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Module-1

Introduction

1. Applications of Power Electronics,
2. Power Semiconductor Devices,
3. Control Characteristics of Power Devices,
4. Types of Power Electronic Circuits.
5. Peripheral Effects.

Power Transistors:

6. Power BJTs: Steady state characteristics.
7. Power MOSFETs: device operation, switching characteristics,
8. IGBTs: device operation, output and transfer characteristics.
9. dI/dt & dv/dt Limitations.

Text Books:

1. Mohammad H Rashid, power Electronics, Circuits, Devices & Applications 3rd/4th Edition Pearson Education Inc 2014

Power Electronics

INTRODUCTION: power electronics is branch of Electrical & electronic Engg. It deals with applications of solid state electronics for the Control & conversion of electric power.

power electronics combine power, electronics & control.

Power deals with the static & rotating power equipment for generation, transmission & distribution of electric power.

Electronics deal with the solid state devices for signal processing to meet the desired control objectives.

Control deals with the steady state & dynamic characteristics of closed-loop system.

The interrelationship of power electronics with power, Electronics & control shown in fig 1

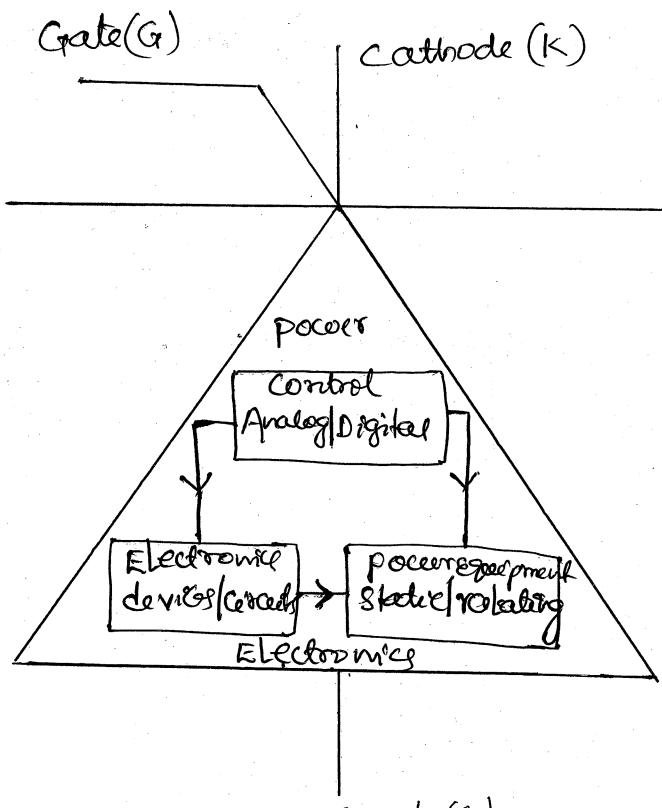


Fig 1: Interrelationship of power electronics with power, Electronics & control

APPLICATIONS OF POWER ELECTRONICS

Following are the applications of power electronics.

① Commercial applications:

Heating systems, ventilating, Air Conditioners, control refrigeration, lighting, Computers & office equipments, UPS, Elevators & Emergency lamps.

② Domestic applications:

Cooking equipments, lighting, Heating, Air Conditioners, Refrigerators & freezers, personal Computers, Entertainment equipment, UPS.

③ Industrial Applications:

pumps, compressors, blowers & fans, machine tools, induction furnace lighting control circuits, industrial lasers & welding equipments.

④ Aerospace applications:

Space Shuttle power supply systems, satellite power systems, aircraft power systems.

⑤ Telecommunications:

Battery chargers, power supply (DC & UPS), cell phone battery chargers.

⑥ Transportation

Traktion control of electric vehicles battery chargers for electric vehicles, Electric locomotives, street-cars, trolley buses, automobile electronics including engine control.

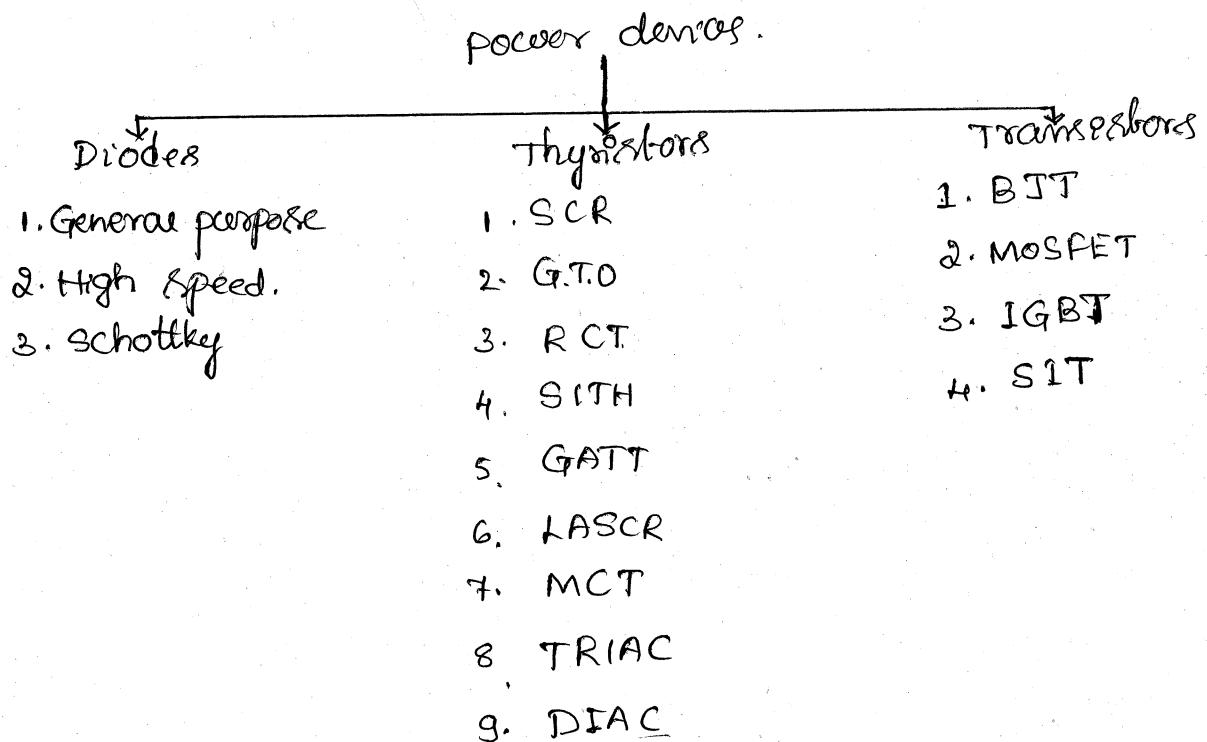
⑦ Utility Systems:

High voltage DC T_x, Alternative energy sources (wind, photovoltaic), fuel cells, energy storage system.

⑧ Medical field - Laser power supplies & medical instruments.

POWER SEMICONDUCTOR DEVICES:

power semiconductor devices are used as an ON/OFF switches in power control circuits. These devices are classified as.



1. Power Diodes:

Power diodes are made of silicon P-n junction with two terminals anode & cathode.

Diode is forward biased when anode is made the with respect to cathode diode conducts fully when diode voltage is more than the cut-in voltage ($0.7V_{for}$)

Diode is reverse biased when cathode is made the with respect to anode, when reverse biased, a small reverse current known as leakage current flows.

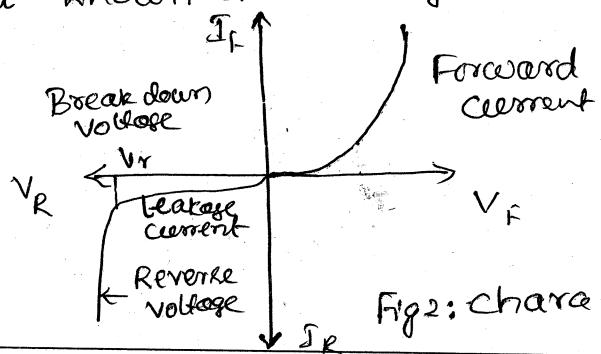


Fig: characteristics of diode.

Power diodes can be classified as.

1. General purpose diode
2. High speed (Fast recovery) diode
3. Schottky diode.

General purpose Diode:

1. They are available upto 600V, 4500A
2. They have high reverse recovery times of about 28μsec
3. They are used in low speed (frequency) applications.
Ex: Line Commutated Converters, diode rectifiers & converter for a low freq upto 1KHz.
4. They are cost effective.

High Speed Diodes (Fast recovery):

1. They are available upto 600V, 1100A.
2. Reverse recovery time varies between 0.1 & 5μsec.
3. Fast recovery diodes are essential for high frequency switching of power converters.
4. major applications - used in electric power conversion i.e. in free wheeling ac-dc & DC-AC Converter Circuits.

Schottky Diodes:

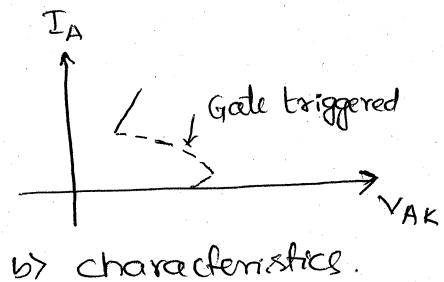
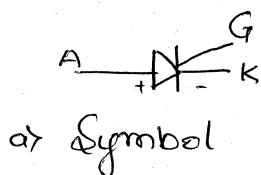
1. Schottky diodes have low on-state voltage & very small recovery time, typically nanoseconds.
2. Their ratings are limited to 100V, 300A. They are used in low voltage & high current dc power supplies.
3. The operating frequency may be as high 100-300kHz as the device is suitable for high frequency applications.

Power Electronics

comparison between different types of diodes.

Sl.no	General purpose diode	Fast-Recovery Diode	Schottky diodes.
1	Upto 6000V & 4500A	Upto 6000V & 1100A	upto 100V & 300A
2	Reverse recovery time is high $t_{rr} = 25\text{msec}$	Reverse recovery time is low $t_{rr} = 0.1\text{msec}$	Reverse recovery time is extremely low $t_{rr} = 1\mu\text{sec}$
3	$V_F = 0.3V$ to $1.2V$	$V_F = 0.8V$ to $1.5V$	$V_F = 0.4$ to $0.6V$
4	Switching freq is low	high	Extremely high
5	Turn off time is high	low	Extremely low

2. Thyristors:



A thyristor has 3 terminals an anode, cathode & gate.

- * The word Thyristor was derived from thyratron & transistor
- * When a small current flows from gate to cathode the thyristor conducts provided that the anode terminal is at a higher potential than the cathode.

Once thyristor is in Conduction mode, the forward voltage drop is very small i.e $0.5V$ to $2V$

- * When thyristor is said to be in Conduction mode, gate circuit has no control & it continues to conduct.

- * Conducting thyristor can be turned off by making the potential of the anode equal to or less than the cathode potential.

Power Electronics

* Thyristors can be sub-divided into different types

1. forced Commutated thyristors
2. Line Commutated thyristors.
3. Gate turn off thyristors (GTO)
4. Reverse Conducting thyristors (RCT)
5. Static Induction Thyristor (SITH)
6. Gate Assisted turn off thyristor (GATT)
7. Light Activated Silicon Controlled rectifiers (LASCR)
8. MOS Controlled thyristors (MCT's)
9. TRIAC - Two Alternating current

1. forced Commutated thyristors are turned off due to an extra circuit called commutation circuitry.

2. Line Commutated thyristors are turned off due to sinusoidal nature of off voltage. They are available with ratings upto 6000V, 4500A

3. GTO's are attractive for forced Commutation of converters & are available upto 4000V, 3000A

5. SITH's are for medium power converters with ratings 1200V, 300A.

4. RCT can be considered as thyristors with an anti-parallel diode. It has high current capability in forward direction, but less capability in reverse direction. They are available upto 4000V, 2000A with switching time of 40 nsec.

6. GATT's are widely used for high speed switching especially in traction (sudden force) applications. They are available upto 1200V, 400A with a switching time of 8 nsec.

Power Electronics

7. IASCR's are available upto 6000V, 1500A with a switching speed of 200 to 400 μsec & are suitable for high voltage power system in HVDC.

8. MCT's can be turned on by a small negative voltage on the MOS gate (cathode to anode) & turned off by a small reverse voltage pulse. They are available upto 1000V, 100A.

9. TRIAC's are used for low power AC applications. widely used on all types of simple heat controls, light controls, motor controls & AC switches.

3. POWER BJT'S

- * Commonly used in power converters at a frequency below 10kHz.
- * They are effectively applied in power rating upto 1200V, 400A.
- * It has 3 terminals Emitter, Base & Collector.
- * It is normally operated as switch in CE configuration.
- * Transistor remains ON as long as base of NPN transistor is at a higher potential than the emitter & base current (I_b) is sufficiently large to drive the transistors in the saturation region.
- * Forward drop of Conducting transistor is in the range of 0.5V to 1.5V. If the base drive voltage is withdrawn, the transistor remains in the non conduction mode.

POWER MOSFET:

- * They are used in high speed power converters.
- * They are available at a relatively low power rating in the voltage range of 1000V, 100A at a frequency range of several tens of kHz.

IGBT

- * They are voltage controlled power transistors.
- * They are inherently faster than BJT & still not quite as fast as MOSFETs.
- * They are suitable for high voltage, high current & frequency upto 20kHz.
- * They are available upto 1700V, 2400A.

SIT - Static Induction Transistor

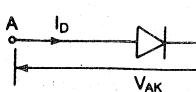
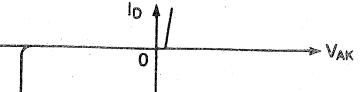
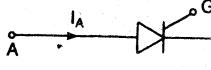
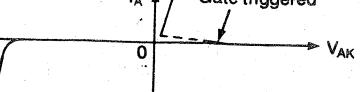
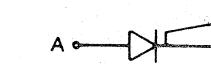
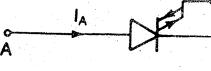
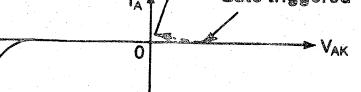
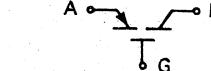
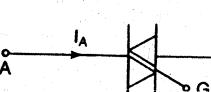
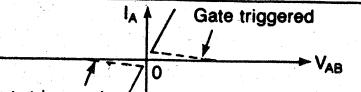
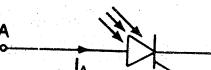
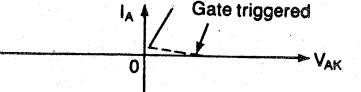
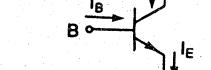
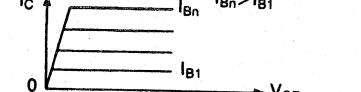
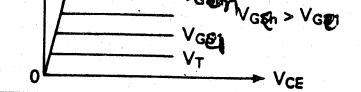
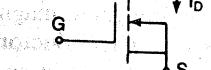
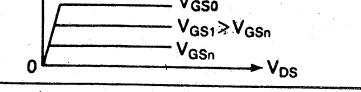
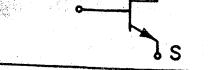
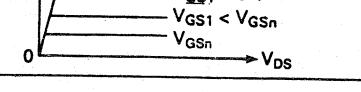
- * It is a high power, high frequency device.
- * It is essentially the solid state version of the triode vacuum tube & is similar to a JFET.
- * It has a low noise, low distortion, high audio frequency power capability.
- * Turn ON & turn off times are very short typically 0.25μsec
- * Ratings of SIT are 1200V, 300A, switching speed can be as high as 100kHz.
- * They are used for high power & high frequency applications.

Ex: Audio, VHF/UHF & Microwave amplifiers.

Power Electronics

Symbol and Characteristics of power Devices.

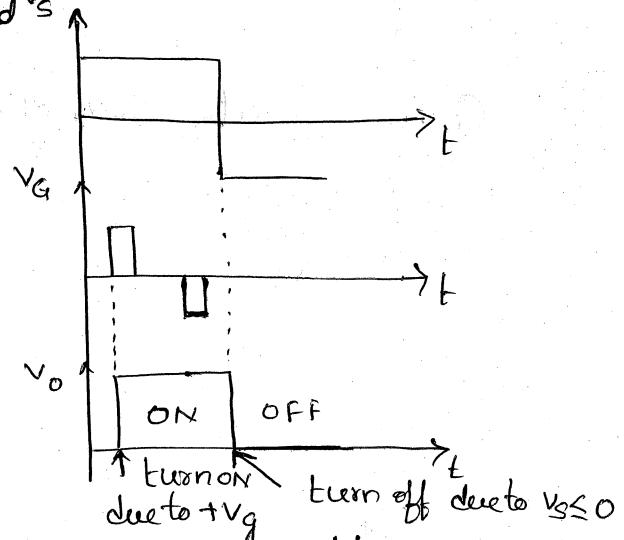
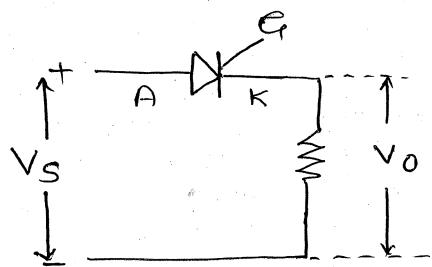
TABLE 1. CHARACTERISTICS AND SYMBOLS OF SOME POWER DEVICES

Devices	Symbols	Characteristics
Diode		
Thyristor		
SITH ✓		
GTO ✓		
MCT ✓		
TRIAC		
LASCR ✓		
NPN BJT		
IGBT		
N-Channel MOSFET		
SIT		

CONTROL CHARACTERISTICS OF POWER DEVICES.

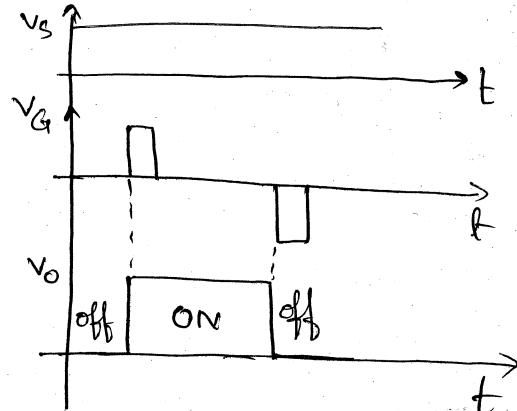
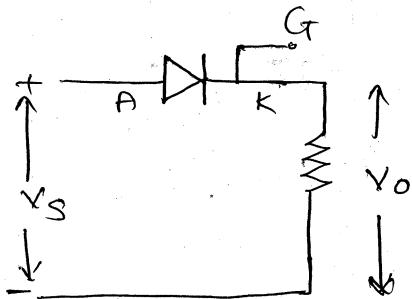
The power semiconductor device can be operated as switch by applying control signals to the gate terminals of thyristors & the required off ps obtained by varying the conduction time of these switching devops.

Thyristor (SCR) (Silicon Controlled Rectifier)



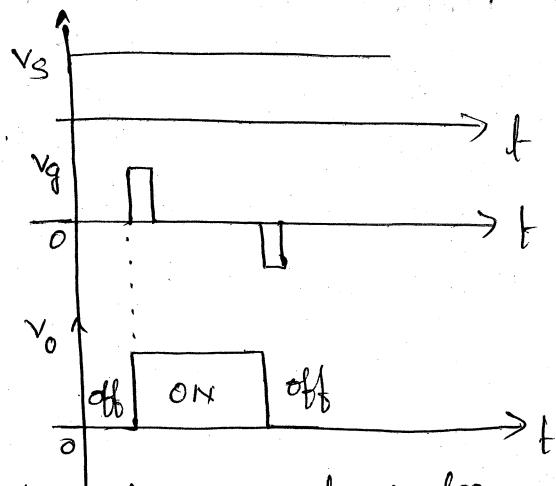
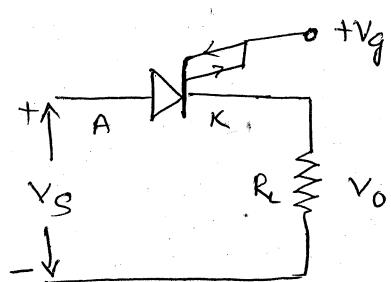
- * SCR | Thyristor ps made to conduct | turned ON by applying +ve gate voltage provided anode potential is greater than cathode voltage
- * Once SCR ps turned on, it behaves like a closed switch & it becomes insensitive to gate signal i.e. gate loses its control over the device
- * SCR can be turned off by reverse bias voltage i.e. $VAK < 0$

SITH - Static Induction Thyristor.



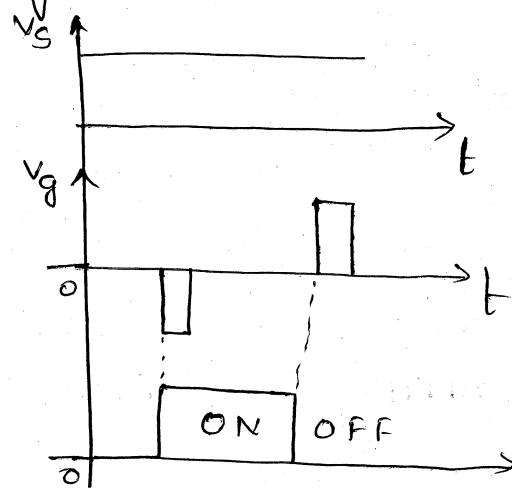
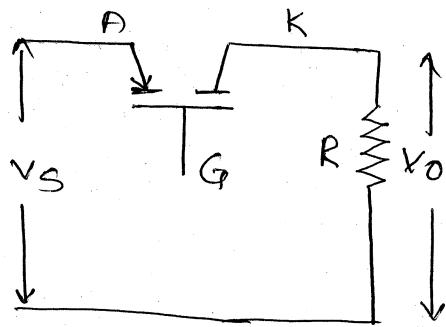
- * SiTH is turned on by applying a positive gate pulse & is turned off by applying negative pulse to the gate.
- * whenever SiTH is turned on the voltage V_S appears across the load when the device is off $V_O = 0$.

G.T.O - (Gate turn off)



GTO turned ON by applying the gate pulse.
turned OFF by applying -ve gate pulse.

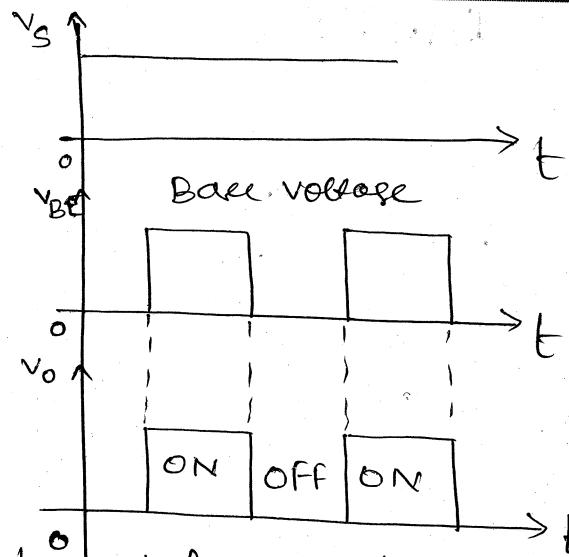
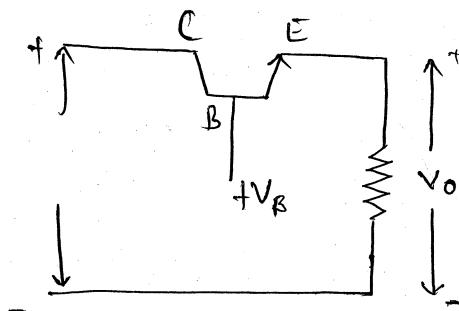
MCT - (MOS Controlled Thyristor)



In MCT the gate pulse causes it to turn off
-ve gate pulse causes it to turn on.

