (unwanted triggering) of the device or may damage the device. The device is protected against the over voltages by connecting the voltage suppresser across the device. The voltage suppressers is a device which has negative resistance. Their resistance decreases when the voltage across them crosses some critical value. The voltage clamping devices can be :

(a) Selenium diode

(b) Metal oxide Veristor (MOV)

(c) Avalanche diode suppresser

(d) Spark gap



2.7.4 Over Current Protection

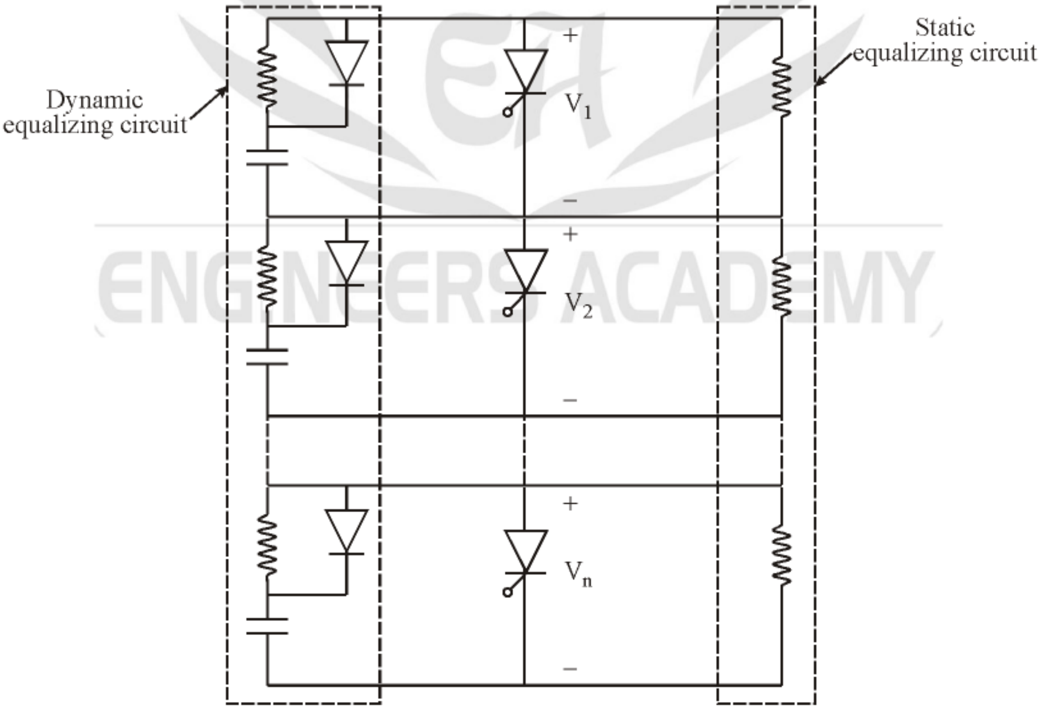
The overcurrent can flow through the device either due to short circuit or due to overloading. The protection against overloading is provided using circuit breaker (CB) and protection against short circuit can be provided using HRC fuse.

2.7.5 Gate Circuit Protection

The flux linkage of the load circuit with the gate cuircuit of different SCR can result in false triggering due to induced voltage.It can be avoided by locating SCR symmetrical on heat sink. *The heat sinks are made up of aluminium.*

2.8 *SERIES OPERATION OF SCRS*

Thyristors are connected in series to increase the overall voltage rating when the system voltage exceeds the rating of single thyristor. Voltage equalization is used to protect the thyristors during turn off by equalizing voltages across individual thyristor . The voltage should not exceed the rating of individual SCR.



Static Equalizing Circuit :

It consist of resistance connected across the thyristor. It is used to equalise the voltage across each thyristor when thyristor are in conducting state or OFF state.

Dynamic Equalizing Circuit :

This circuits used to equalise the voltage across the thyristor during dynamic condition that is during turn on and turn off process. This circuit serves the dual purpose, it equalize the voltage during dynamic condition and simultaneously it protects the device against the $\frac{dv}{dt}$.

In other word the dynamic circuit is also behaves as snubber circuit.