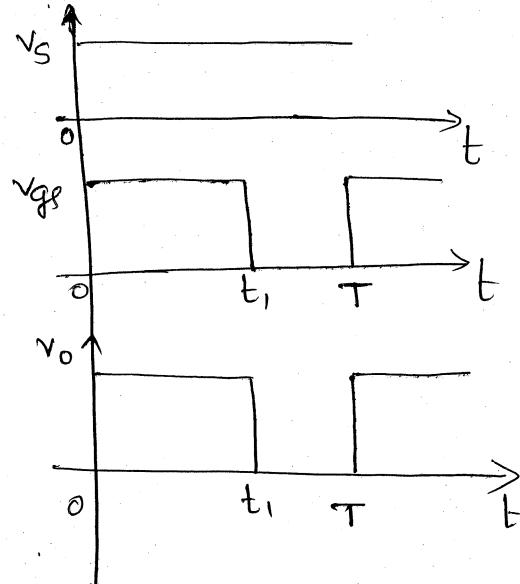
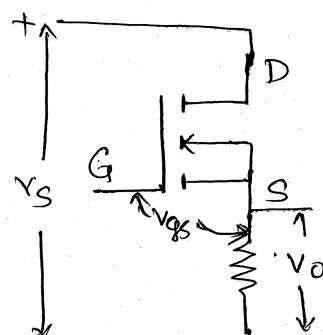
Power Electronics

Transistor - BJT



- * Control voltage V_B is applied between base & emitter of transistor
- * when V_{BE} is +ve BJT turn ON & V_S appear across the load
- when V_{BE} is -ve BJT turn OFF & $V_S = 0$
hence $V_O = 0$.

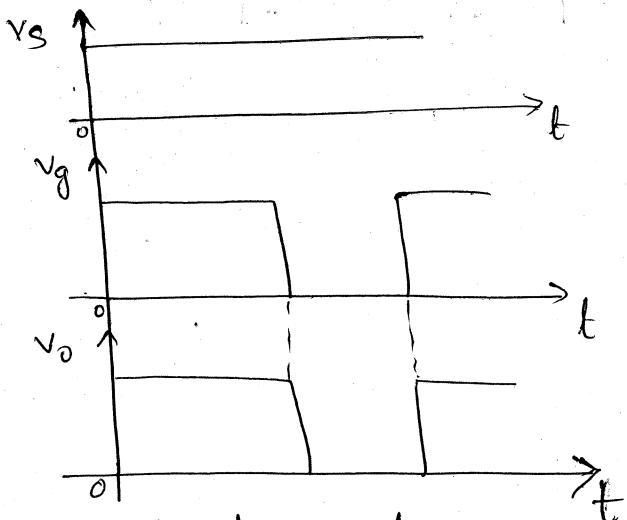
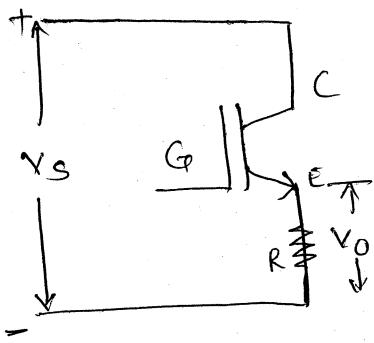
MOSFET



MOSFET is voltage controlled device, hence it requires a gate voltage to turn ON as long as gate voltage is +ve. the MOSFET Conducts off voltage $V_O = V_S$ & if MOSFET is off $V_O = 0$.

Power Electronics

IGBT:



IGBT is voltage controlled device.

when V_{GS} is +ve IGBT Turned ON & $V_D = V_S$

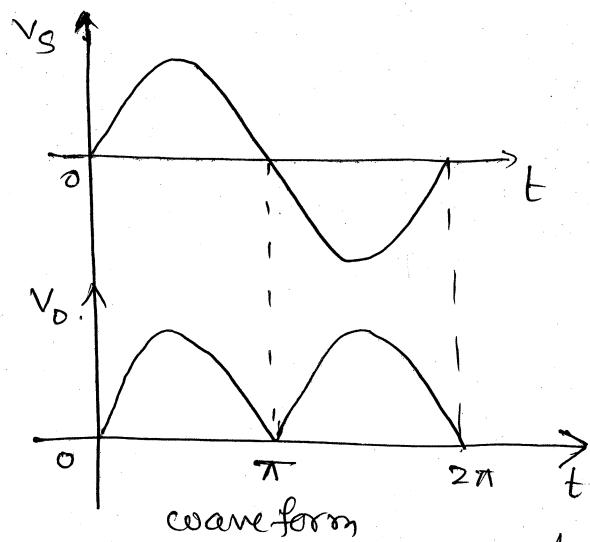
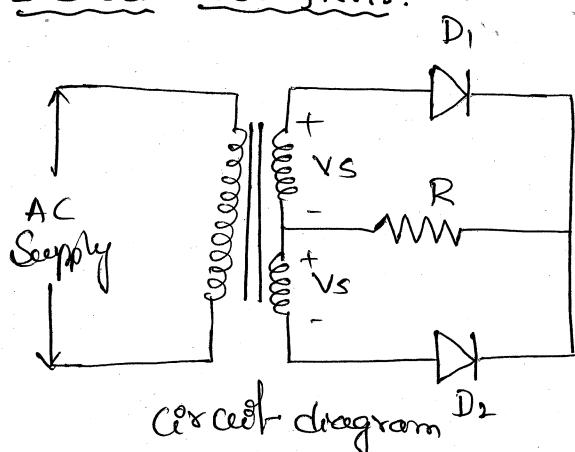
when V_{GS} is -ve or 0 ————— OFF & $V_D = 0$

TYPES OF POWER ELECTRONIC CIRCUITS:

The power Electronics Circuits can be classified into six types.

- 1) Diode Rectifiers. - UnControlled rectifier
- 2) AC-DC Converter - Controlled rectifier
- 3) AC-AC Converter - CycloConverter or AC voltage Controller.
- 4) DC-DC Converter - DC-Chopper
- 5) DC-AC Converter - Inverter.
- 6) Static Switches

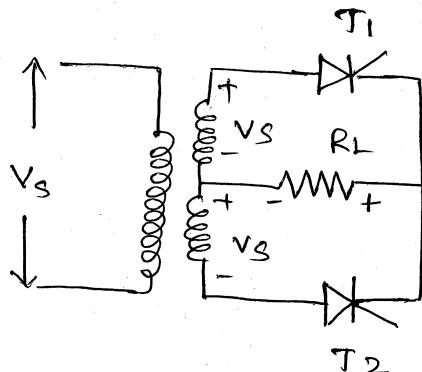
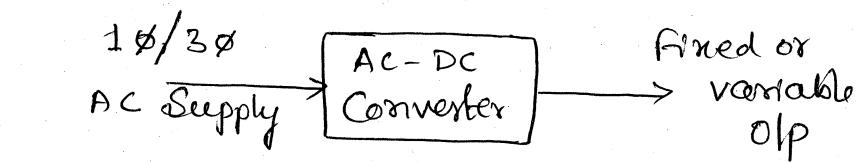
1. Diode Rectifiers:



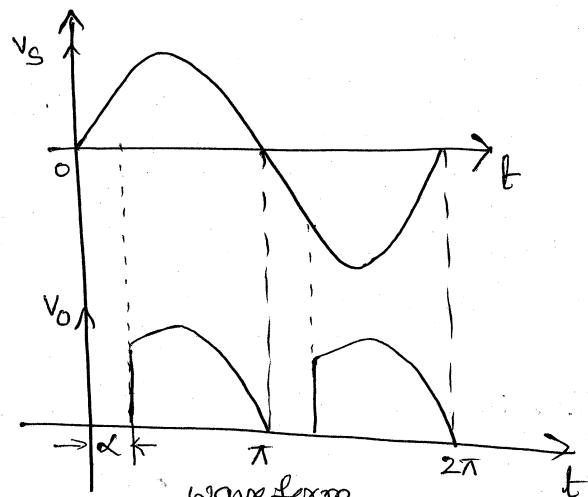
A diode rectifier Circut-Convert AC voltage into fixed DC voltage as shown in fig. The i/p voltage to the rectifier v_i could be either single phase or 3 ϕ .

Used in DC drives, UPS & HVDC Systems.

AC-DC Converter [Controlled Rectifier]



Circuit diagram

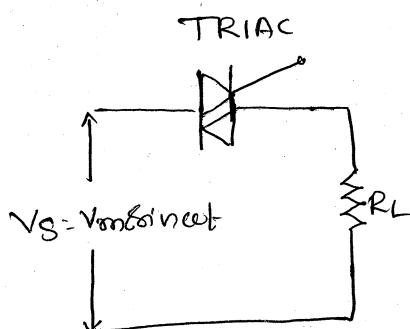


The average value of the o/p voltage can be controlled by varying the conduction time or fixing angle(α)

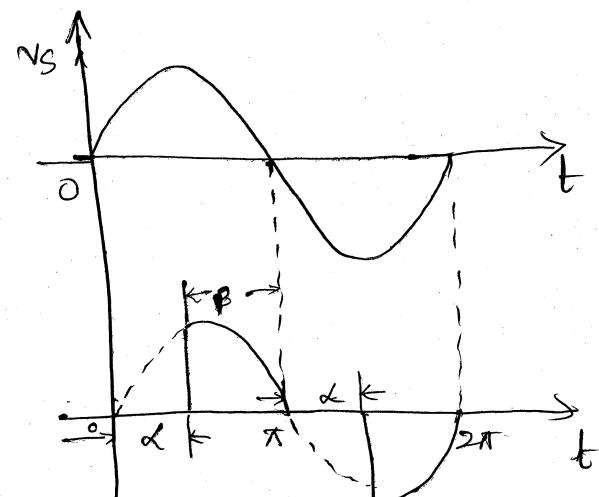
The above circuit consists of natural commutated thyristors

Used in DC drives, UPS & HVDC system.

AC-AC Converters (AC voltage controllers)

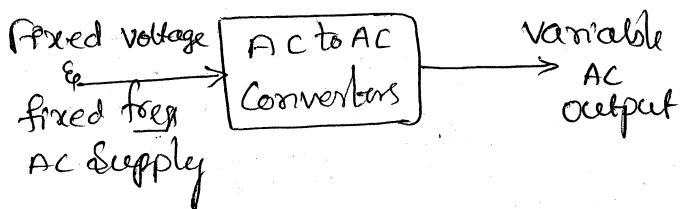


Circuit diagram



waveforms.

Power Electronics



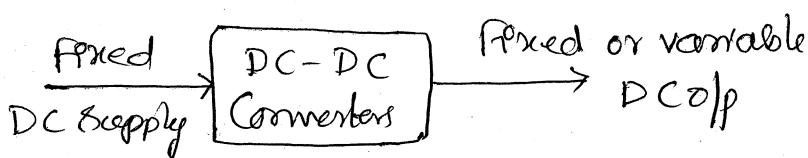
It is used to obtain a variable ac o/p voltage from a fixed ac source.

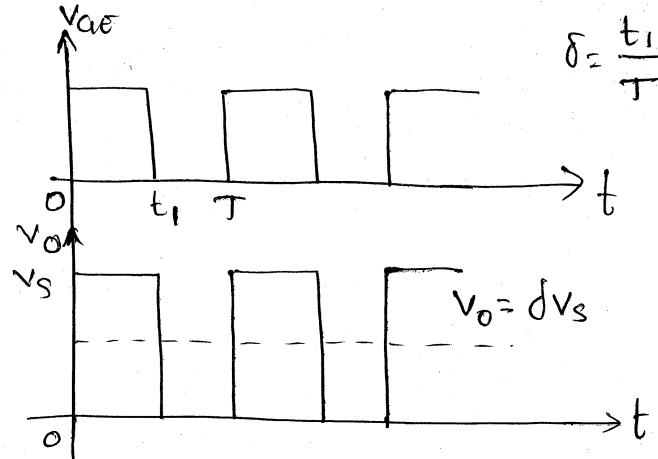
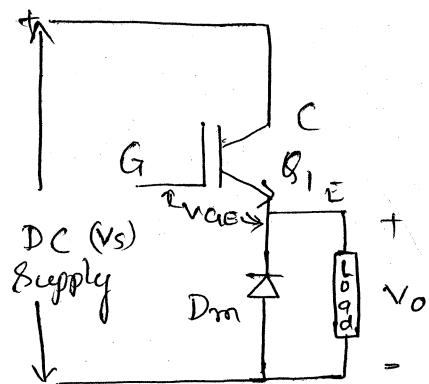
Single phase Converter with TRIAC is shown in fig & o/p voltage is controlled by varying the conduction time of TRIAC or firing angle (α)

Uses: AC traction drives, Light Control, motor Control & heat Control

DC-DC Converter [choppers]

- * A DC-DC Converter is also known as a Chopper or switching regulators.
- * The i/p to this Converter is fixed DC voltage & o/p is either fixed or variable DC voltage.
- * Transistor chopper is shown in circuit diagram the average o/p voltage is controlled by varying the conduction time t_1 of transistor Q_1 (IGBT)
- * Duty cycle of the chopper $t_1 = \delta T$, where T = chopping period
- * Uses: DC Drives, SMPS, Speed Control of DC motors, Electric traction, Subway Cars.

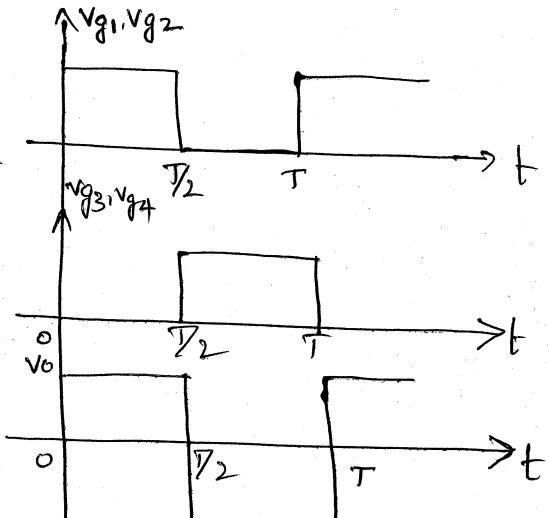
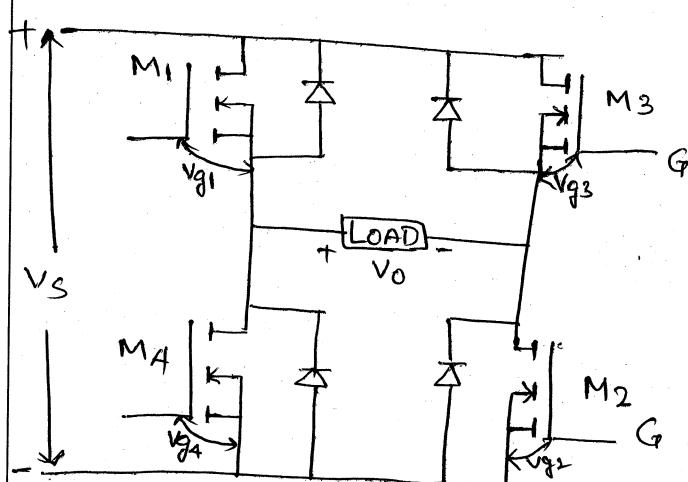
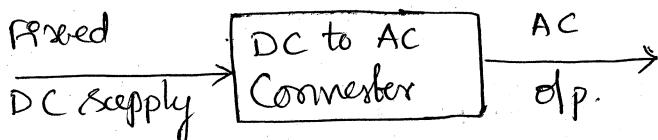




Circuit diagram

waveform.

DC-AC Converter [Inverter]



- * DC-AC Converter is also known as an Inverter
- * A 1φ transistor inverter is shown in fig.
- * If M₁ & M₂ Conduct for one half period & M₃ & M₄ Conduct for the other half. the o/p voltage V_o is of alternating form.
- * The o/p voltage can be controlled by varying the conduction time of transistors.
- * Applications: Speed Control of Induction motors, standby & emergency power supply.

Power Electronics

Static Switches:

Since the power devices can be used as static switches or contactors the supply to these switches could be either AC or DC & switches are called as AC static switches or DC switches [i.e. Instantaneously it supplies power from source to load ex: UPS]

Peripheral Effects.

- * Due to the switching of power semiconductor devices, the power converter will introduce voltage & current harmonics into the supply system & on the OLP of converters.
- * These harmonics will distort the OLP & cause interference with the communications & signalling etc. Hence to reduce these harmonic levels, the filters are used at both input & output of the converters. These filters attenuate the harmonic & noise.

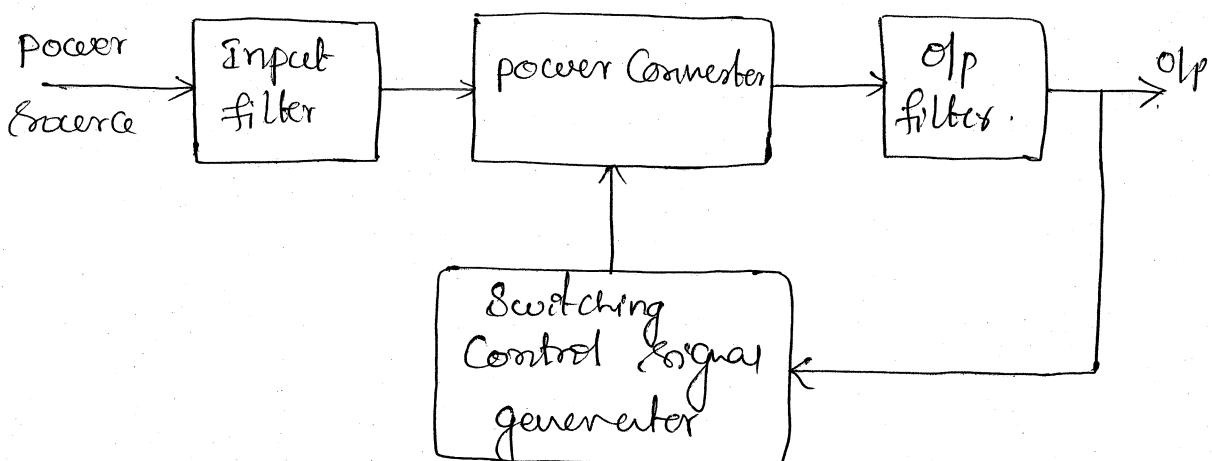


Fig: Block diagram of generalized power converter.

- * In order to reduce this problem (peripheral effect) it is required to know the quality of power & contents of harmonics.

Power Electronics

- * This can be analyzed by calculating the total harmonic distortion (THD), displacement factor (DF) & IP power factor (IPF).
- * These factors can be determined by analyzing the voltage & current waveform with the help of Fourier series.
- * The power converter can cause radio frequency interference due to electromagnetic radiation & the gating circuits may generate erroneous signals. This interference can be avoided by grounded shielding.

Properties of power Semiconductor devices.

- * High switching speed.
- * Low noise.
- * Low power dissipation.
- * High flexibility.

Power Electronics

POWER TRANSISTORS

- * Power transistors have controlled turn ON & turn OFF characteristics & are used as switching elements, are operated in saturation region, resulting in a low ON state voltage drop.
- * The switching speed of modern transistors is much higher than that of thyristors & are extensively used in DC-DC & DC-AC Converters.
- * Voltage & Current rating are lower than those of thyristors & are used in low to medium applications.
- * Power transistors are classified as.

1. Bipolar Junction Transistor (BJT)
2. Metal Oxide Semiconductor Field Effect Transistor (MOSFET)
3. Static Induction Transistor (SiT)
4. Insulated gate bipolar transistor (IGBT)

1. Bipolar Junction Transistor (BJT)

- ④ A bipolar transistor is formed by adding a second p or n region to pn junction diode
- ④ There are two types of BJT a) NPN & b) PNP
- ④ There are 3 terminals a) Emitter b) Base c) collector.
- ④ A bipolar transistor has two junctions.
 - a) Base to Emitter junction
 - b) Collector-base junction

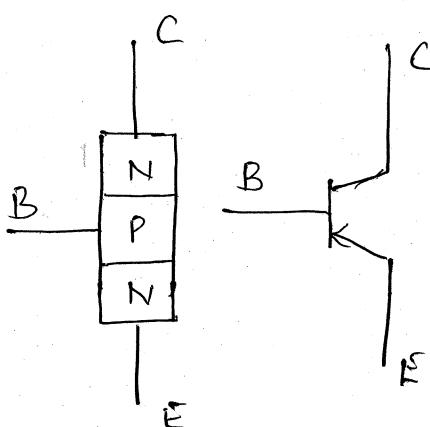


Fig a) NPN Transistor

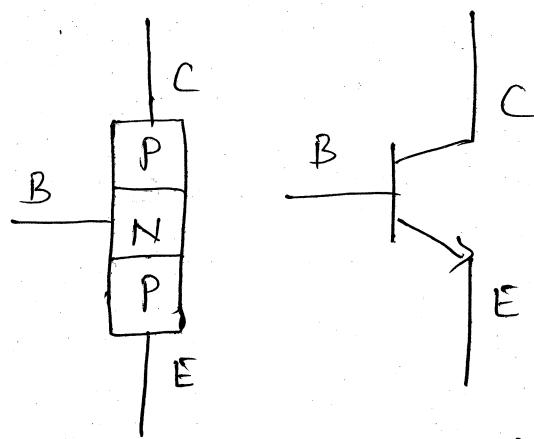


Fig b) PNP Transistor

- ⇒ In NPN type current flows from Collector to Emitter when base to Emitter junction is forward biased & transistor turned ON, whereas in PNP current flows from Emitter to Collector when transistor turned ON.
- ⇒ Base drive has full control over Conduction of BJT

Steady State Characteristics:

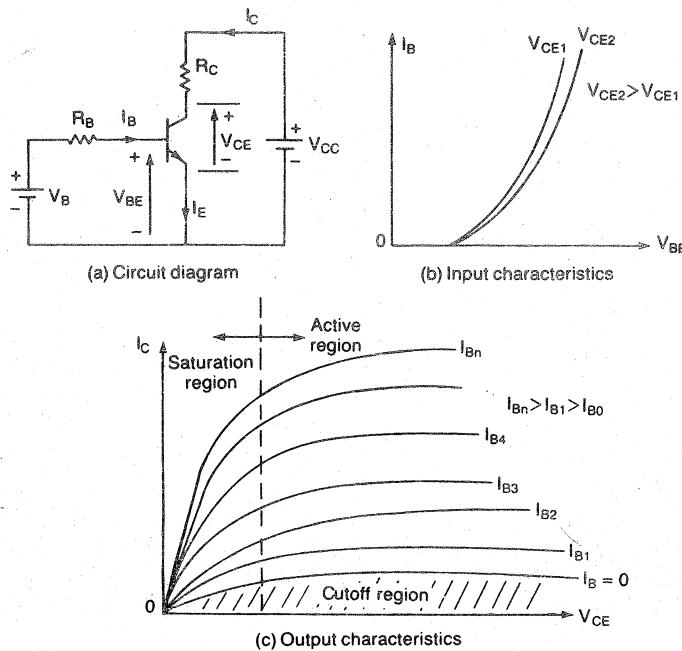


Figure 1. Characteristics of NPN-transistors.

Above fig shows CE Configured BJT circuit diagram, IP characteristics (I_B v/s V_{BE}), OP characteristics (I_C v/s V_{CE})
Transistor operated in 3 regions.

⇒ Cut off region: In this region transistor is OFF because both junctions are reverse biased (I_B is not enough to turn ON transistor).

⇒ Active region: In this region transistor acts as an amplifier. CBJ is reverse biased & BEJ is forward biased hence I_C is amplified by gain, V_{CE} decrease with I_B .

⇒ Saturation region: In this region transistor is ON & Both BEJ & CBJ are forward biased hence I_C is

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Sufficiently high so that V_{CE} low & transistor acts as switch.

* Transfer characteristics of BJT shown in below fig.

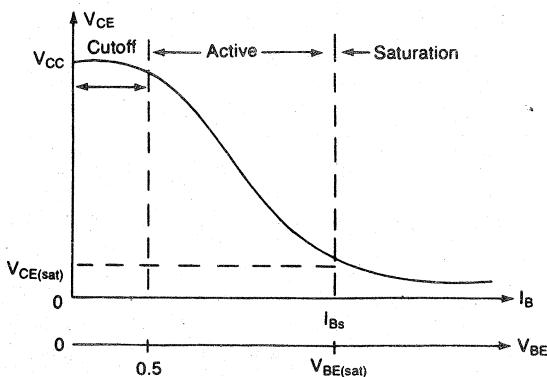
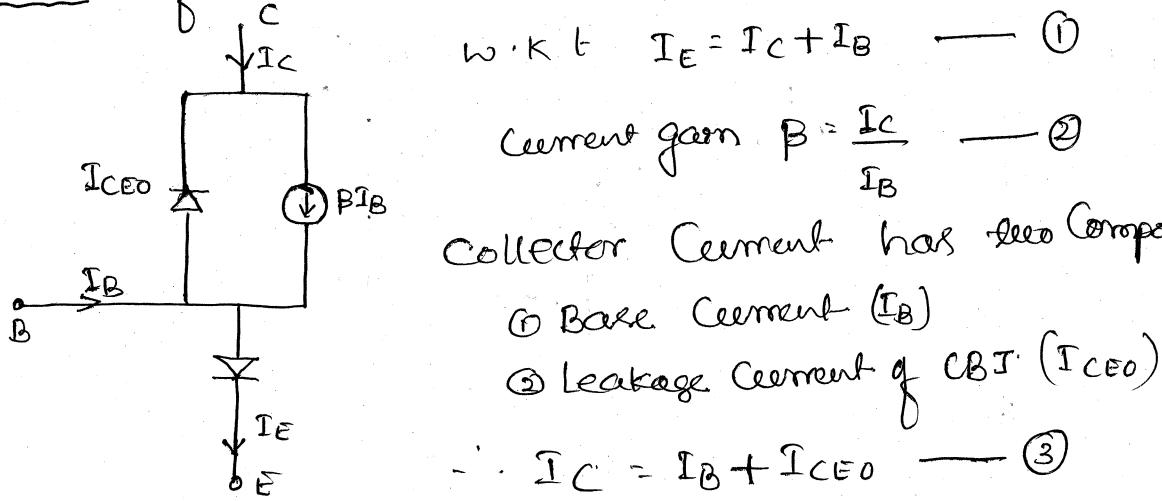


Figure 2 Transfer characteristics.

Model of NPN Transistor:



Substitute Eqn (3) in (1)

$$I_E = B I_B + I_B + I_{CEO}$$

$$I_E = I_B(B+1) + I_{CEO}$$

here I_{CEO} or C-E leakage current with bare open contact & can be considered negligible compared to $B I_B$

$$\therefore I_E = I_B(1+B)$$

$$I_E = I_B B \left(\frac{1}{B} + 1 \right)$$

$$I_E = I_C \left(1 + \frac{1}{B} \right)$$

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$$I_E = I_C \left(\frac{B+1}{B} \right) \Rightarrow I_E \left(\frac{B}{B+1} \right) = I_C \quad \boxed{B > 1}$$

also $I_C = \alpha I_E$

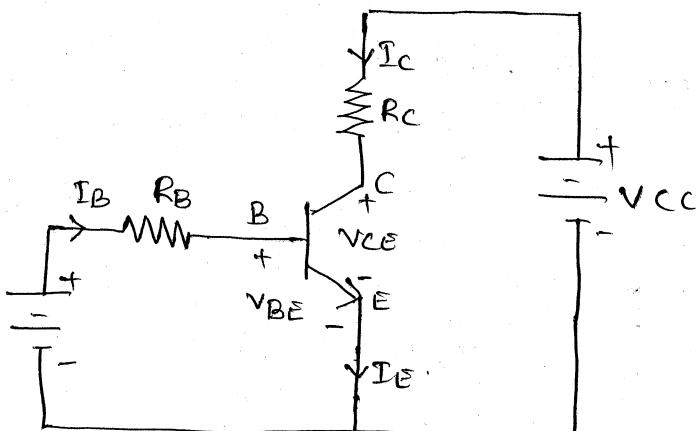
where Constant α is related to B by

$$\alpha = \frac{B}{B+1}$$

or $B = \frac{\alpha}{1-\alpha}$

Transistor as a switch:

Transistor operated as a switch shown in fig below



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

$$* V_{CE} = V_{CC} - I_C R_C$$

$$= V_{CC} - \beta I_B R_C$$

$$= V_{CC} - \beta \frac{R_C}{R_B} (V_B - V_{BE})$$

also

$$V_{CE} = V_{CB} + V_{BE}$$

or

$$V_{CB} = V_{CE} - V_{BE} \quad \text{--- (1)}$$

Eqn (1) shows that as long as $V_{CE} > V_{BE}$, the CBJ is reverse biased & transistor is in active region

Power Electronics

which can be obtained by setting $V_{CB} = 0$ & $V_{BE} = V_{CE}$ is given as

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

$$I_{BM} = \frac{I_{CM}}{\beta_F}$$

I_{CM} = maximum I_C

I_{BM} = maximum I_B

If base current is increased above I_{BM} , V_{BE} increases, the I_C increases & V_{CE} falls below V_{BE} . This will continue until CBJ is forward biased with V_{BC} of about 0.4 to 0.5V, the transistor then goes into saturation.

Transistor saturation is defined as the point above which may increase in the base current does not increase the I_C significantly.

In saturation region I_C is ^{remain} almost constant if the Collector to Emitter saturation voltage is $V_{CE(sat)}$, the collector current is

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} \quad \& \quad I_{B(sat)} = \frac{I_{C(sat)}}{\beta}$$

Normally, the circuit is designed so that I_B is higher than I_{BS} the ratio of I_B to I_{BSat} is called over drive factor (ODF)

$$ODF = \frac{I_B}{I_{BSat}}$$

The ratio of I_{CS} to I_B is called forced β (β_f)

$$\beta_f = \frac{I_{CSat}}{I_B}$$

The total power loss in the transistor is

$$P_T = V_{BE} I_B + V_{CE} I_{CSat}$$

Power Electronics

Problem

①. The bipolar transistor is specified to have β in the range 8 to 40. The load resistance is $R_C = 11\Omega$ the DC supply voltage is $V_{CC} = 200V$ & open circuit voltage to the base circuit $V_B = 10V$. If $V_{CE(sat)} = 1V$ & $V_{BE(sat)} = 1.5V$ find

- The value of R_B that results in saturation with ODF of 5
- forced β
- the power loss P_T in the saturation.

Solution.

Given data

$$V_{CC} = 200V$$

$$\beta_{min} = 8$$

$$\beta_{max} = 40$$

$$R_C = 11\Omega$$

$$ODF = 5$$

$$V_B = 10V$$

$$V_{CE(sat)} = 1V$$

$$V_{BE(sat)} = 1.5V$$

$$W.K.T. I_{CSat} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{200 - 1}{11} = 18.1A$$

$$IB_{Sat} = \frac{I_{CS}}{\beta_{min}} = \frac{18.1}{8} = 2.2625A$$

$$I_B = ODF \times I_{B(Sat)} = 5 \times 2.2625 = 11.3125A$$

$$a) R_B = \frac{V_B - V_{BE(sat)}}{I_B} = \frac{10 - 1.5}{11.3125} = 0.7514\Omega$$

$$b) \beta_f = \frac{I_{CSat}}{I_B} = \frac{18.1}{11.3125} = 1.6$$

$$c) P_T = V_{BE(sat)} \cdot I_B + V_{CE(sat)} \cdot I_{CSat}$$

$$P_T = (1.5 \times 11.3125) + (1 \times 18.1)$$

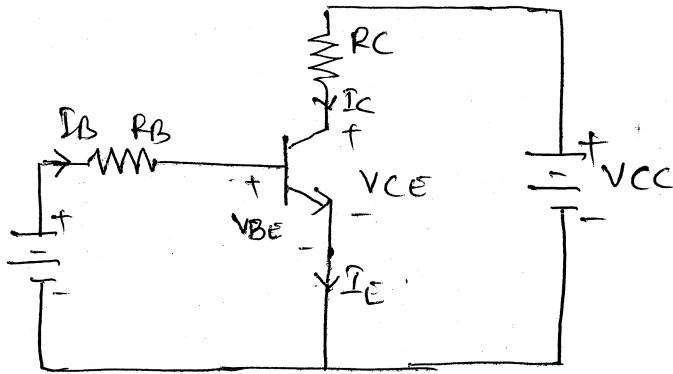
$$P_T = 35.07W$$

② For the switching circuit of transistor shown in below fig. calculate

i) the forced β of transistor.

ii) The maximum ODF if the specified $\beta = 10$

iii) The power loss P_T of the transistor.



Given data

$$V_{CC} = 100V$$

$$V_B = 5V$$

$$R_B = 0.8\Omega$$

$$R_C = 12\Omega$$

$$V_{CE(sat)} = 1V$$

$$V_{BE(sat)} = 1.5V$$

$$\beta = 10$$

$$i) \beta_{forced} = \frac{I_{C(sat)}}{I_B}$$

$$\therefore I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{100V - 1V}{12\Omega} = 8.25A$$

$$I_B = \frac{V_B - V_{BE(sat)}}{R_B} = \frac{5V - 1.5V}{0.8\Omega} = 4.375A$$

$$\beta_{forced} = \frac{I_{C(sat)}}{I_B} = \frac{8.25A}{4.375A} = 1.89$$

$$ii) ODF = \frac{I_B}{I_{B(sat)}}$$

$$\therefore I_{B(sat)} = \frac{I_{C(sat)}}{\beta} = \frac{8.25}{10} = 0.825$$

$$ODF = \frac{4.375}{0.825} = 5.3$$

$$iii) P_T = V_{BE(sat)} I_B + V_{CE(sat)} I_{C(sat)}$$

$$P_T = (1.5 \times 4.375) + (1 \times 8.25) -$$

$$P_T = 14.8W$$

2 POWER MOSFET:

Power MOSFET is voltage control device & requires only a small input current. It has 3 terminals
 (a) Gate (b) Drain (c) Source.

The switching speed is very high & switching time are of the order of nanoseconds

power MOSFET used in low power high frequency converter applications. (about 100kHz)

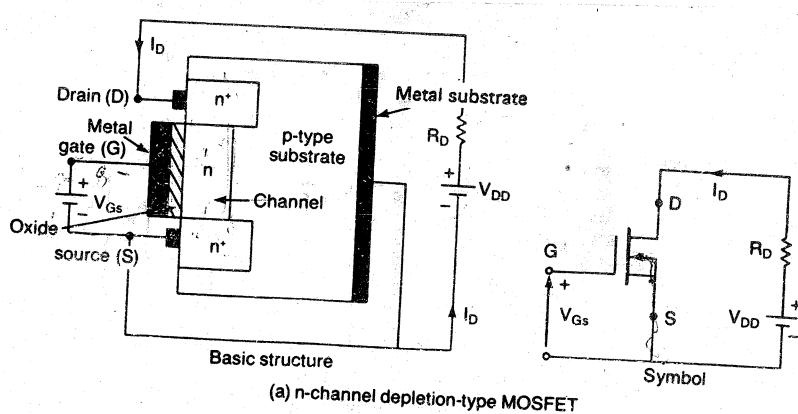
There are two types of MOSFET's

(a) Depletion type — [n - channel]
 [p - channel]

(b) Enhancement type — [n - channel]
 [p - channel]

Depletion Type MOSFET

- * An n-channel depletion type MOSFET is formed on a p-type silicon substrate with two heavily doped n+ silicon for low resistance connection.
- * The gate is isolated from the channel by a thin oxide layer. There are three terminals gate, drain & source, substrate is connected to source.
- * Gate to Source (V_{GS}) could be either positive or negative.



(a) n-channel depletion-type MOSFET

Power Electronics

operation.

* When $V_{GS}=0V$ V_D applied & current flows from drain to source

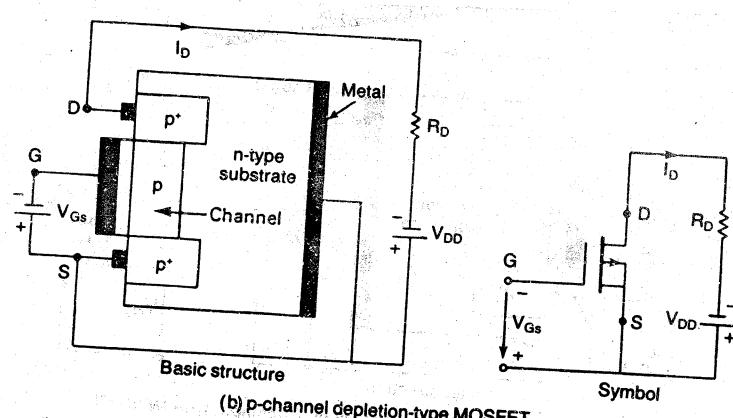
* When V_{GS} is negative the negative potential will tend to pressue electrons towards the p-type substrate & attracts hole from p-type substrate. \therefore recombination occurs & will reduce the number of free electrons on the n-channel for conduction & I_D reduces.

If V_{GS} is made -ve enough the channel will be completely depleted & $I_D=0$

The value of V_{GS} when this happens is called pinch off voltage V_p . $[V_{GS}=V_p, I_D=0]$

* When V_{GS} is +ve, the channel becomes wider & I_D increases.

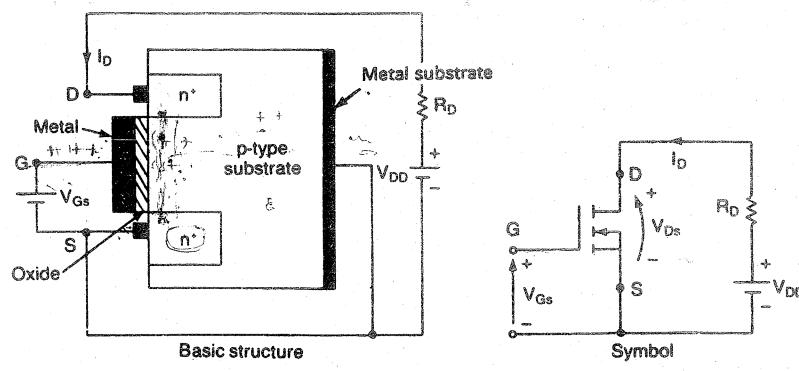
For P-channel depletion type MOSFET, the polarities of V_{DS} , I_D & V_{GS} are reversed as shown in below fig.



(b) p-channel depletion-type MOSFET

Figure Depletion-type MOSFETs.

Enhancement type MOSFET:



(a) n-channel enhancement-type MOSFET

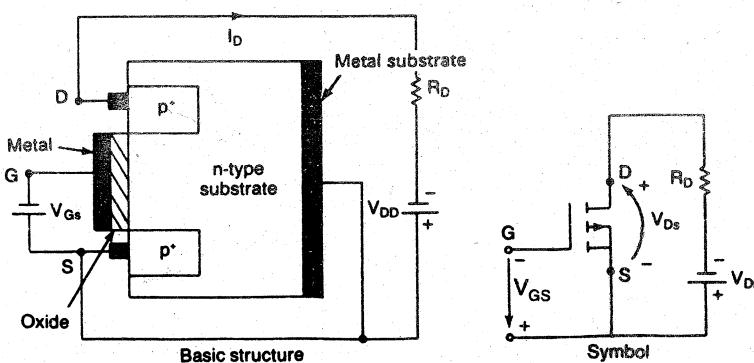
* An n-channel enhancement type MOSFET has no physical channel.

* If $V_{GS} = 0V$ & when V_{DS} is applied, no current flows due to the absence of a n-channel.

* If V_{GS} & V_{DS} is positive, an induced voltage will attract the electrons from the P-Substrate & accumulate them at the surface beneath the oxide layer.

* If V_{GS} is greater than or equal to a value known as threshold voltage V_T , a sufficient number of electrons are accumulated to form a virtual n-channel & the current flows from drain to source.

* In p-channel enhancement type MOSFET, polarity of V_{GS} V_{DS} & direction of current are reversed.

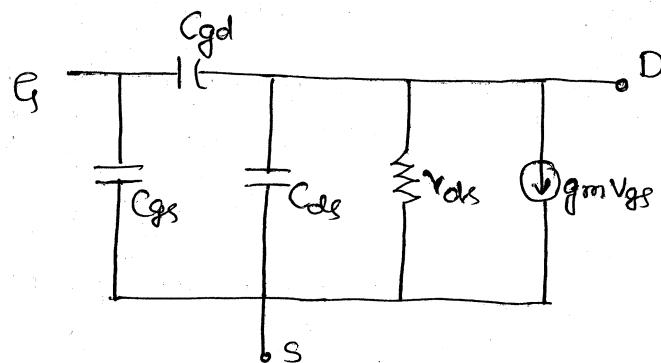
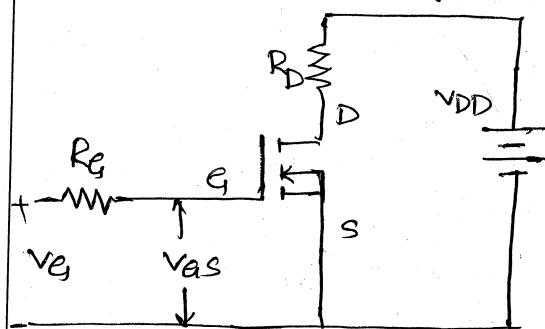


(b) p-channel enhancement-type MOSFET

Figure Enhancement-type MOSFETs.

Switching Characteristics

The circuit diagram & switching model of MOSFET & IGBT are shown in fig below.



Circuit diagram

Switching model of MOSFET

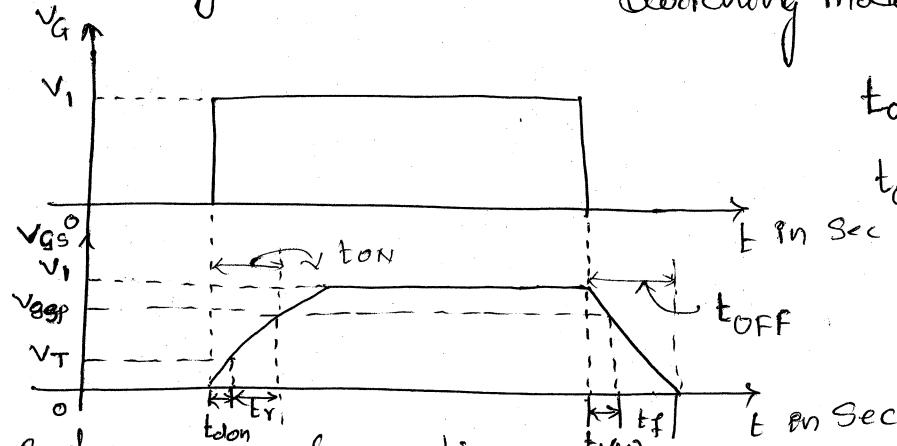
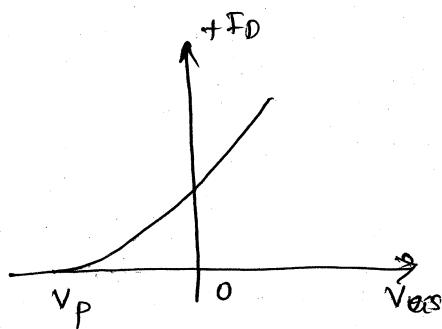


Fig- Switching waveforms & times.

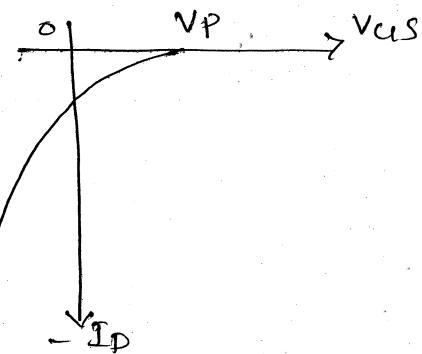
- * Turn-on delay ($t_{d(on)}$) is the time that is required to charge the Si_p capacitance to threshold voltage level.
- * The rise time t_r is the gate changing time from the threshold level to the full gate voltage V_{GSp} , which is required to drive the transistor into the linear region.
- * The turn off delay time ($t_{d(off)}$) is the time required for the Si_p capacitance to discharge from the overdrive gate voltage V_1 to the pinch off region V_{AS} most decrease significantly before V_{DS} begins to rise.
- * The fall time t_f is the time that is required for the Si_p capacitance to discharge from the pinch off region to threshold voltage.
- * If $V_{AS} \leq V_T$, the transistor turns off.

Steady State characteristics:

- * MOSFETs are voltage controlled device & have a very high Z_{IP} impedance.
- * Gate draws a very small leakage current of the order of nano amperes.
- * The current gain which is the ratio of drain current I_D to the ip gate current I_G is of the order of 10^9 .
- * The transconductance which is the ratio of I_D to V_{GS} defines the transfer C/s i.e. $g_m = \frac{\partial I_D}{\partial V_{GS}} \Big|_{V_{DS}=\text{constant}}$
- * Transfer C/s of n-channel enhancement mosFETs are shown on fig

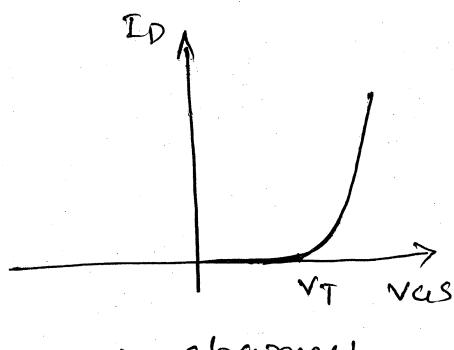


n channel

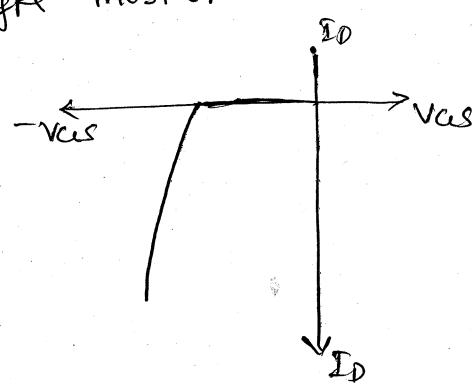


p- channel

Fig: Depletion type MOSFET



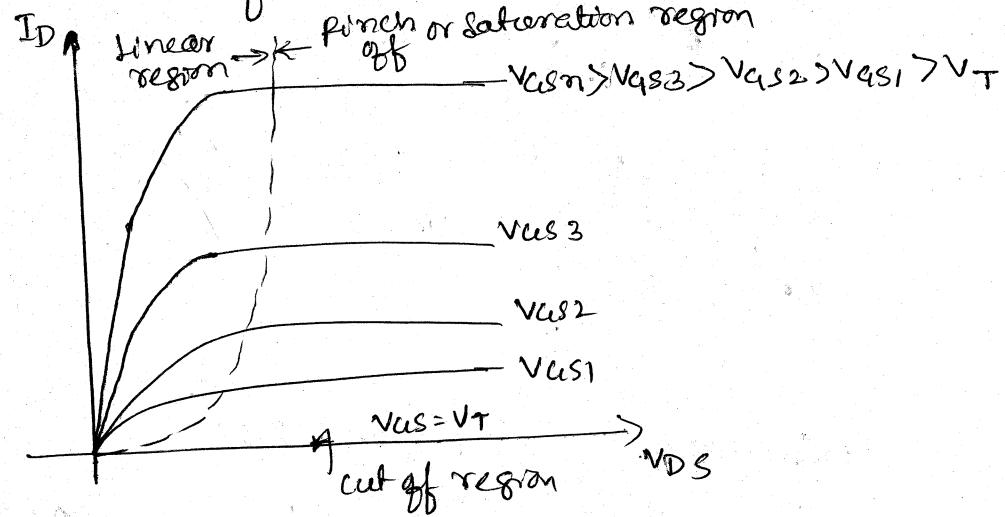
n-channel



p- channel

Fig: Enhancement type MOSFET

Op characteristics of n-channel enhancement MOSFET



MOSFET operated on 3 regions.