String Efficiency (η) :

String efficiency, $$\eta = \frac{\text{Total voltage across the string (whole system)}}{\text{(No. of SCR)* (Rating of one SCR)}}$$

$$\eta = \frac{V_s}{n \times V_{TR}}$$

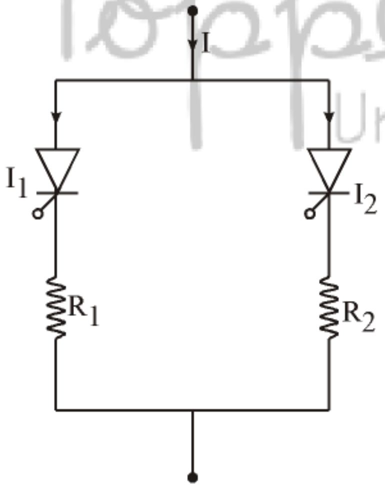
Derating factor $\quad \text{DRF} = 1-\eta$

2.9 *PARALLEL OPERATION OF SCRs*

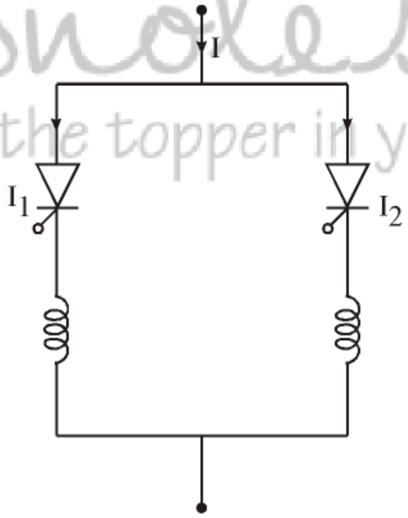
SCRs are connected in parallel to increase over all current rating when the load current exceeds the current rating of individual SCRs. current equalization circuit is used to protect the Thyristor against very large current through a thyrister having smallest turn on time during the turn on process?

Static Equalizing Circuit

It is used to distribute the load current among the thyristor in proper to their rating. This consist of the resistances connected in series with the SCRs.



Static Equalizing Circuit



Dynamic Equilizing Circuit

The static equalising circuit can not be used during dynamic condition because of different turn on and turn off time of SCR. The dynamic equalizing circuit is used to equalize the load current among the SCR during turn on and turn off processes, it consists of inductor connected in series with each thyristor.

The inductor connected in series with the SCR protects against the $\frac{di}{dt}$ during turn on.

2.10 *THYRISTOR COMMUTATIONS TECHNIQUES*

Commutation of thyristor is nothing but turning off thyristor. A thyristor can be turned off by using the following technique.

(a) By reducing the anode current below the holding current.

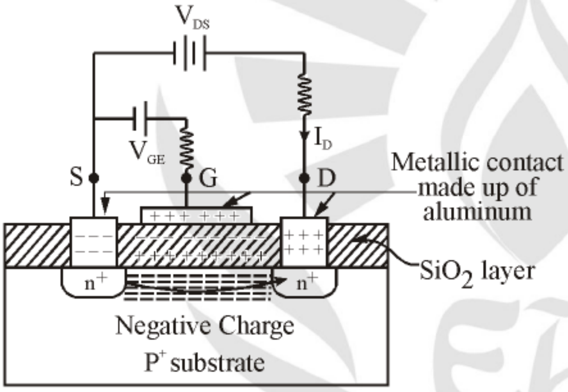
(b) By applying large impulse of voltage (in reverse direction) across the thyristor.

2.11 *POWER MOSFET*

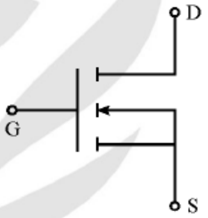
2.11.1 Basic Device Structure:

Power MOSFETs (Metal Oxide Semiconductor Field Effect Transistor) are the most commonly used power devices due to their low gate drive power, fast switching speed and superior paralleling capability. Most power MOSFETs feature a vertical structure with Source and Drain on opposite sides of the wafer in order to support higher current and voltage.Through MOSFETs are mainly used for <200V voltage rating due to their higher channel density and thus lower on-resistance. Planar MOSFETs are good for higher voltage ratings since on-resistance is dominated by epi-layer resistance and high cell density is not beneficial. The basic MOSFET operation is the same for both structures. Unless specified, the N-channel trench MOSFET is discussed in this application note.