1. Cut off region where $V_{GS} \leq V_T$.

2. Pinch off or saturation region where $V_{DS} \gg V_{GS} - V_T$

3. Linear region where $V_{DS} \leq V_{GS} - V_T$

* Pinch off occurs at $V_{DS} = V_{GS} - V_T$

* In linear region, ID varies in proportion to V_{DS} due to high ID & low V_{DS} , power MOSFETs are operated in the linear region for switching actions.

* In saturation region, ID remains almost constant for any increase in the value of V_{DS} & the transistor are used in this region for voltage amplification.

* The op resistance $\rho_o = R_{DS}$ which is defined as

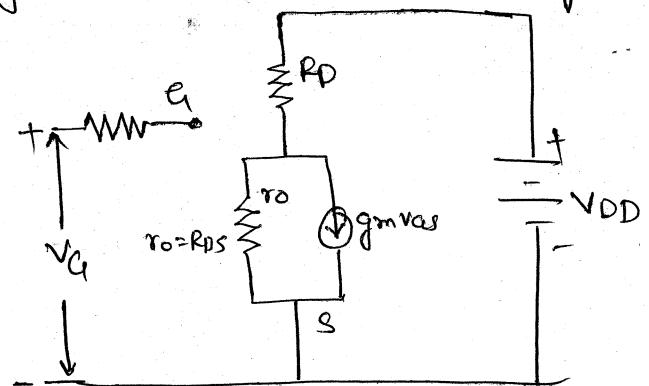
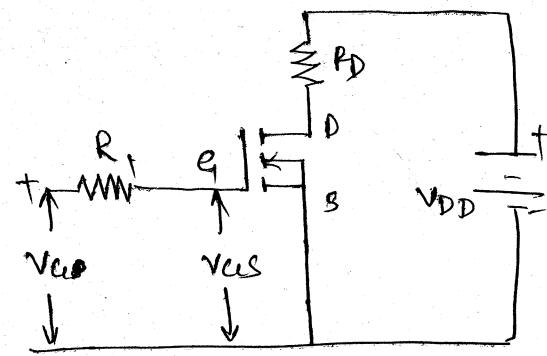
$$R_{DS} = \frac{\Delta V_{DS}}{\Delta I_D}$$

The ρ_o is normally very high in the pinch-off region (MOS) & very small in linear region.

* For depletion type MOSFET, the gate voltage could be either +ve or -ve

* Enhancement type MOSFET responds to +ve gate voltage only.

* The power MOSFETs are generally enhancement type.



Comparison of BJT & MOSFET.

BJT

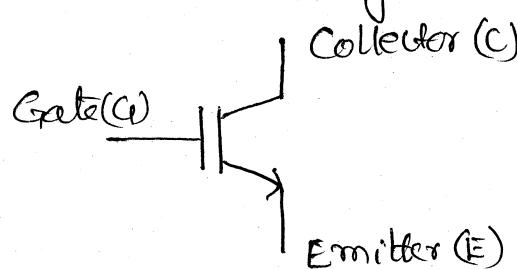
1. It is Current Controlled device.
2. Switching frequency is low.
3. more Conduction loss.
4. Suitable for low frequency applications.
5. BJT has +ve temp Co-efficient.
6. Secondary breakdown can take place.
7. BJT are less sensitive to voltage spikes.

MOSFET

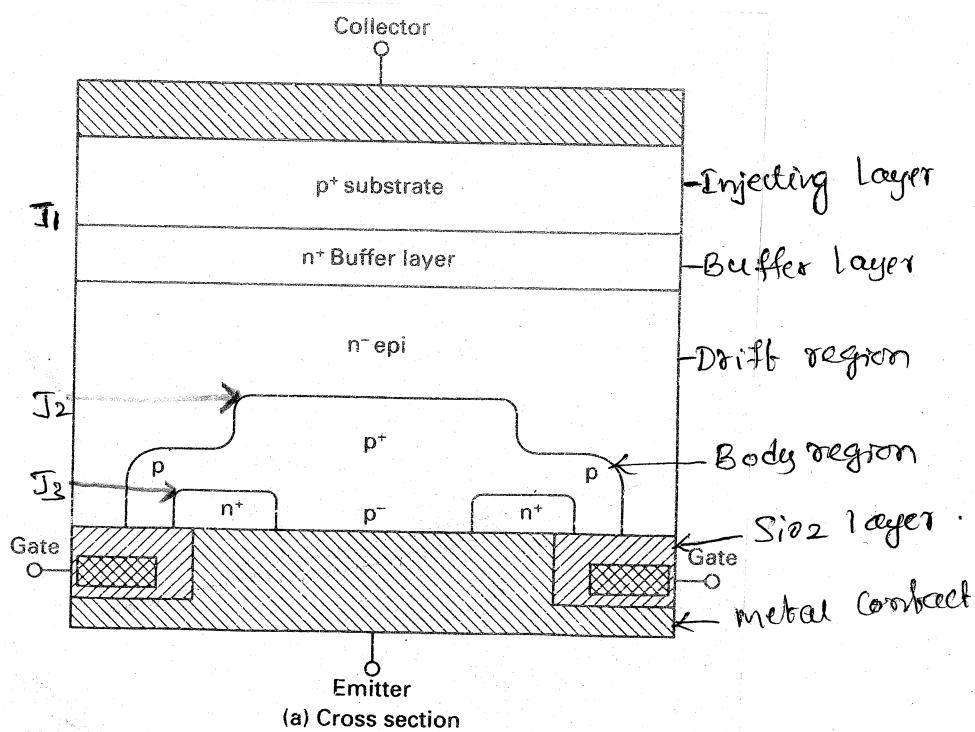
1. voltage Controlled device.
2. Switching frequency is high.
3. Low Conduction Loss.
4. Suitable for high frequency applications.
5. MOSFET has +ve Temp Co-efficient.
6. No possibility of Secondary breakdown.
7. more Sensitive.

IGBT (Insulated Gate Bipolar Transistor).

- * An IGBT Combines the advantages of BJT's & MOSFET's.
- * An IGBT has high I_{sp} impedance like MOSFET & low on state conduction losses like BJT's.
- * It has no second breakdown problem like BJT.
- * The gate Circuit of MOSFET & Collector-Emitter Circuit of BJT are combined together to form IGBT.



- * The IGBT has 3 terminals Gate, Collector & Emitter. Current flows from Collector to Emitter whenever a voltage between gate & emitter is applied & IGBT is said to have turned ON when gate-emitter voltage is removed, IGBT turns off. Thus gate has full control over the conduction of IGBT.
- * Cross section of an IGBT is shown in below fig.



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- * It is identical to that of MOSFET except the p+ substrate. However the performance of an IGBT is closer to that of a BJT than a MOSFET. This is due to the p+ substrate, that is responsible for the minority carrier injection onto the n-region.
- * An IGBT is made of 4 alternate PNPN layers & could latch like a transistor given the necessary condition $(\alpha_{npn} + \alpha_{pnp}) > 1$.

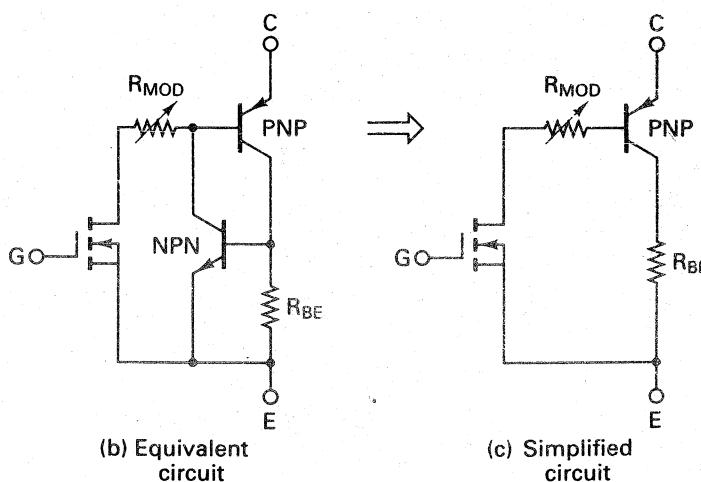
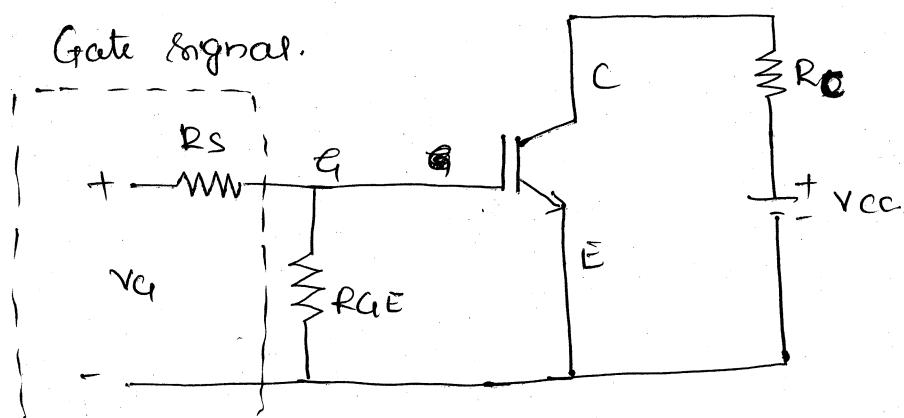


Figure Cross section and equivalent circuit for IGBTs.

* The equivalent circuit shown in above fig.



Device operation:

- * Consider the Cross section & equivalent circuit of IGBT shown fig a, b & c.
- * Cross section of an IGBT is identical to that of an MOSFET except the p+ substrate.
- * performance of IGBT is closer to that of a BJT than MOSFET. This is due to the p+ substrate which is responsible for the minority carrier injection into the n-region.
- * An IGBT is made of 4 alternate PNPN layers & looks like a thyristor given the condition $(\alpha_{pnp} + \alpha_{npn}) > 1$
- * The n+-buffer layer & wide epi base reduce the gain of the NPN terminal by external design, thereby avoiding latching.
- * IGBT have two structures of IGBTs - punch through (PT) & non punch through (NPT). In PT IGBT structure, the switching time is reduced by use of a heavily doped n+-buffer layer in the drift region near the collector. In the NPT structure, carrier lifetime is kept more than that of a PT structure, which causes conductivity modulation of the drift region & reduce the on-state voltage drop.
- * IGBT is a voltage controlled device similar to a power MOSFET.

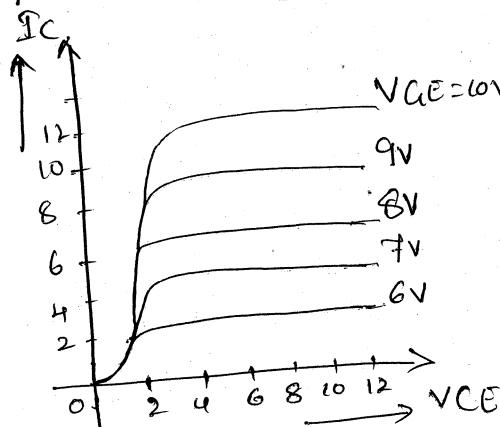
An IGBT is turned on by just applying a negative gate voltage to open the channel for n carriers & turned off by removing the gate voltage to close the channel.

It requires a very simple driver circuit. It has lower switching & conducting losses - whole sharing

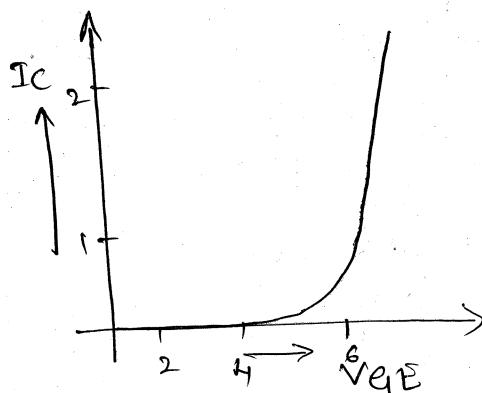
many features of power MOSFETs such as ease of gate drive, peak current capability & ruggedness.

* An IGBT is inherently faster than a BJT & the switching speed of IGBT is inferior to that of MOSFETs.

Output and Transfer characteristics:



a>



- b>

* Typical op. cl's of I_C v/s V_{CE} are shown for various V_{GE} in fig (a).

* The typical transfer cl's of I_C v/s V_{GE} is shown in fig. (b)

* The current rating of a single IGBT can be upto 1200V, 400A & the switching frequency can be upto 20KHz.

* IGBTs are finding increasing applications in medium power applications such as DC & AC motor drives, power supplies, solid state relay & contractors.

$\frac{di}{dt}$ and $\frac{dv}{dt}$ Limitations:

- * Transistor require certain turn-on & turn off time. Neglecting the delay time(t_d) & storage time(t_s), the typical voltage & current waveforms of a BJT switch are as shown below

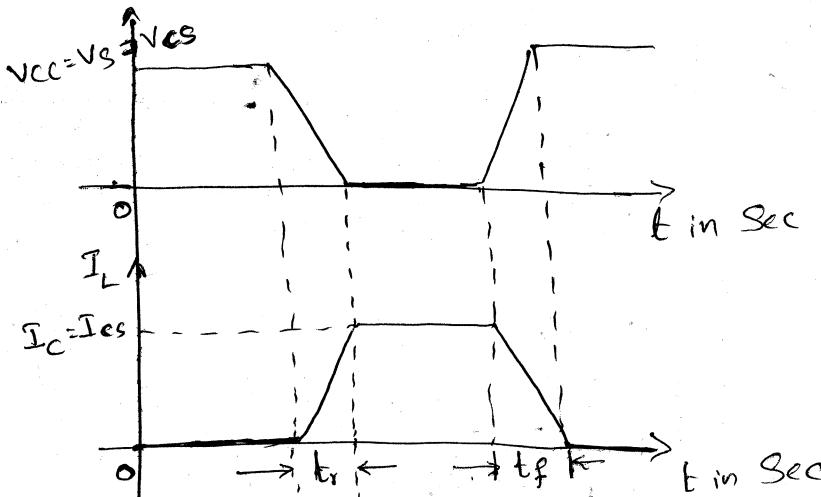


Fig: voltage & current waveform.

- * During turn on, the Collector Current rises & $\frac{di}{dt}$ is

$$\frac{di}{dt} = \frac{I_L}{t_r} = \frac{I_{CS}}{t_r} \quad \text{--- (1)}$$

- * During turn-off, the Collector-emitter voltage must fall in relation to the fall of the I_C & $\frac{dv}{dt}$ is

$$\frac{dv}{dt} = \frac{V_S}{t_f} = \frac{V_{CE}}{t_f} \quad \text{--- (2)}$$

- * The Conditions $\frac{di}{dt}$ & $\frac{dv}{dt}$ in eqn (1) & (2) are set by the transistor switching C/L & must be satisfied during turn on & turn off.

- * protection Circuits are normally required to keep the operating $\frac{di}{dt}$ & $\frac{dv}{dt}$ within the allowable limits of the transistor.

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protection circuit:

- * A typical transistor switch with $\frac{di}{dt}$ & $\frac{dv}{dt}$ protection is shown in fig. with clp waveform.
- * The RC network across the transistor is known as the snubber circuit or snubber & limits the $\frac{dv}{dt}$.
- * The inductor L_s which limits the $\frac{di}{dt}$ is sometimes called a series snubber.

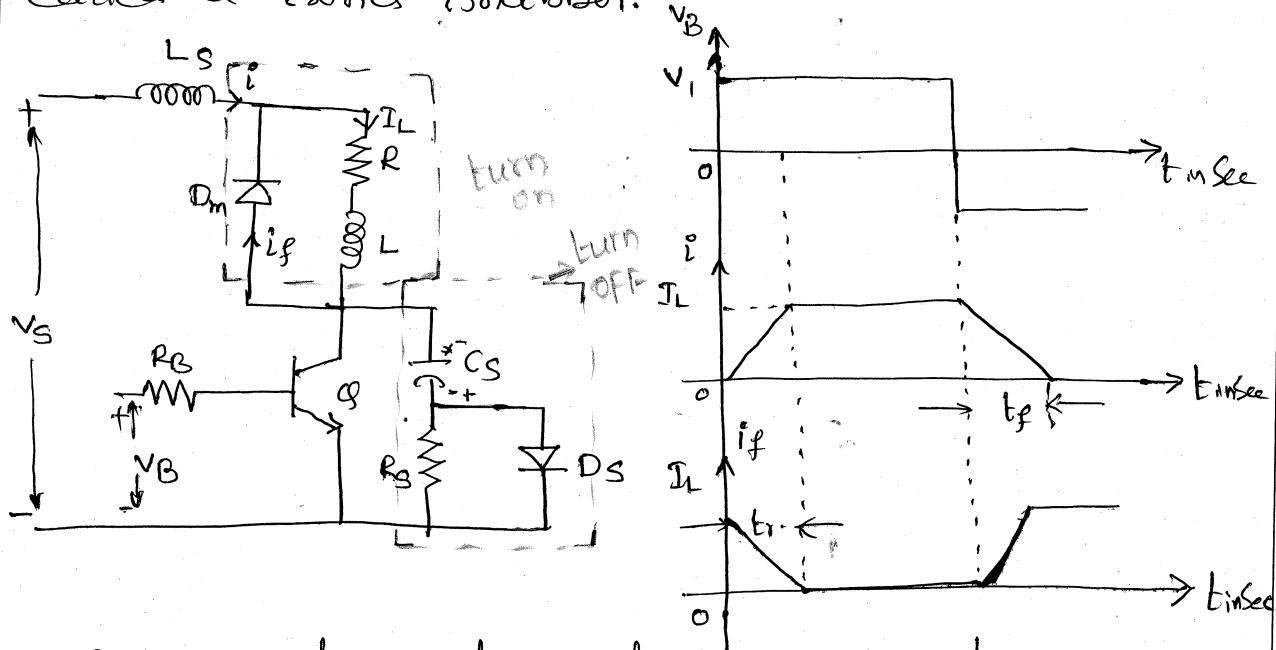


Fig: Transistor switch with $\frac{di}{dt}$ & $\frac{dv}{dt}$ protection

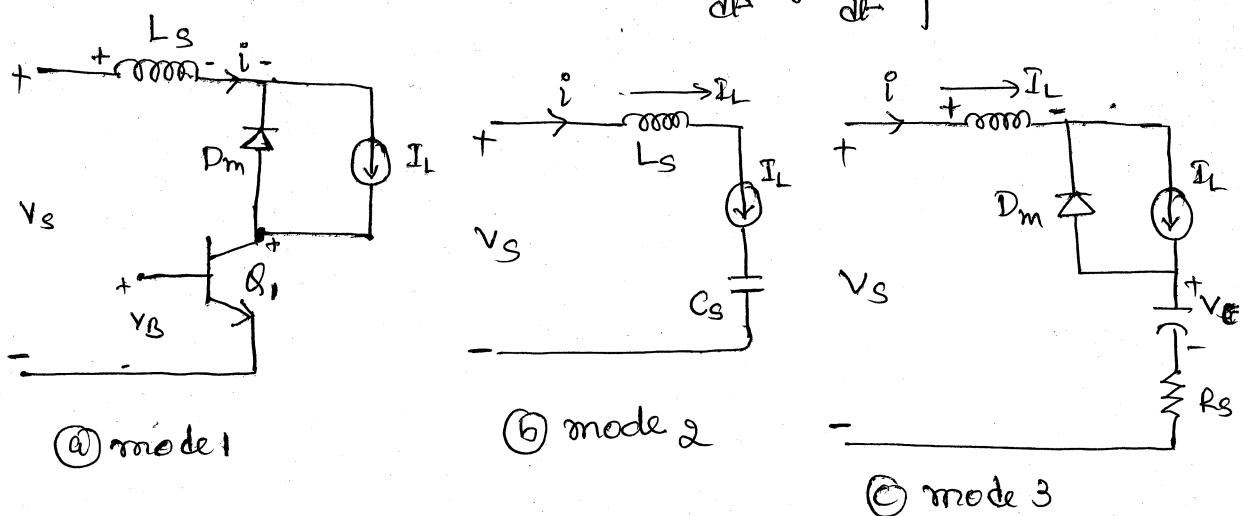


Fig: Equivalent Circuits.

- * Let us assume that under steady state conditions the load current i_L is free wheeling through diode D_m , which has negligible reverse recovery time.

- * When transistor Q₁ is turned on, the I_C rises & current of diode D₁ falls. ∴ D₁ behaves as short circuit.

The equivalent circuit during turn-on is shown in fig mode(1) & turn on diff is.

$$\frac{di}{dt} = \frac{V_s}{L_s} \quad \text{--- (3)}$$

Equating eqn ① to ③ gives the value of L_s

$$\frac{V_s}{L_s} = \frac{I_L}{t_f}$$

$$\text{i.e. } L_s = \frac{V_s \cdot t_f}{I_L} \quad \text{--- (4)}$$

- * During turn off, the capacitor C_S charges by I_L & equivalent circuit is shown in fig mode ②. The capacitor voltage appears across the transistor & $\frac{dv}{dt}$ is

$$\frac{dv}{dt} = \frac{I_L}{C_S} \quad \text{--- (5)}$$

Equating eqn ② to ⑤ gives the value of C_S

$$\frac{I_L}{C_S} = \frac{V_s}{t_f}$$

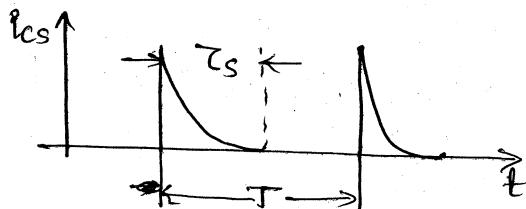
$$C_S = \frac{I_L \cdot t_f}{V_s} \quad \text{--- (6)}$$

- * Once the capacitor is charged to V_s, the free wheeling diode turns on. Due to the energy stored on L_s, there is a damped resonant circuit as shown in fig mode ③

- * RLC circuit is normally made critically damped to avoid oscillations for best critical damping δ_c ,

$$R_S = 2 \sqrt{\frac{L_S}{C_S}} \quad (\text{for critically damped in RLC}).$$

* The capacitor C_S has to discharge through the transistor & this increase the peak current rating of the transistor. The discharge through the transistor can be avoided by placing resistor R_S with C_S instead of placing R_S across D_S .



* The discharge current is shown in fig above when choosing the value of R_S , the discharge time $R_S C_S = T_S$ should also be considered. A discharge time of one third the switching period T_S is usually adequate.

$$3 R_S C_S = T_S = \frac{1}{f_S}$$

$$\text{i.e } R_S = \frac{1}{3 f_S C_S}$$

Note:

Conduction Angle: The total angle at which the thyristor conduct.

Fireing Angle: θ_S is the angle at which the thyristor forced.

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Module-2

Thyristors

1. Introduction,
2. Principle of Operation of SCR,
3. Static Anode-Cathode Characteristics of SCR,
4. Two transistor model of SCR,
5. Gate Characteristics of SCR,
6. Turn-ON Methods,
7. Turn-OFF Mechanism,
8. Turn-OFF Methods: Natural and Forced Commutation – Class A and Class B types,
9. Gate Trigger Circuit: Resistance Firing Circuit, Resistance capacitance firing circuit, VJT Firing Circuit.

Text Books:

1. M.D Singh and K B Khanchandani, Power Electronics, 2nd Edition, Tata Mc Graw Hill, 2009,

Power Electronics

1. INTRODUCTION

Thyristors are a family of power Semiconductor device. They are extensively used on power Electronic Circuits & operated as bistable switches from non-conducting to conduction state.

Thyristor have lower ON-state Conduction losses & higher power handling capability.

The SCR is the most widely used & important member of the thyristor family. This device has revolutionised the art of solid state power control.

The name thyristor is derived by a combination of thyatron & transistor.

2. PRINCIPLE OF OPERATION OF SCR

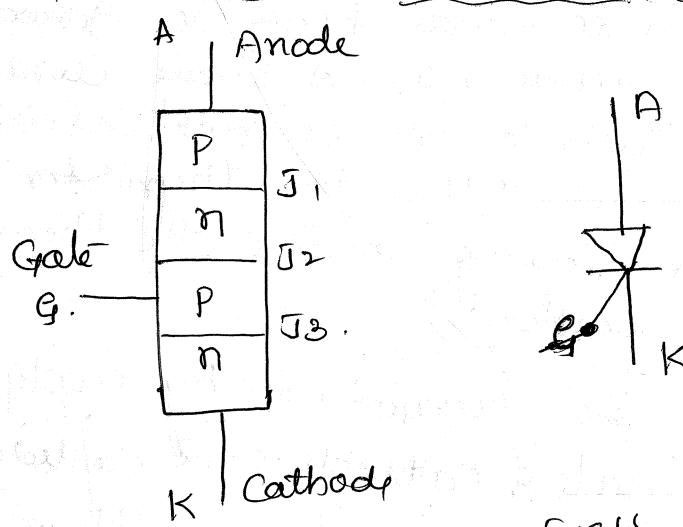


Fig a) Structure

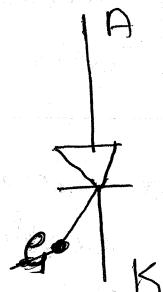
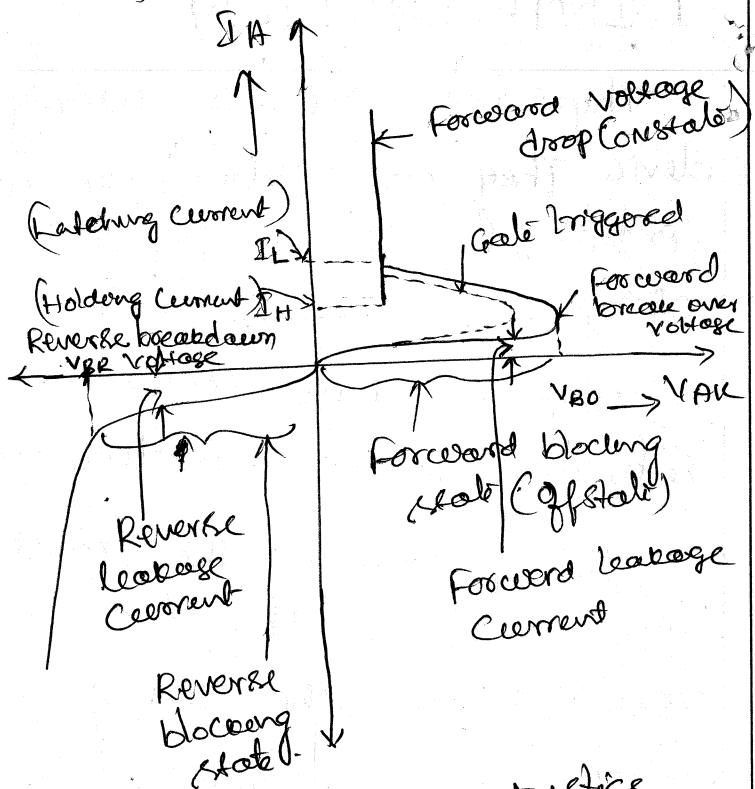
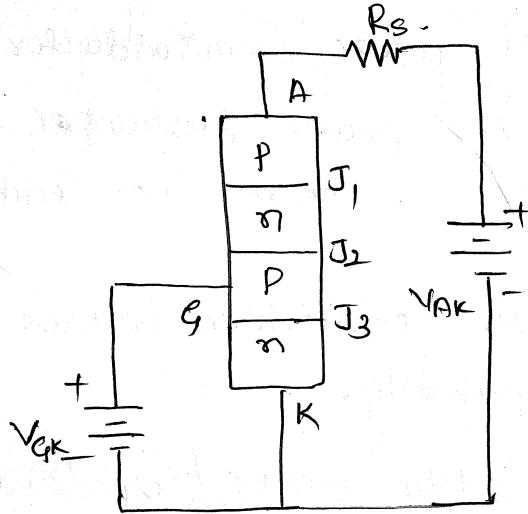


Fig b) Symbol.

A thyristor is a 4 layer device, 3 Junctions & 3 terminals. The terminals are Anode (A), Cathode (K) & Gate (G).



Fig(c) Circuit diagram.

Fig(d) V-I characteristics.

when the Anode voltage is made +ve w.r.t -ve Cathode, the Junction J₁ & J₃ are forward biased & the Junction J₂ is Reverse biased. hence the forward voltage is to be held by junction J₂. A small current flows from anode to cathode this current is called as forward leakage current thru the thyristor & said to be in forward blocking mode (The thyristor treated as an open switch.)

A Thyristor can be turned ON by applying a gate pulse b/w gate & cathode & it is called in forward Conduction mode. In this mode thyristor is in ON Condition & behaves as a closed switch.

when anode voltage is made -ve w.r.t to Cathode, the thyristor is reverse biased. Junction J₁ & J₃ are reverse biased where as Junction J₂ is forward biased. hence a very small

(2)

Current flows from cathode to Anode. This current is called reverse leakage current & this mode is called reverse blocking mode.

At reverse breakdown voltage, the reverse current increases rapidly. At the same time reverse breakdown the high voltage is present across the Thyristor & hence current flows through it hence larger power dissipation takes place in thyristor due to this dissipation will damage Thyristor.

During reverse blocking mode, the gate signal should not be applied. If the gate signal is applied b/w gate & Cathode junction J_3 is forward biased hence current starts flowing.

3. STATIC ANODE-CATHODE CHARACTERISTICS OF SCR

* The elementary circuit diagram & static V-I c/s shown in below fig.

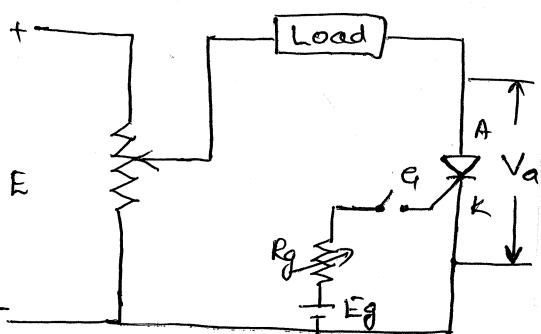
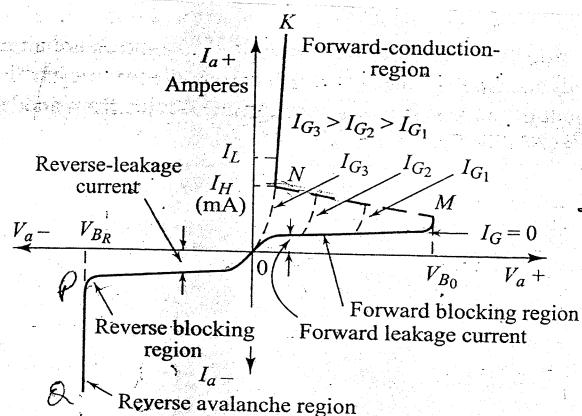


Fig @ Elementary Circuit



V_{B_0} = Forward breakover voltage; V_{B_R} = Reverse breakover voltage; I_G = Gate current; I_L = Latching current; and I_H = Holding current

Fig. V-I characteristics

* The V-I c/s of SCR is divided into three regions of operation.

- ① Reverse Blocking region;
- ② Forward blocking region.
- ③ Forward Conduction region.

1. Reverse Blocking Region:

- * When anode is made negative w.r.t cathode gate is kept open, thyristor becomes reverse biased.
- * In the reverse biased condition Junction J₁ & J₃ are reverse biased, J₂ is forward biased. ∴ only a small leakage current ($\approx 1 \text{ mA}$) flows.
- * If reverse voltage is increased & when it exceeds V_{BR} (reverse breakdown voltage), an avalanche will occur at J₁ & J₃ increasing the current sharply.
- * During reverse blocking mode, the gate signal should not be applied. If the V_G makes J₃ forward biased hence current starts flowing this adds to reverse leakage current.

2. Forward Blocking Region:

- * In this region, anode is made positive w.r.t cathode J₁ & J₃ will be forward biased & J₂ is reverse biased
- * Hence small Anode Current flows through the device is called as forward leakage current.
- * Region on of V-I C/S is known as the forward blocking region when the device does not conduct.

3. Forward Conduction Region:

S.C.R can be turned on in two ways.

- a) By keeping $V_{AK} > V_{BO}$ & $V_G = 0$ (Gate open)
 - b) By maintaining $V_{AK} < V_{BO}$ & by applying +V_G.
- ④ When anode to cathode voltage is increased with gate contact kept open (i.e. $V_G = 0$), at $V_{AK} = V_{BO}$, avalanche breakdown occurs at junction J₂. As a result very large amount of current starts flowing through the device & the device is said to be ON.

from the C/S Centre MN region shows the switching

(3)

of SCR from off state to ON state. NK shows sharp increase in current.

⑥ When a gate signal ($V_g > V_{Gt}$) is applied, the thyristor turns-on before V_{B0} is reached ($V_g < V_{Ak} < V_{B0}$).

Higher the gate current (I_g), lower the forward break-over voltage (V_{Ak})

From characteristics curve $V_{Ak} \leq V_{B0}$ & $I_g = 0$

for $I_g = 0$, $V_{Ak} < V_{B0}$

for $I_{g2} > I_{g1}$, $V_{Ak2} < V_{Ak1} < V_{B0}$

for $I_{g3} > I_{g2} > I_{g1}$, $V_{Ak3} < V_{Ak2} < V_{Ak1} < V_{B0}$

Latching Current: Minimum forward current that flows through the thyristor to keep it in forward conduction mode (ON state) at the time of triggering. $\therefore I_L > I_H$.

Holding Current: Minimum forward current that flows through the thyristor to keep it in forward conduction mode when forward current reduce below holding current thyristor turn off.

The holding current of the thyristor is in order of 8 to 10mA.

The forward voltage is maintained below V_{B0} & the thyristor is turned ON by applying a +ve voltage b/w gate & cathode this can be shown by dashed line.

shoew by dashed lines.

Problems:

- ① The SCR shown in figure has the latching Current of 20mA & is fired by the pulse with 50usec. Determine the SCR triggers or not.

Solu? $i(t) = \frac{V_S}{R} \left(1 - e^{-\frac{t}{R \cdot L}}\right)$

$$i(t) = \frac{V_S}{R} \left(1 - e^{-\frac{t \cdot R \cdot L}{L}}\right)$$

A Step voltage is applied to the RL load. when SCR

turn ON. the current flows through RL Circ.

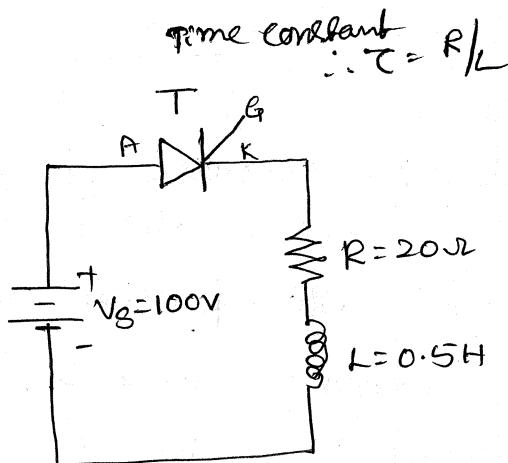
$$\therefore i(t) = \frac{100}{20} \left(1 - e^{-\frac{50 \times 10^6 \times 20}{0.5}}\right)$$

$$i(t) = 10\text{mA} \quad (\text{The current through the SCR})$$

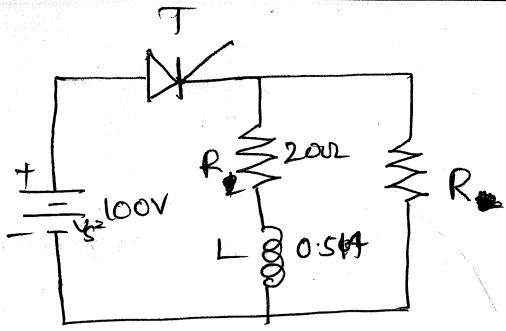
$\therefore i(t) < I_L$ for 50usec pulse width

Hence SCR will not be triggered.

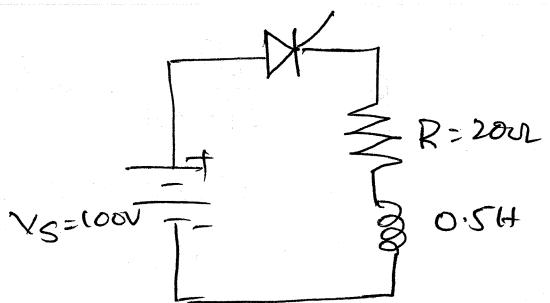
- ② The Thyristor Circuit shown below, the SCR has a latching Current of 50mA & is fired by a pulse width of 50usec. Show that without resistance (R), the thyristor will fail to remain on when firing pulse ends & then find the minimum value of R to ensure firing.



(4)



without R.

Given data

without R

$$V_S = 100$$

$$R = 20\Omega$$

$$L = 0.5H$$

$$I_L = 50mA$$

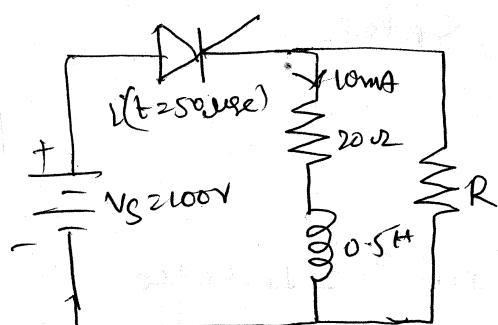
pulse width = 50ms

Soluⁿ $i(t) = \frac{V_S}{R} \left(1 - e^{-t/RL} \right)$

$$= \frac{100}{20} \left(1 - e^{-50 \times 10^{-6} \times \frac{20}{0.5}} \right) = 10mA$$

$i^o(t) < I(t)$ so it will not be triggered.

C. $i^o(t)$ less than the given latching current

To determine R.

If we neglect the voltage drop acr SCR field, V_S will appear across R.

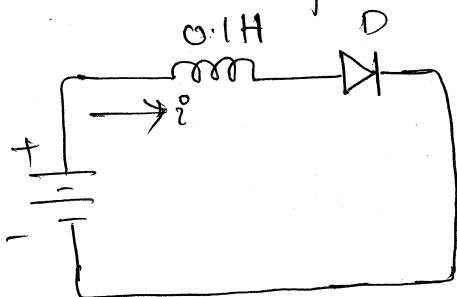
Hence

$$V_S = 4 \text{ mA} \cdot R.$$

$$R = \frac{100}{4 \text{ mA}} = 25 \text{ k}\Omega$$

Thus a maximum $R = 2.5 \text{ k}\Omega$ will ensure firing of the SCR.

- ③ If the Latching Current in the circuit is 4 mA, obtain the minimum width of the gating pulse required to properly turn-ON the SCR.



Soluⁿ

The Circuit Equations

$$V = L \cdot \frac{di}{dt}$$

$\therefore i = \text{Latching current}$, $t = \text{pulse width}$

$$dt = \frac{L}{V} di$$

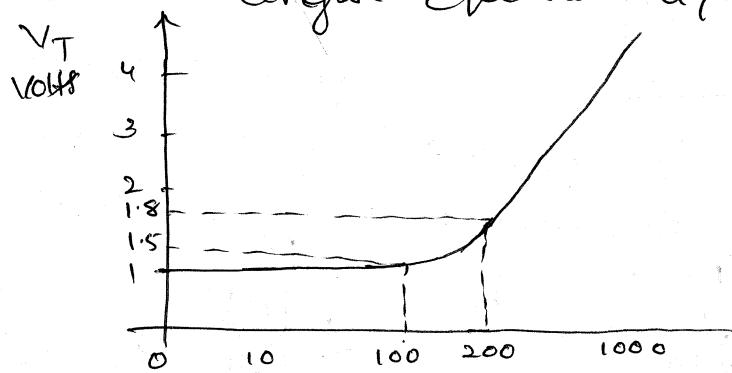
Integrating on both sides.

$$t = \frac{L}{V} i$$

$$t = t_{\min} = \frac{0.1}{100} \times 4 \times 10^{-3} = 4 \text{ microsec}$$

(5)

- ④ A typical V-I CLS for a thyristor in ON state is shown below. Complete the average power loss due to the rectangular current pulse of $I_{av} = \text{const}$ for conduction angles equal to $\alpha = 180^\circ$ by 360°



V-I CLS in ON state I_T in (amp)

Solu?

Let I_m be the current during conduction & zero otherwise

$$I_{av} = \frac{I_m \cdot \beta}{360} \quad \text{where } \beta = \text{Conduction angle.}$$

$$= 100 \times \frac{180}{360}$$

$$\text{Q1} \text{ for } \beta = 180^\circ \quad I_m = \frac{I_{av} \times 360}{\beta} = \frac{100 \times 360}{180} = 200 \text{ A}$$

From the fig Corresponding $V_T = 1.8V$

$$\text{Avg power loss } P_{avg} = 1.8 \times 200 \times \frac{180}{360} = 180 \text{ W.}$$

b) for $\beta = 360^\circ$

$I_m = I_{av} = 100 \text{ A}$, Corresponding $V_T = 1.5V$.

$$P_{avg} = V_T I_T = 1.5V \times 100 = 150 \text{ W.}$$

3. TWO TRANSISTOR MODEL OF SCR

The regenerative or latching action due to a +ve feedback can be demonstrated by using a two transistor model of thyristor.

A conventional SCR can be best visualised as two transistors, a PNP & NPN pair connected to form a regenerative feedback pair as shown in below fig.

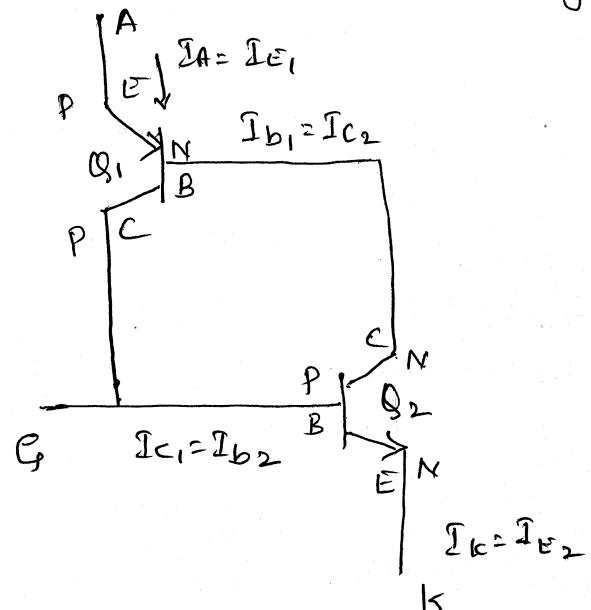
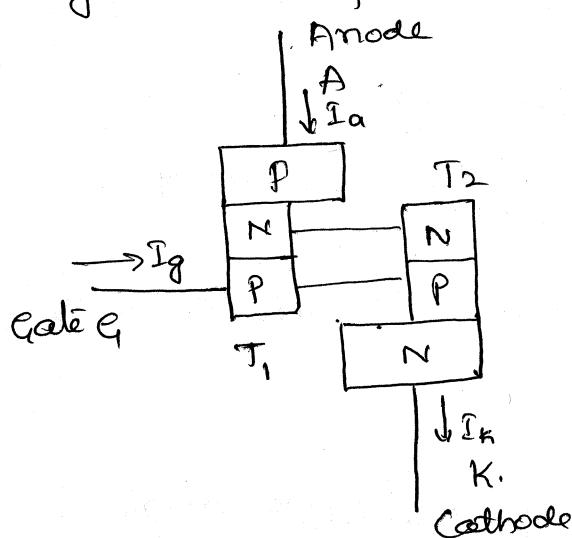


Fig a) Two transistor analogy of S.C.R.

The base of Q_1 is connected to collector of Q_2 . Similarly, base of Q_2 is connected to collector of Q_1 , these transistors forms Common base Configuration.

The Collector Current I_c of the thyristor is related to Emitter Current ΣE & the leakage current of the collector-base junction (i.e. I_{CBO}) $I_c = \alpha \Sigma E + I_{CBO}$ (1)

The Common base current gain is defined as $\alpha = \frac{I_c}{\Sigma E}$.

For transistor Q_1

$$I_{c1} = \alpha \Sigma E_1 + I_{CBO1} \quad \text{--- (2)}$$

(6)

From the fig. $I_{E_1} = I_A$.

See State eqn (2) in equation (2)

$$I_{C_1} = \alpha_1 I_A + I_{CB01} \quad \text{--- (3)}$$

where

$\alpha_1 = C_B$ Current gain of Q_1

$I_{CB0} = \text{Collector to base leakage current of } Q_1$

Similarly for transistor Q_2

$$I_{C_2} = \alpha_2 I_{E_2} + I_{CB02} \quad \text{--- (4)}$$

$$\therefore I_{E_2} = I_K$$

$$I_{C_2} = \alpha_2 I_K + I_{CB02} \quad \text{--- (5)}$$

where

$\alpha_2 = C_B$ Current gain of Q_2

$I_{CB02} = \text{Collector to base leakage current of } Q_2$

From the fig.

$$I_A = I_{C_1} + I_{C_2} \quad \text{--- (6)}$$

See State eqn (2) & (5) in (6)

$$I_A = \alpha_1 I_A + I_{CB01} + \alpha_2 I_K + I_{CB02}$$

$$\therefore I_K = I_A + I_q$$

$$I_A = \alpha_1 I_A + I_{CB01} + \alpha_2 I_A + \alpha_2 I_q + I_{CB02} \quad \text{---}$$

$$I_A - \alpha_1 I_A - \alpha_2 I_A = I_{CB01} + I_{CB02} + \alpha_2 I_q$$

$$I_A (1 - \alpha_1 - \alpha_2) = I_{CB01} + I_{CB02} + \alpha_2 I_q$$

$$I_A = \frac{I_{CB01} + I_{CB02} + \alpha_2 I_q}{(1 - \alpha_1 - \alpha_2)} \quad \text{--- (7)}$$

The current gain α_1 varies with the Emitter Current I_E . The current $I_A = I_E \frac{\alpha_1}{\alpha_2}$ varies with I_E as $I_A = I_D + I_Q$.

A typical variation of current gain α_1 with the Emitter Current I_E is shown below.