Layer diagram of N-channel enhancement type MOSFET



Trench MOSFET Structure



Symbol of MOSFET

Source : Terminal at which majority carrier enter into the device.

Drain : Terminal at which majority carrier leave the device.

Gate : Control input voltage is applied.

The MOSFET work in two modes called Depletion mode and enhancement mode, the Conducting channel of MOSFET can be *n*- channel and *p*-channel.

The layer diagram of enhancement mode is shown in the figure above.In enhancement mode n-channel MOSFET, source and drain layer are n^+ are defused inside the p^+ substrate shown in the diagram.

The external terminal of source and drain are mode through metallic contacts and SiO_2 *layer is used to isolate the gate from P substrate.*

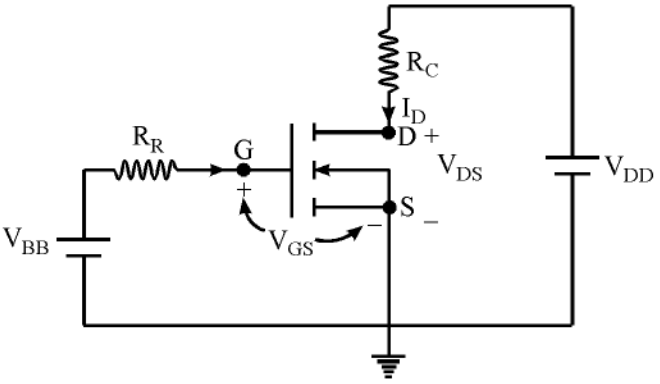
2.11.2 Working :

During enhancement mode, the drain is kept at positive potential as compare to source and a voltages V_{GS} with its positive terminal at gate is connected between gate and source due to the positive potential at gate (G), the dielectric layer (SiO_2layer) gets polarized and thus result into electrostatic field in the P substrate.

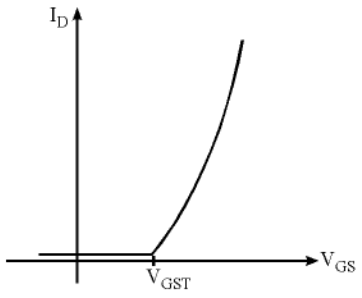
This electrostatic field results in formation of n-channel between source and drain and current start flowing from drain to source through the device.

2.11.3 Transfer Characteristic :

It is between V_{GS} and I_D



N-channel Power MOSFET circuit



Transfer characteristic

Note: *MOSFET is voltage controlled (VCCs)device and BJT is current control device (CCCs).*

For high frequency operation, MOSFET is used and UJT is used only for triggering circuit not for switching circuit..

$$V_{GST} = \text{Threshold voltage}$$

It is the minimum value of

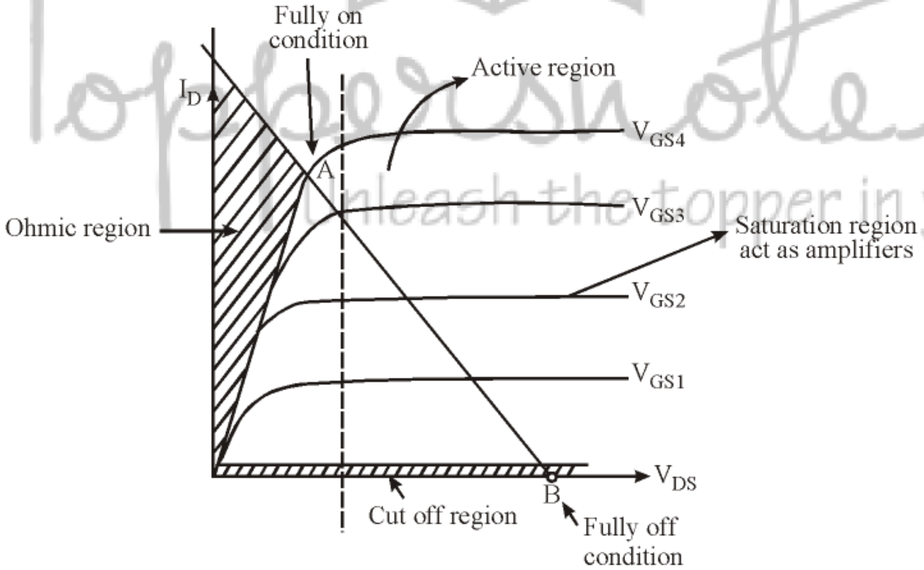
V_{GS} *required for the formation of n-channel.*