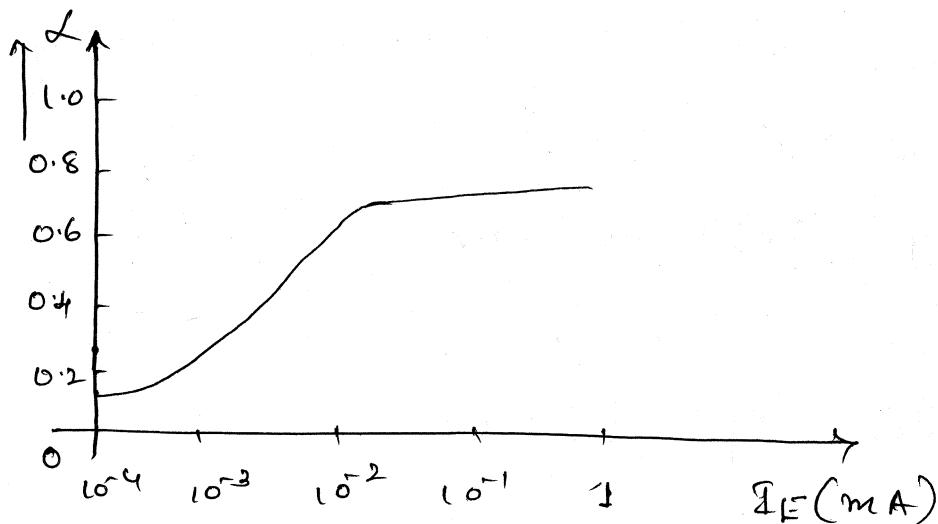


Fig. b) Typical variation of Current gain with Emitter Current.

If the gate current I_g is suddenly increased (say to 1 mA), this will immediately increase anode current I_A , which will further increase α_1 & α_2 .

α_2 depends on R_A & I_E .

The increase in the values of α_1 & α_2 would further increase I_A \therefore there is a regenerative feedback effect.

If $(\alpha_1 + \alpha_2)$ tends to be unity, the denominator goes to zero, resulting in a large value of anode current I_A & the transistor will turn ON with some gate current.

4. THYRISTOR TURN-ON METHODS

When Anode positive w.r.t. Cathode, a thyristor can be turn-on by one of the following methods

- ① Thermal or high temperature triggering.
- ② Light triggering.
- ③ High voltage triggering.
- ④ die/dt triggering
- ⑤ Gate triggering.

① Thermal or high temperature triggering:

If the temp* of thyristor is high, there will be increase in no of electron hole pairs, which increase the leakage current. This increase in current causes α_1 & α_2 to increases. Due to regenerative action ($\alpha_1 \alpha_2$) may tend to be ready & the thyristor may be turned ON.

This type of turn-on may cause thermal runaway & is normally avoided.

② Light triggering:

If light is allowed to strike the junctions of a thyristor, the electron-hole pairs will increase & the thyristor may be turned ON.

The light activated thyristor are turned-on by allowing light to strike the silicon wafers.

③ High Voltage Triggering:

If the forward Anode to Cathode voltage is greater than the forward breakdown voltage V_{BO} , significant leakage current will flow to initiate regenerative turn-on. This type of turn-on may be destructive and should be avoided.

④ $\frac{dv}{dt}$ Triggering: If the rate of rise of Anode-Cathode is high, the charging current of the capacitive junction may be sufficient enough to turn on the thyristor.

A high value of charging current may damage the thyristor & device must be protected against high $\frac{dv}{dt}$.

⑤ Gate Triggering: If a thyristor is forward biased the injection of gate current by applying the gate voltage between gate & Cathode turn on the thyristors.

As the gate current is increased, the forward blocking is decreased. $I_T \uparrow$

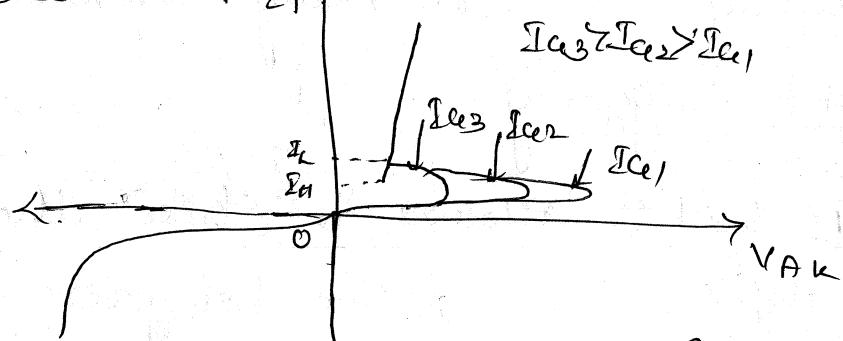


Fig. 4.7 Effect of gate current on forward blocking voltage.

5. DYNAMIC TURN-ON CHARACTERISTICS.

The transition from one state to another state does not take place instantaneously, it takes finite periods of time.

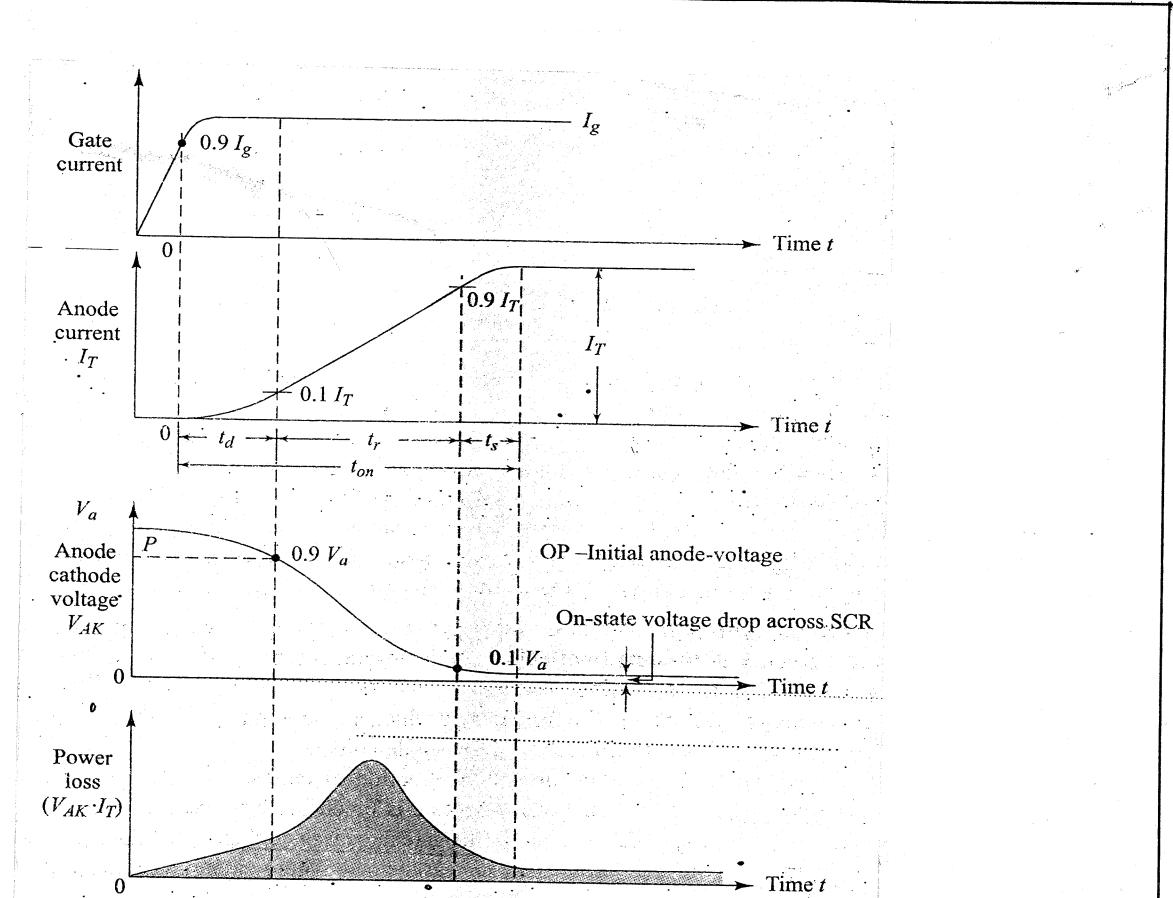


Fig. Waveforms during SCR turn-on

The turn-on time of SCR is subdivided into three distinct periods.

① Delay time ② Rise time ③ Spread time.

Delay time: This is the time between the instant at which the gate current reaches 90% of its final value & the instant at which the anode current reaches 10% of its final value.

It can also be defined as the time during which anode voltage falls from V_a to $0.9V_a$ where V_a is the initial value of the anode voltage.

Rise time: This is the time required for the anode current to rise from 10 to 90% of the final value.

It can also be defined as the time required for the forward blocking off-state voltage to fall from

0.9 to 0.1 of its initial value. OP (Initial anode voltage).

It is inversely proportional to the magnitude of gate current & its build up rate. Thus t_r can be minimized if high & steep current pulses are applied to the gate.

Spread Time: During the spread time (t_s) the Conduction spreads over the Complete Cross Section of the Thyristor

The spread time is the time required for the forward blocking voltage to fall from 0.1 to its value of its ON state voltage drop (1 to $1.5V$)

After the spread time, anode current attains steady state values & the voltage drop across SCR is equal to the on-state voltage drop of the order of 1 to $1.5V$.

Turn-on time (t_{on}) - This is the sum of the delay time rise time & spread time, typically of the order of 1 to 4 usec depends upon the anode circuit parameters & the gate signal waveforms

TURN OFF MECHANISM (Turn off characteristics)

Once the SCR starts conducting on appreciable forward current the gate has no control over it & the device can be brought back to the blocking state only by reducing the forward current to a level below that of the holding current. process of turn off is called Commutation.

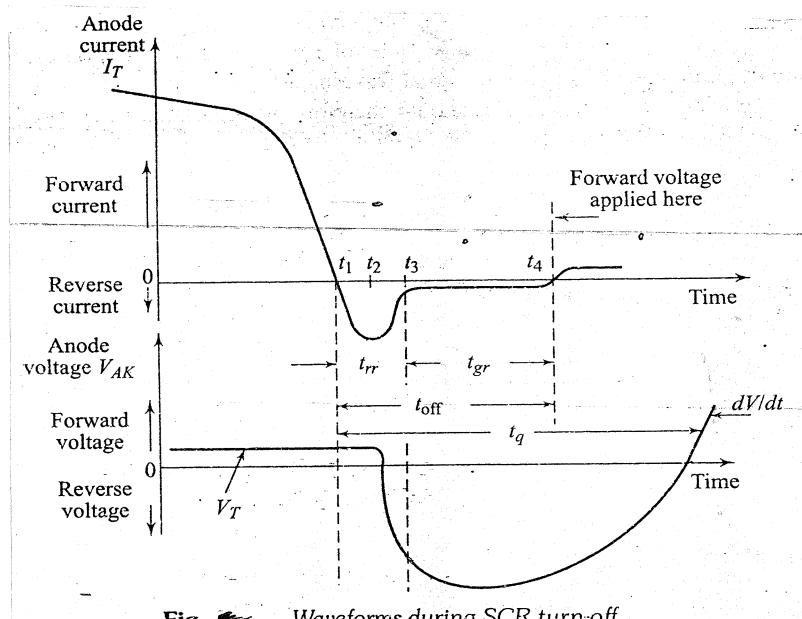


Fig. Waveforms during SCR turn-off

However if a forward voltage is immediately applied after reducing the anode current to zero it will not block the forward voltage & will start conducting again although it's not triggered gate pulse as the carriers (holes & electrons) in the p-n layers are still favourable for conduction. ∴ it is essential that the thyristor is reverse bias for a finite period after the anode current has reached zero.

The total turn-off time is divided into two time intervals.

- (a) Reverse recovery time (t_{rr})
- (b) Gate recovery time (t_{gr})

At instant t_1 , anode current becomes zero after t_1 , anode current builds up in the reverse direction. The reason for the reversal of anode current after t_1 is due to the presence of carriers stored in the 4 layers. The reverse recovery current becomes excess carriers from the end junctions J_1 & J_3 after the instant $t_1 < t_3$.

At instant t_2 when about 60% of the stored charges are removed from the outer 2 layers, carrier density across J_1 & J_3 begins to decrease & with this reverse recovery current also starts beginning but gradual thereafter. The fast decay of recovery current causes a reverse voltage across the device due to coil inductance.

At instant t_3 junctions J_1 & J_3 are able to block a reverse voltage, however the thyristor is not yet able to block a forward voltage because carriers called trapped carriers are still present at junction J_2 during interval t_3 to t_4 these carriers recombine.

Reverse Recovery time: Once anode current zero, the device starts to turn off but not immediately & it will take some time to turn off.

The time taken by the minority carriers present in PN junction to recombine with the opposite charges & to be neutralized. This time is called reverse recovery time.

Gate Recovery time (t_{gr}): The time taken by charges for the recombination when reverse voltage is maintained over the thyristor.

$$\therefore t_{off} = t_{nr} + t_{gr} \quad \therefore t_{off} = \text{turn off time.}$$

(FO)

GATE CHARACTERISTICS OF SCR

In a thyristor gate is connected to the cathode through PN junction & hence gate C/S of the device are similar to that of a diode.

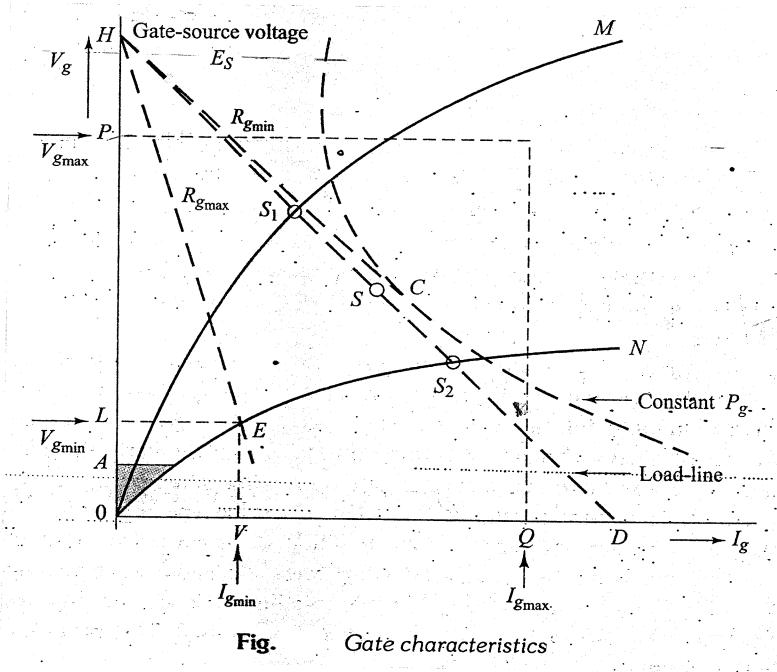


Fig. Gate characteristics

The design specification pertaining to gate C/S are usually provided by the manufacturers.

Here, positive gate to cathode voltage V_g & positive gate to cathode current I_g represent dc values.

All possible safe operating points for the gate are bounded by the low & high Current limits for the V-I C/S, maximum gate voltage & the hyperbola representing maximum gate power within these boundaries there are 3 regions of importance.

- (1) The first region OA lies near the origin defined by the maximum gate voltage that will not

trigger any device.

This value is obtained at the maximum rated junction temperature (usually 125°C). The gate must be operated in this region whenever forward bias is applied across the thyristor & triggering is not necessary. In other words, this region sets a limit on the maximum false signals that can be tolerated on the gate firing circuit.

(2) The second region is further defined by the minimum value of gate-voltage & current required to trigger all devices at the minimum firing points of all devices, that is it is a forbidden region for the firing circuit. ∴ a signal on this region may not always fire all devices or never fire any at all.

OL & OV are the minimum gate voltage & gate current limits respectively.

(3) The third region is the largest & shows the limits on the gate signal for reliable firing. Ordinarily a signal in the lower left part of this region is adequate for firing for applications where fast turn on is required a hard firing signal in the upper right part of the region may be needed.

In fig Curve ON & OM corresponds to the possible spread of the C/S for SCR's of the same rating

For best results, the operating point S, which may change from S_1 to S_2 must be as close as possible to the permissible Pg Curve & must be contained with in the →

maximum & minimum limits of gate voltage & gate current provides the necessary head drop for the device.

For selecting the operating point usually a load line of the gate source voltage $I_S = \frac{V_S}{R_S}$ drawn as HD.

The gradient of the load line HD ($= \frac{0H}{OD}$) will give the required gate source resistance. Rg. The maximum value of this source resistance is given by the line HE, where E = point of intersection of line indicating the minimum gate voltage & gate current. The minimum value of gate source source resistance is obtained by drawing a line HC tangential to Pg curve.

SCR turn-on time can be reduced by using gate current of higher magnitude.

Gate pulse width is usually taken as equal to or greater than SCR turn-on time (t_{on})

If T is the pulse width

$$T > t_{on}$$

with pulse firing, if the frequency of firing f is known, the peak instantaneous gate power dissipation P_{gmax} can be obtained as

$$P_{gmax} = V_g I_g = \frac{P_{gav}}{f \cdot T}$$

$$\therefore f = \frac{1}{T}, f = \text{freq of firing}$$

$T = \text{pulse width in sec.}$

$$\frac{P_{gav} \cdot T}{T_1} > P_{gav} \text{ or } P_{gav} \cdot T \cdot f > P_{gav}$$

$$\frac{P_{gav}}{f \cdot T} > P_{gm}$$

the limiting case

$$\frac{P_{gav}}{f \cdot T} = P_{gm}, \text{ or } f = \frac{P_{gav}}{T \cdot P_{gm}}$$

A duty cycle is defined as the ratio of pulse-on period to periodic time of pulse.

pulse-on period is T & periodic time is T_1

$$\therefore \text{Duty cycle } f = \frac{T}{T_1} = \frac{f \cdot T}{T_1}$$

$$\therefore \frac{P_{gav}}{f} \leq P_{gm}$$

$$\text{or } \frac{P_{gav}}{f} = P_{gm}$$

problems

① An S.C.R has a $V_g - I_g$ C/S given as $V_g = 1.5 + 8I_g$. In a certain application, the gate voltage consists of rectangular pulses of $12V$ & of duration of 5msec with duty cycle 0.2 .

a) Find the value of R_g series resistor in gate circuit to limit the peak power dissipation in the gate to $5W$.

b) Calculate average power dissipation in the gate.

Solu

a) During Conduction.

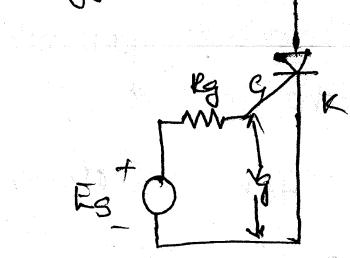
$$V_{gr} = R_g I_g + V_g = R_g I_g + 1.5 + 8I_g$$

$$12V = (R_g + 8)I_g + 1.5 \quad \text{--- (1)}$$

$$\text{peak power loss} = V_g \cdot I_g = 5$$

$$\therefore 5 = (1.5 + 8I_g) I_g \Rightarrow 8I_g^2 + 1.5I_g - 5 = 0$$

Trigger circuit



$$I_g = \frac{-1.5 \pm \sqrt{(1.5)^2 - 160}}{16} = 0.7 A.$$

Substitute I_g in in equation ①

$$12 = (R_g + 8) \cdot I_g + 1.5$$

$$I_g = 12 = (R_g + 8) 0.7 + 1.5$$

$$\boxed{R_g = 7 \Omega}$$

\Rightarrow Avg power loss = peak power loss * duty cycle

$$\boxed{P_{avg} = 5 \times 0.2 = 1 W.}$$

- ② If the $V_g - I_g$ characteristics of an S.C.R is assumed to be a straight line passing through the origin with a gradient of 3×10^3 calculate the required gate source resistance. Given $E_{gs} = 10V$ & allowable $P_g = 0.012W$

Sol:

$$P_g = 0.012$$

$$V_g \cdot I_g = 0.012 \quad \text{--- } ①$$

$$\therefore \text{gradient} = \frac{V_g}{I_g} = 3 \times 10^3$$

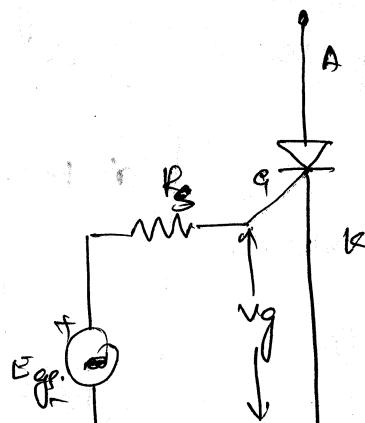
$$3 \times 10^3 I_g = V_g \quad \text{--- } ②$$

Substitute ② in ①

$$3 \times 10^3 I_g \cdot I_g = 0.012$$

$$I_g^2 = \frac{0.012}{3 \times 10^3} \Rightarrow I_g = 2 mA$$

$$\therefore V_g = \text{gradient} \cdot I_g = 3 \times 10^3 \times 2 mA = 6V$$



$$E_g = R_s I_g + v_g$$

$$10 = R_s \times 2 \times 10^{-3} + 6$$

$$R_s = 2 \text{ k}\Omega$$

- 3) For an SCR, the gate-cathode C.S is given by a straight line with a gradient of 16V/amp passing through the origin, the maximum turn on time is 4 msec & minimum gate current required to obtain this quick turn-on is 500mA. If the gate source voltage is 15 V.
- a) Calculate the resistance to be connected in series with SCR gate.

- b) Compute the gate power dissipation, given that the pulse width is equal to the turn-on time & that the average power dissipation is 0.3 W. Also compute the maximum triggering frequency that will be possible when pulse firing is used.

Sol:

Given,

$$I_{gm\min} = 500 \text{ mA}, 20.5 \text{ A}$$

$$\frac{v_g}{I_g} = 16 \text{ V/A},$$

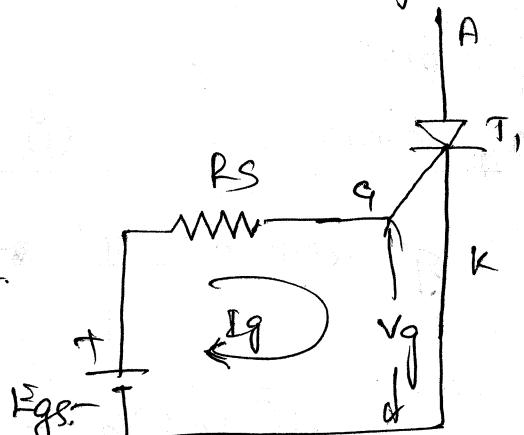
$$I_g$$

$$v_g = 16 \times 0.5 = 8 \text{ V}.$$

$$\text{or } R_s = \frac{v_g - v_g}{I_g}$$

$$= \frac{15 - 8}{0.5} = 14 \text{ k}\Omega$$

$$R_s = 14 \text{ k}\Omega$$



b) Power dissipation,

$$P_g = v_g \cdot I_g = 8 \times 0.5 = 4 \text{ W}.$$

$$P_{g\max} = \frac{P_{gav}}{f \cdot T_{on}} \Rightarrow 4 = \frac{0.3 \times 10^6}{f \times 4}$$

$$f = F = 19 \text{ kHz}$$

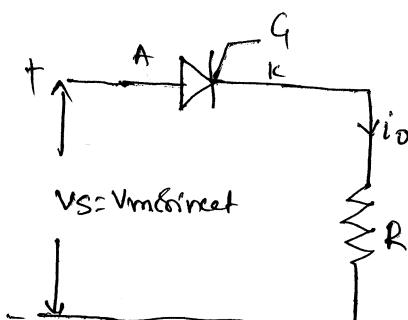
TURN-OFF METHODS

- * The process of turning off of SCR is called Commutation.
- * Commutation can be classified as two types.
 1. Natural Commutation.
 2. Forced Commutation.

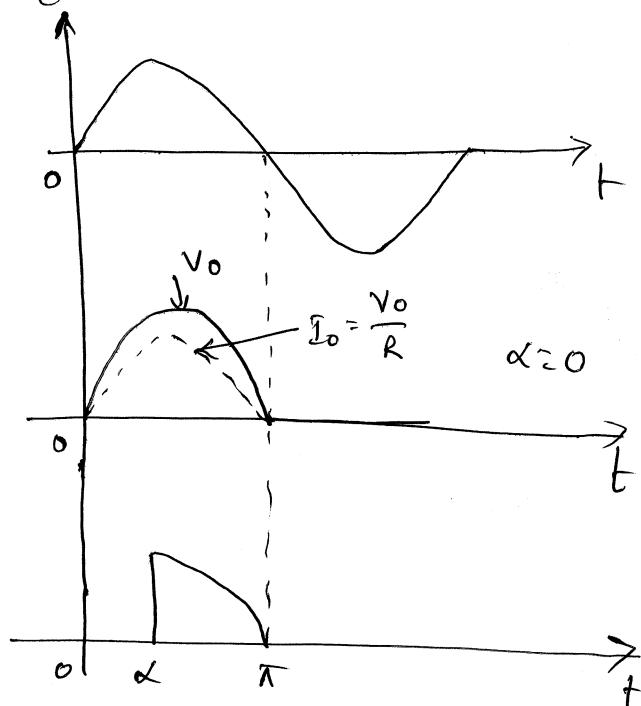
Natural Commutation or Line Commutation:

- * It is simplest & most widely used method of Commutation which make use of the alternating reversing nature of ac voltage.

When the reverse voltage is AC. During the half cycle Thyristor T_1 is forward biased & conducts then dpv voltage is appear across load. During -ve half cycle Thyristor T_1 is reverse biased & it does not conduct & is automatically turned off due to natural behaviour of the holding voltage.

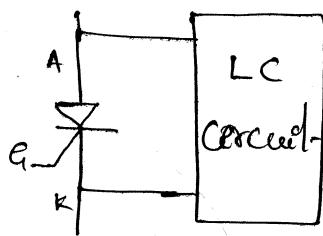


Applications: Used in AC voltage controller, Cyclo converters & phase controlled rectifier.



Forced Commutation:

External circuitry used to turn off the SCR is called forced Commutation. Commonly used Commutation circuit is normally LC circuit.



classifications of forced Commutation.

- ① Class A - Self Commutation by resonating load.
- ② Class B - Self Commutation by parallel LC circuit.
- ③ Class C - Complementary Commutation.
- ④ Class D - Auxiliary voltage Commutation (Impulse Commutation)
- ⑤ Class E - External pulse Commutation.
- ⑥ Class F - AC line Commutation.

Class A - Self Commutation by resonating load.

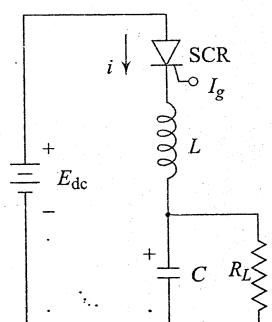


Fig. 1.1 Load in parallel with capacitor

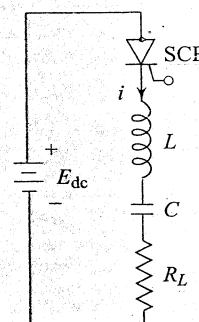


Fig. 1.2 Load in series with capacitor

Fig. 1 Class A commutation circuit

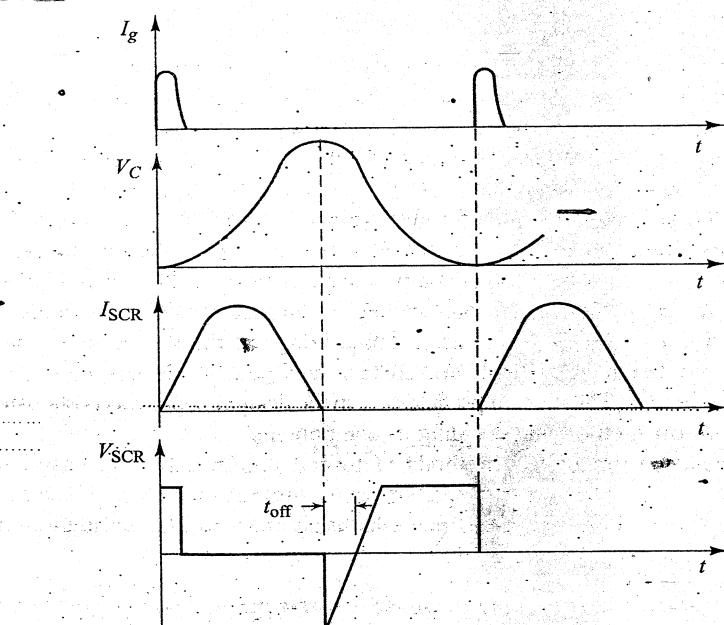
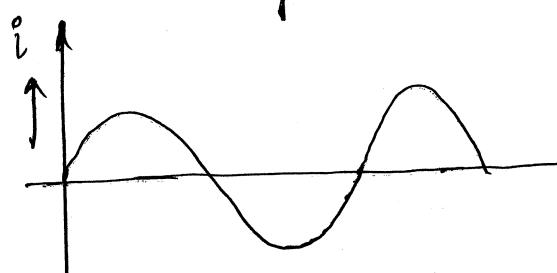


Fig. 2 Voltages and currents in Class A (load is parallel with capacitor).

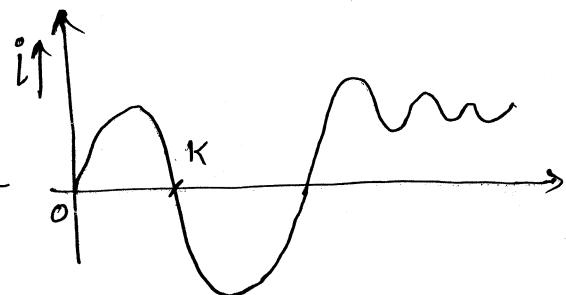
This is also known as resonant Commutation. In this type of Commutation Circuit using L-C Component in Series with Load fig 1 & Load R_L is in parallel with Capacitor in fig 1.1 & R_L is in series with the L-C circuit in fig 1.2.

In the process of Commutation, the forward current passing through the device is reduced to less than the level of holding current of the device. Hence this method is also known as Current Commutation method. The waveforms of thyristor voltage, current & Capacitor voltage are shown on above fig. 2.

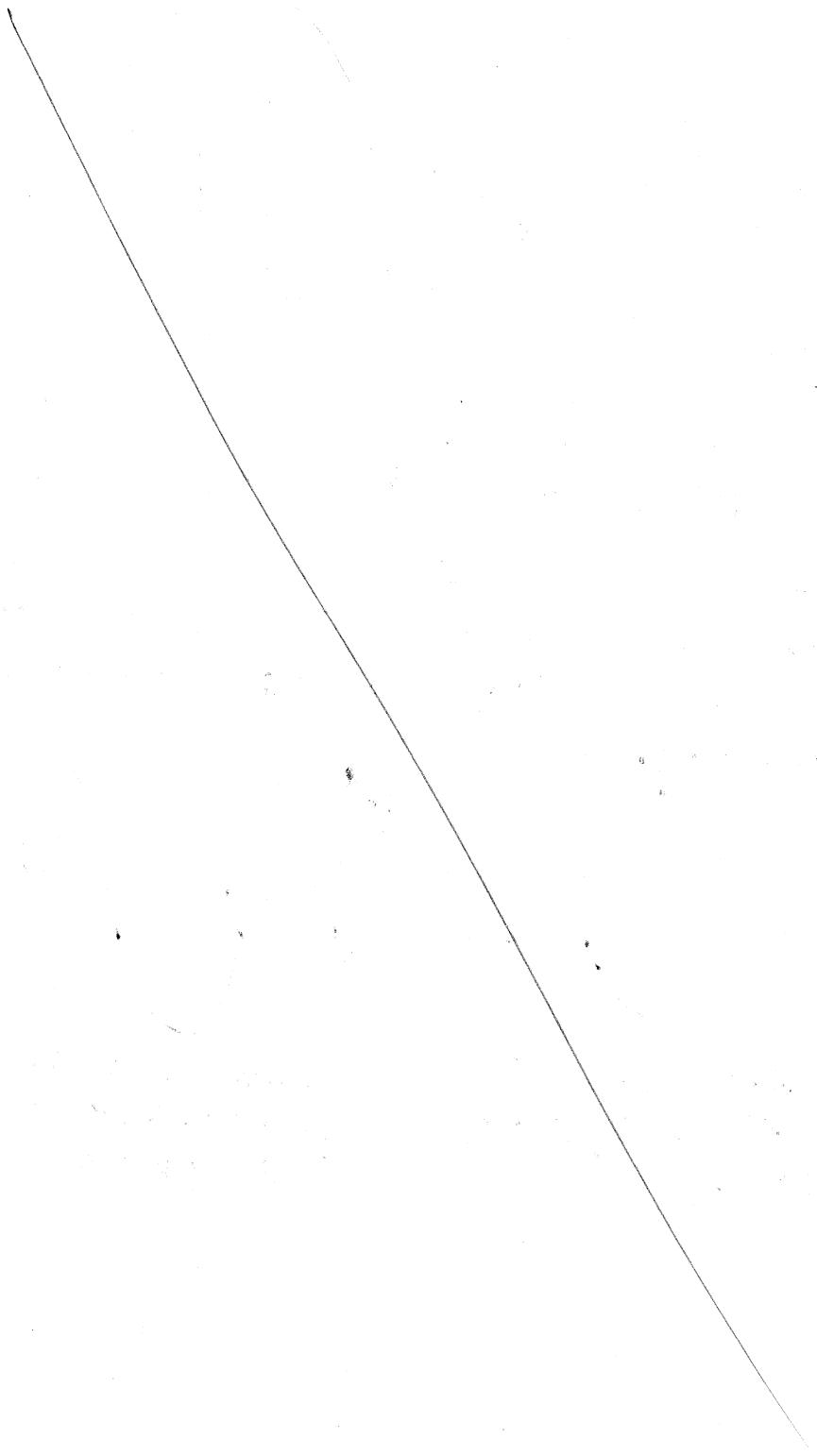
The load resistance R_L & the Commutating Components are so selected that their combination forms an underdamped circuit & is excited by a d.c. source, a current waveform shown in below fig.



waveform of the current produced when capacitor in series,



waveform of the current produced when capacitor in parallel



Class B - Self Commutation by an LC-circuit.

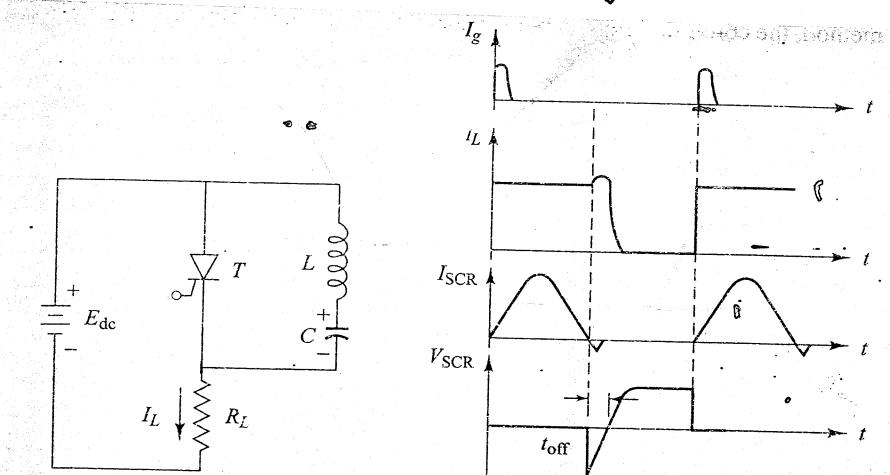


Fig. 3.1 Class B commutation circuit

Fig. 3.2 Associated waveforms

* In class B Commutation LC resonating Circuit across SCR is not in Series with load. Commutating Current & waveforms shown in above fig 3.1 & fig 3.2

* Initially as soon as supply voltage E_{dc} is applied the capacitor C starts charging upper plate positive & lower plate negative.

* when Thyristor T is triggered current flows in two directions.

- The load current I_L flows through the path $E_{dc} + T + R_L + E_{dc}$.

b) Commutating Current I_c .

The moment thyristor T is turned on, capacitor C starts discharging through the path $C + L + T + C$ when the capacitor completely discharged, it starts getting charged with reverse polarity. Due to the reverse voltage a Commutating Current I_c starts flowing which oppose the load current I_L . when the Commutating current I_c is greater than the load current I_L the Thyristor (T) becomes turned off. when the Thyristor T is turned off capacitor C again starts getting charged to its

original polarity through L & load. when C fully charged thyristor will be ON again

In class B Commutation method, the Commutating component does not carry the load current, SCR turns off automatically after it has been turned on.

Design Considerations:

equation for LC circuits are

$$L \frac{di}{dt} + \frac{1}{C} \int i^2 dt = 0$$

$$L \frac{d^2 i}{dt^2} + \frac{1}{C} i(t) = 0$$

Taking Laplace transform of the above equation

$$\left[s^2 L + \frac{1}{C} \right] I(s) = 0$$

$$\therefore i(t) = E_{ac} \sqrt{\frac{C}{L}} \sin \omega_0 t$$

where

$$\omega_0 = \sqrt{\frac{1}{LC}}$$

\therefore peak Commutation Current is

$$I_c(\text{peak}) = E_{ac} \sqrt{\frac{C}{L}}$$

In this class B Commutation method, the peak discharge current of the capacitor is assumed to be twice the load current I_L & time for which the SCR is reverse biased is approximately equal to one-quarter period of the commutating circuit.

$$I_c(\text{peak}) = 2 I_L = E_{ac} \sqrt{\frac{C}{L}}$$

$$\therefore t_{off} = \frac{\pi}{2} \sqrt{LC}$$

7. Gate Trigger Circuits:

An S.C.R can be switched from off state to ON state in several ways. There are.

1. forward voltage triggering.

2. $\frac{d\theta}{dt}$ triggering

3. Temp^x triggering

4. Light triggering.

5. Gate triggering.

The instant of turning on the S.C.R can't be controlled by the first 3 methods listed above. ∴ Gate triggering is the most common method of turning on the SCR because this method lends itself accurately for turning on the SCR at the desired instant of time.

1) R Triggering. ($\alpha = 90^\circ$)

* α = Fixing angle

$$\alpha + \beta = 180^\circ$$

2) R C Triggering ($\alpha = 180^\circ$)

a) R C Triggering using Half wave Rectifier

b)  Fall wave Rectifier

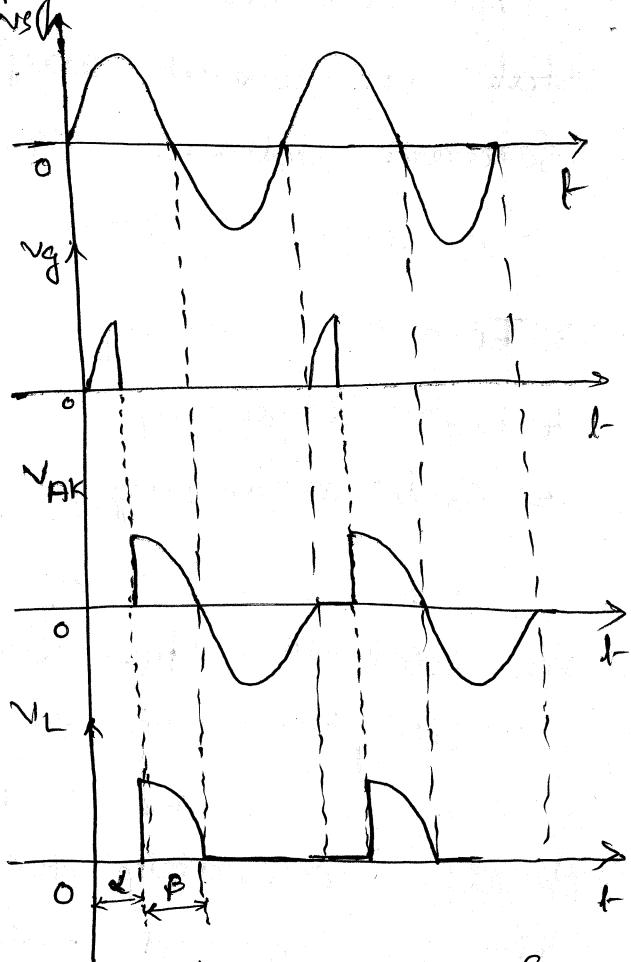
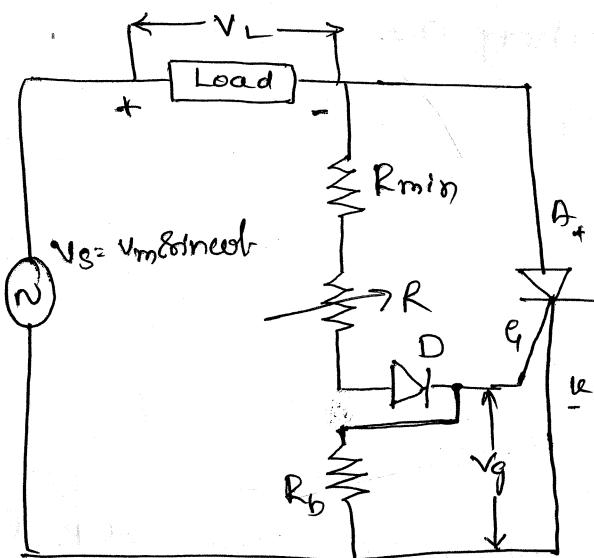
3) UJT Triggering. ($\alpha = 180^\circ$)

4) Digital Triggering ($\alpha = 180^\circ$)

1. Resistance Triggering.

It is a simple method for varying the trigger angle in the load. Instead of using a gate pulse to trigger the S.C.R, the gate current is supplied

by an A.C. source of voltage v_s through Resistor R & Diode, shown in below fig.



R is the variable resistor.
 R_b is the stabilizing resistor
 R_{min} is the current limiting resistor.

when $R=0$ (i.e minimum),

Gate current may flow from source through load, R , D & gate to cathode. This current should not exceed maximum permissible gate current I_{gm} .

$$\frac{V_m}{R_{min}} \leq I_{gm} \text{ or } R_{min} \geq \frac{V_m}{I_{gm}}$$

V_m = maximum value of source voltage.

Resistance R_b should have such a value that maximum voltage drop across it does not exceed maximum permissible gate voltage (V_{gm}). This can happen only when $R=0$.

$$\frac{V_m}{R_{min} + R_b} \leq V_{gm}$$

$$\therefore R_b \leq \frac{(R + R_{min}) V_{gm}}{V_m - V_{gm}}$$

As the resistance R_{min} & R large, gate-trigger current draws a small current. Diode D allows the flow of current during the half cycle only. i.e. gate voltage V_g is half wave dc pulse. The amplitude of this dc pulse can be controlled by varying R .

The potentiometer R_2 determines the gate voltage amplitude. When R is large, current is small & voltage across R_b i.e. $V_g = i R_b$ is also small. As V_{gp} (peak of gate voltage) is less than V_{gt} (Gate trigger voltage), SCR will not turn ON. Load voltage $V_o = 0$, $i_o = 0$. & Supply voltage V_s appears across S.C.R.

Trigger Circuit of Resistance only: As soon as V_g becomes equal to V_{gt} for the first time S.C.R is turned on.

The resistance triggering can't give firing angle beyond 90° .

A relationship between peak gate voltage V_{gp} & gate trigger V_{gt} may be expressed as follows.

$$V_{GP} \cdot \sin \alpha = V_{GT}$$

$$\alpha = \sin^{-1} \left(\frac{V_{GT}}{V_{GP}} \right)$$

$$\text{Since } V_{GP} = \frac{V_m \cdot R}{R_{min} + R + R_b}$$

$$\alpha = \sin^{-1} \left[\frac{V_{GT} (R_{min} + R + R_b)}{V_m \cdot R} \right]$$

V_{GT} , R_{min} , R_b & V_m are fixed & α directly proportional to R .

The thyristor will trigger when the instantaneous anode voltage

$$e_s = I_{G(min)} (R + R_{min}) + V_d + V_{G(min)}$$

where

$I_{G(min)}$ = min^m gate current to trigger thyristor

V_d = voltage drop at diode

$V_{G(min)}$ = gate voltage to trigger the thyristor

problems

- 1) The circuit in fig. uses an SCR with $I_{G(min)} = 0.1mA$ & $V_{G(min)} = 0.5V$. The diode is silicon & peak amplitude of v_p is $22V$. Determine the trigger angle α for $R = 100k\Omega$, $R_{min} = 10k\Omega$.

Soln.

First find instantaneous voltage e_s .

$$e_s = I_g (R + R_{min}) + V_D + V_g$$

$$= 0.1 \text{ mA} (110 \text{ k}\Omega) + 0.7 + 0.5 \text{ V} = 12.2 \text{ V}$$

e_s is the sine wave

$$e_s = V_m \sin \omega t$$

$$e_s = V_m \sin \alpha$$

$$\alpha = \sin^{-1} \left(\frac{e_s}{V_m} \right)$$

$$= \sin^{-1} \left(\frac{12.2}{24} \right)$$

$$\boxed{\alpha = 30.6^\circ}$$

- 2) For the thyristor on R firing circuit. The gate voltage required to trigger $V_{gb} = 0.6 \text{ V}$, & the corresponding gate current is $I_{ge} = 250 \mu\text{A}$. The diode used is of silicon material & the Lp voltage is $V = 100 \text{ V}_{\text{dc}}$. Find the firing angle α at which the thyristor will turn on if $R_{min} = 0 \text{ k}\Omega$

$$R = 220 \text{ k}\Omega.$$

Soh

$$e_s = I_g (R + R_{min}) + V_D + V_g$$

$$= 250 \times 10^6 (220 \times 10^3) + 0.7 + 0.6$$

$$\underline{\underline{e_s = -58.8 \text{ V}}}$$

The Supply voltage $V = 100$ (since $\phi = 0^\circ$)

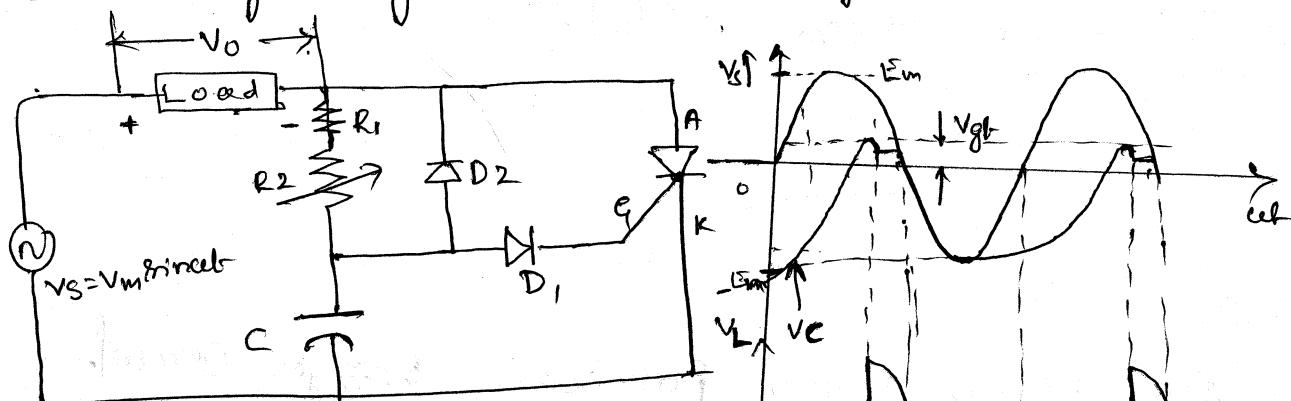
$$\alpha = \sin^{-1} \left(\frac{es}{Vm} \right)$$

$$= \sin^{-1} \left(\frac{58.8}{100} \right)$$

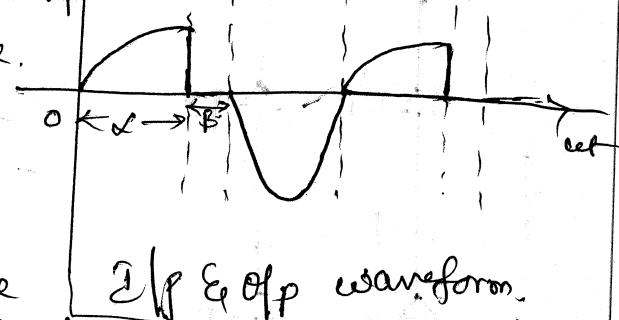
$$\boxed{\alpha = 36.01^\circ}$$

R C. Firing Circuits.

a) R.C firing using Half wave trigger circuit



RC - half wave firing



On & Off waveform.