$$V_{GST} = 2 \text{ to } 3V$$

2.11.4 Output Characteristics :

It is plotted between V_{DS} and I_D with V_{GS} as a parameter.

In ohmic region it works as ON, in cut-off it works as OFF



Active regions means the device is working as an amplifier.

When the MOSFET is operated in switching mode it works in either cut off or at the edge of the ohmic region.

- **Breakdown Voltage:**

  At B, V_{DSS} is usually defined as the drain to source voltage when leakage current is 250 uA. The leakage current flowing between source and drain is denoted by I_{DSS}. The leakage current flowing between source and drain is denoted by I_{DSS}. It is measured at 100% of the B, V_{DSS} rating. As temperature increases, I_{DSS} increases and at B, V_{DSS} also increases for power MOSFETs.

- **On-State Characteristics:**

We consider here power MOSFET under two different modes of operations: the first quadrant operation and the third quadrant operation.

Threshold Voltage :

Threshold voltage. $V_{GS(TH)}$, is defined as the minimum gate bias which can form a conducting channel between the source and drain.

For power MOSFETs, it is usually measured at the drain-source current of 250 μA. Gate oxide thickness and doping concentration of the channel can be used to control the $V_{GS(TH)}$.

Typically, 2-4 V is designed for gate drive of 10-15 V. With the scaling down of the CMOS technology, the gate drive of the power MOSFET drops to 2.5-4.5 V.

Therefore, lower threshold voltage of 1-2V are needed for these applications. The threshold voltage has a negative temperature coefficient, which means it decreases with increasing temperature.

Transconductance:

Transconductance, g_{fs}, which is defined as the gain of the MOSFETs, can be expressed as the following equation.

$$g_{fs} = \frac{\Delta I_{DS}}{\Delta V_{GS}}$$

$$g_{fs} = \frac{\mu_n . C_{OX} W}{L_{CH}}$$

It is usually measured at saturation region with fixed V_{DS}. The transconductance is influenced by gate width (W), channel length (L_{CH}), mobility (μ_n), and gate capacitance (C_{OX}) of the devices. g_{fs} decreases with increasing temperature due to the decreasing carrier mobility.

2.12 *POWER DIODES*

Power diodes are uncontrolled devices, these are available with the rating varying from 1A to several thousand A and the voltage rating varying from 15V to 50 kV.

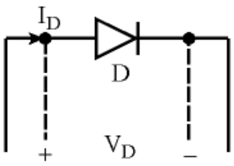
Power diode can be classified into three different categories called

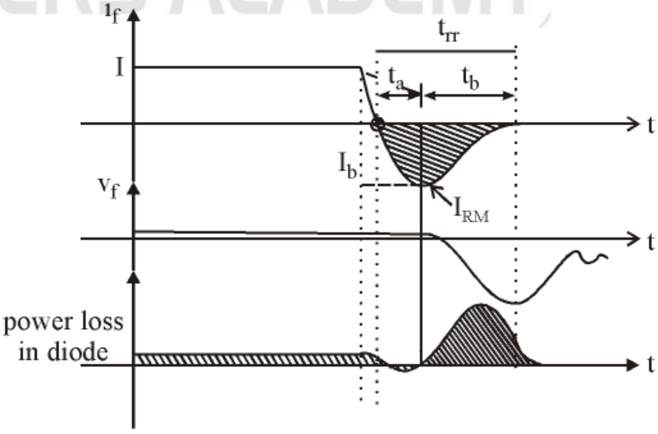
(a) General purpose

(b) Fast recovery diode

(c) Schottky diode

Switching Characteristics of Diode





Reverse recovery characteristics