During +ve half cycle of up V_{gt} & capacitor charges to the peak apply voltage through diode D_1 with lower plate +ve ckt to upper plate ($\frac{+}{-}$). The diode D_1 is provided in order to pass R_2 during each +ve half cycle of the supply so the capacitor charges quickly to the negative. peak value of the Supply vgt V_m .

When the capacitor charging voltage becomes equal to $V_{gt} + V_d$, the SCR turns ON.

The value of RC for zero off voltage

$$R \cdot C \approx \frac{1.3 T}{2} \quad \therefore T = \frac{1}{f}$$

The maximum value of R_2 is determined by

$$V_S > I_{gt} \cdot R_2 + V_C$$

$$V_S \approx I_{gt} \cdot R_2 + V_{gt} + V_d$$

$$R_2 = \frac{V_S - V_{gt} - V_d}{I_{gt}}$$

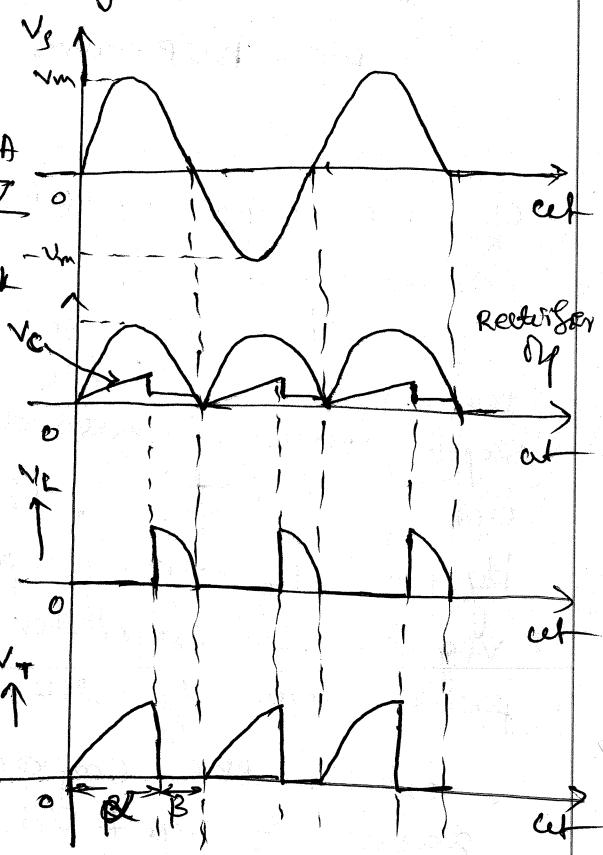
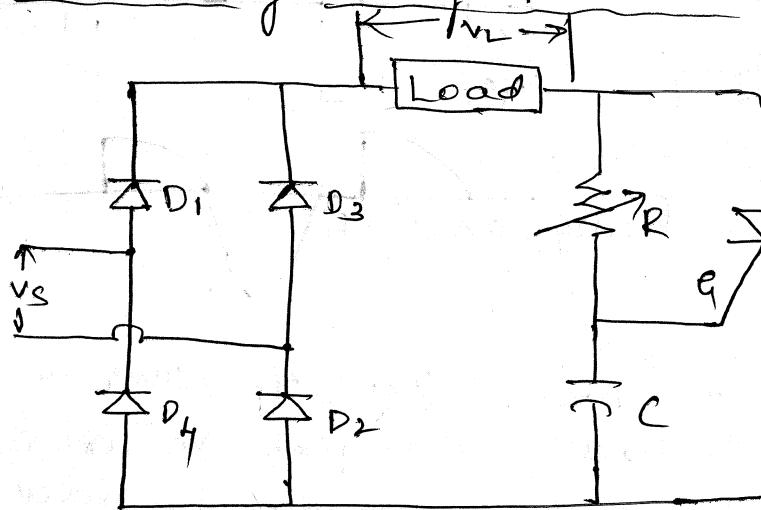
V_d = Vgt drop across diode

V_{gt} = minm gate turn on voltage

I_{gt} = Gate turn on current

By varying R_2 the firing angle can be varied from 0° to 180° .

R.C Firing Using Full wave trigger circuit.



In R.C Half wave triggering cat the power delivered to the load ex only during the half cycle. This limitation can be overcome by using fullwave R.C triggering circuit.

AC v/p angular (ωs) is converted into pulsating DC by fullwave bridge rectifier cat. This allows the SCR to be triggered on for both half cycle of the AC v/p voltage, which doubles the power delivered to the load.

When capacitor charges to a voltage equal to V_{gt} , SCR trigger & rectified voltage, V_{dc} appears

(20)

across load. The value of R_C can be obtained from the following relation

$$R_C \geq \frac{50T}{2}$$

$$R = R_2$$

$\therefore R_2$ can be calculated as,

$$V_S = I_{gt} R + V_C$$

$$R_2 = \frac{V_S - V_C}{I_{gt}}$$

Formulas

$$1) V_{BO} = V_m \sin \alpha$$

$$V_m = \sqrt{2} V_{rms}$$

$$2) \alpha = 810^{-1} \left(\frac{V_{BO}}{V_m} \right)$$

$$V_{BO} = V_S$$

$$3) \text{Delay angle or Firing angle}$$

$$\alpha = 180^\circ - \beta$$

$$4) \text{Conduction angle}$$

$$\beta = 180^\circ - \lambda$$

Problems

- ① A thyristor has the forward breakdown voltage of 175V when the gate pulse of 2mA is made to flow. Find the delay angle & conduction angle if a sine wave of 350V peak is applied.

Given data

$$V_{BO} = V_S = 175V$$

$$I_g = 2mA$$

$$V_m = 350V$$

$$\alpha = 90^\circ$$

$$\beta = 90^\circ$$

Solⁿ

$$V_S = V_m \sin \alpha$$

$$\alpha = \sin^{-1} \left(\frac{V_S}{V_m} \right)$$

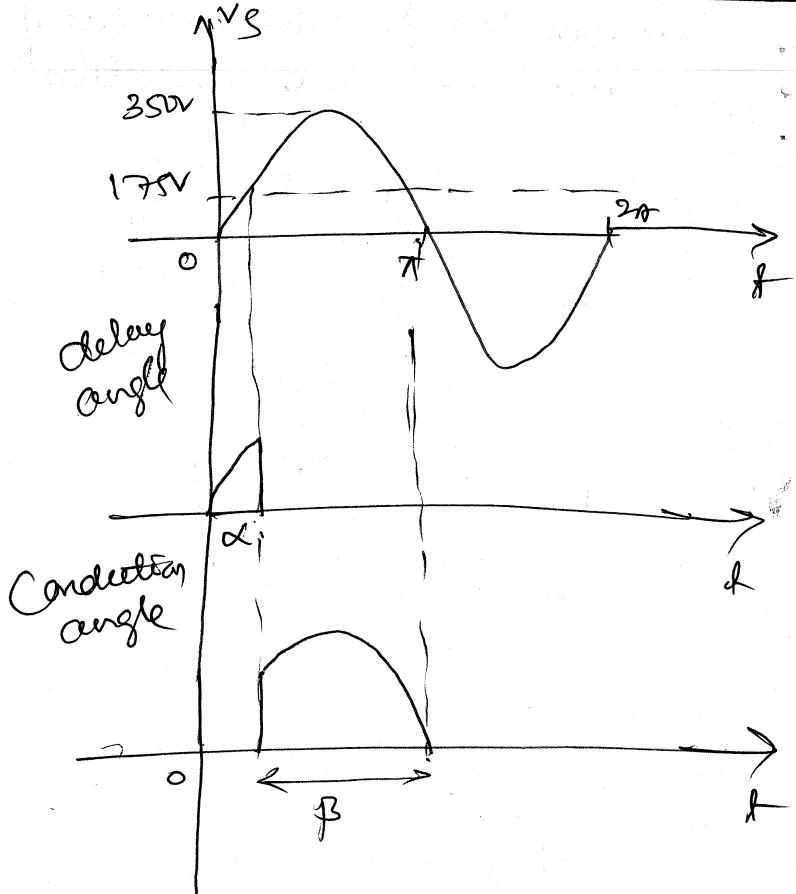
$$\alpha = \sin^{-1} \left(\frac{175}{350} \right)$$

$$\boxed{\alpha = 30^\circ}$$

$$\beta = 180 - \alpha$$

$$\beta = 180 - 30^\circ$$

$$\boxed{\beta = 150^\circ}$$



Note:

- $\therefore \alpha + \beta = 180^\circ$
- $180^\circ \cancel{=} 180^\circ$

Unijunction Transistor (UJT)

UJT stands for Unijunction Transistor made up of n-type silicon material to which p-type emitter is embedded.

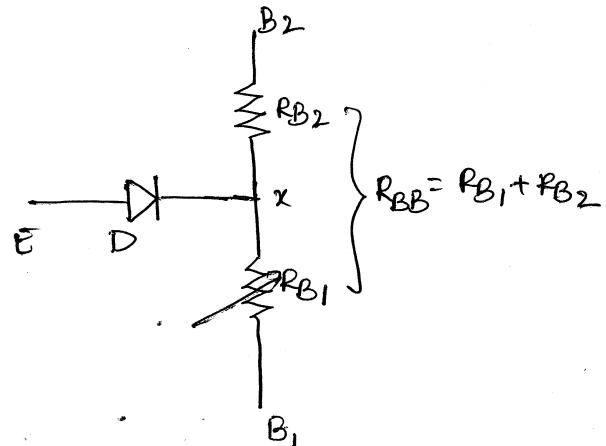
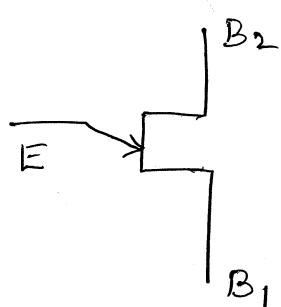
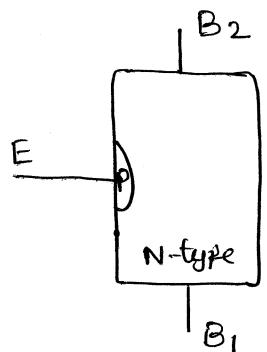


Fig @ Construction

Fig @ Symbol

Fig @ Equivalent Circuit

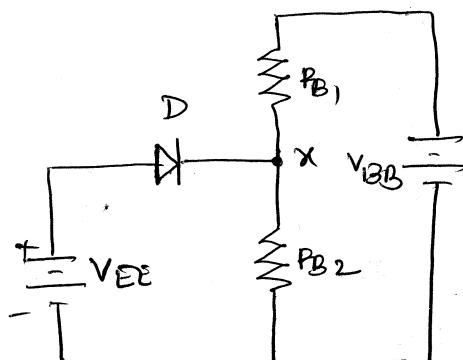
- * It has three terminal Emitter (E), Base 1 (B₁) & Base 2 (B₂)
- * R_{B1} & R_{B2} are the two external resistance present between bases w.r.t to point X.
- * When voltage V_{BB} is applied across the bases the potential of point X w.r.t B₁ is given by.

$$V_X = \frac{V_{BB} R_{B1}}{R_{B1} + R_{B2}} = \frac{R_{B1}}{R_{BB}} \cdot V_{BB}$$

$$V_X = \eta \cdot V_{BB}$$

where η = intrinsic stand off ratio.

$$\eta = \frac{R_{B1}}{R_{B1} + R_{B2}} = \frac{R_{B1}}{R_{BB}}$$

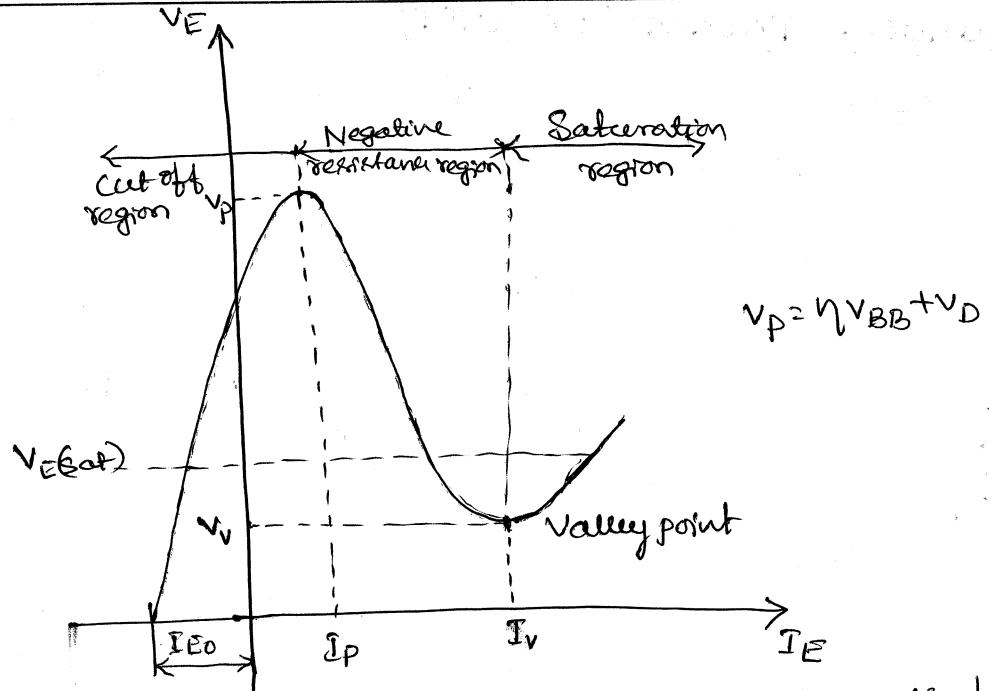


Circuit diagram.

Typical value of η is 0.51 to 0.82.

R_{BB} has value on the range 5-10 kΩ.

The characteristics of UJT can be divided into three regions.



Cut off region: when the Emitter voltage V_E is less than V_p P-n junction is reverse biased. A small amount of reverse saturation current I_{EO} flows through the device.

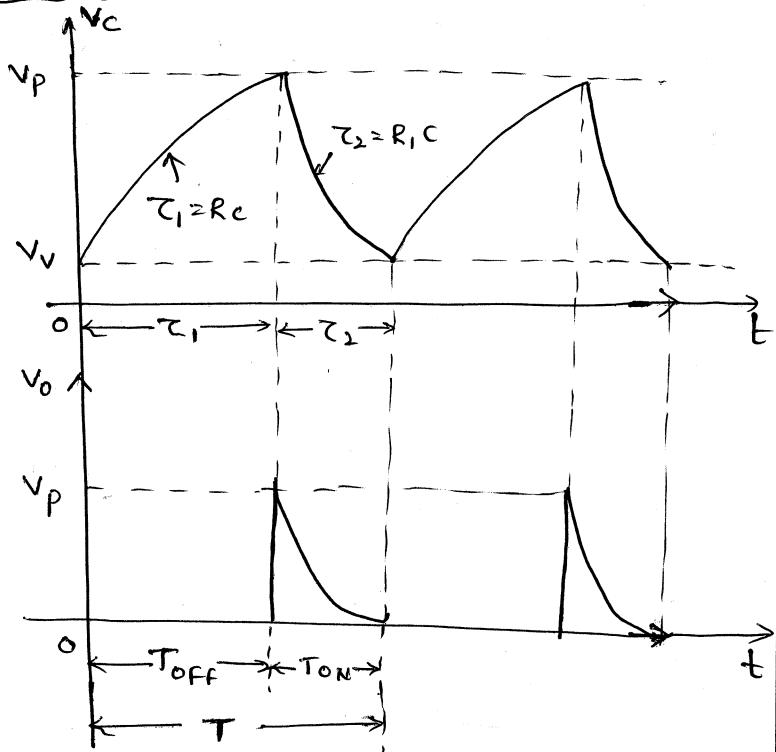
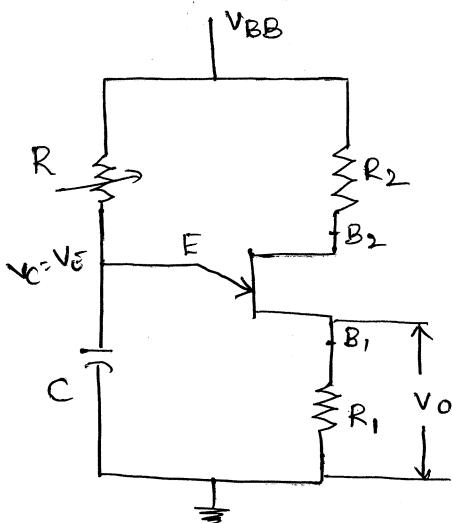
Negative Resistance region: when the Emitter voltage V_E becomes equal to V_p (peak voltage), the P-n junction becomes forward biased & I_E start flowing the voltage across the device decreases as the current increases. Hence the current through the device increases. This region is called negative resistance region. This decrease the resistance R_B , till region continues till Valley point.

Saturation Region:

Further increase in the I_E beyond the Valley point current I_v drives the device in the Saturation region. The voltage corresponding to the Valley point is called Valley Voltage (V_v).

The negative resistance region b/w peak & Valley point gives us the switching characteristics for use in SCR triggering circuit.

UJT Relaxation Oscillator:



* When DC Supply V_{BB} is applied, Capacitor C begins charging through resistor R exponentially towards V_{BB} during this charging Emitter contact of UJT is an open circuit.

* The Control voltage or Capacitor voltage $V_C = V_E$ is given by $V_C = V_E = V_{BB} \left(1 - e^{-t/R_C}\right)$

Charging time Constant is given by $\tau_1 = R_C$

* when this $V_E = V_C$ reaches the peak point $V_p = \eta V_{BB} + V_D$, the UJT turns ON & capacitor C will discharge through R_1 . Discharging time Constant is given by

$$\tau_2 = R_1 C$$

τ_2 is smaller than τ_1

* when discharging voltage drops to Valley point V_V , UJT turns off & charging cycle is repeated.

* Charging & discharging of capacitor repeats for time period T & is given by

$$T = \frac{1}{f} = R C \ln \left(\frac{1}{1-\eta} \right)$$

\therefore the values of n lies b/w 0.51 to 0.82

$R_{2\text{ss}}$ limited to a value b/w 3 k Ω to 3 M Ω

* $R_{2\text{ss}}$ used for thermal stability of V_p the value of R_2 can be calculated by using formula.

$$R_2 = \frac{10^4}{n V_{BB}}$$

* The maximum Value of R is determined by

$$R_{\max} = \frac{V_{BB} - V_p}{I_p} = \frac{V_{BB} - (n V_{BB} + V_D)}{I_p}$$

* Minimum Value of R is given by

$$R_{\min} = \frac{V_{BB} - V_V}{I_V}$$

* R_1 Can be calculated as,

$$R_1 = \frac{V_{BB}}{\text{Leakage Current}} - R_2 - R_{B1} - R_{B2} \quad \text{or}$$

$$\tau_2 = R_1 C$$

$$R_1 = \frac{\tau_2}{C}$$

$$\text{To show } T = RC \ln\left(\frac{1}{1-n}\right)$$

$$V_E = V_C = V_{BB} \left(1 - e^{-t/RC}\right)$$

when Capacitor charges to peak value.

$$V_C = V_p \quad R = R \quad (\text{charge through } R)$$

$$\therefore V_p = V_{BB} \left(1 - e^{-t/RC}\right) \quad \text{--- ①}$$

$$\text{W.K.T peak voltage } V_p = n V_{BB} + V_D \quad \text{--- ②}$$

Equate ① & ②

$$n V_{BB} + V_D = V_{BB} \left(1 - e^{-t/RC}\right)$$

$$n V_{BB} = V_{BB} - V_{BB} \left(e^{-t/RC}\right)$$

Q3

$$n \cdot v_{BB} = v_{BB} (1 - e^{-t/RC})$$

$$e^{-t/RC} = 1 - n$$

taking natural log on both sides.

$$\frac{1}{e^{-t/RC}} = \frac{1}{1-n}$$

$$e^{+t/RC} = \frac{1}{1-n}$$

$$t/RC = \ln\left(\frac{1}{1-n}\right)$$

$$t = RC \ln\left(\frac{1}{1-n}\right)$$

when $t = T, T = RC \ln\left(\frac{1}{1-n}\right)$

frequency of oscillation is given by $f = \frac{1}{T}$

$$f = \frac{1}{T} = \frac{1}{RC \ln(1/n)}$$

SYNCHRONIZED UJT FIRING (TRIGGERING) or (Ramp Triggering)

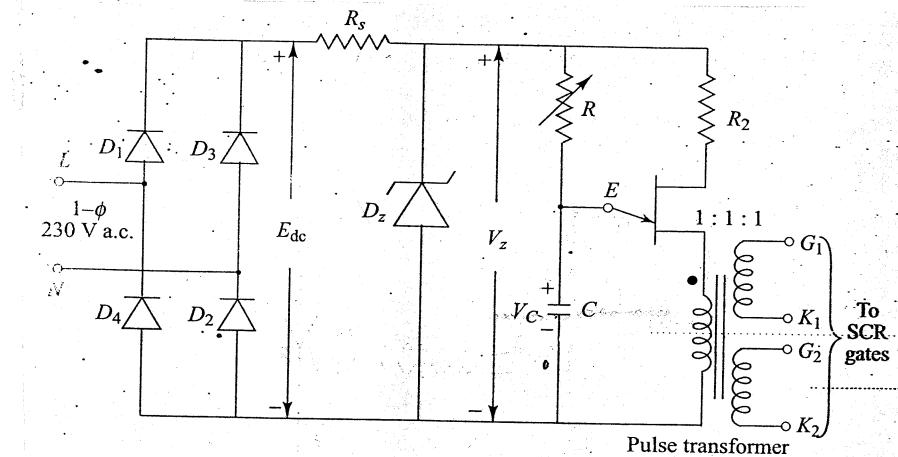


Fig. Synchronized UJT trigger-circuit

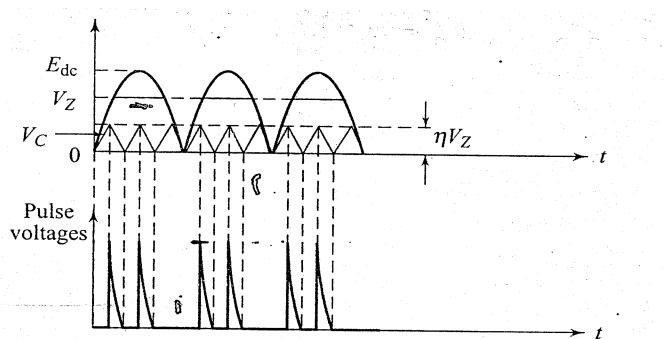


Fig. Generation of output pulses

- * Synchronized UJT triggering & its waveforms shown in above fig.
- * The Diode $D_1 - D_4$ rectifies AC to DC
- * Resistor R_s leaves V_{dc} to a suitable value for the Zener diode & UJT
- * Zener diode D_z is used to clip the rectified voltage to a fixed voltage V_z hence Zener diode provides stabilization than $+ve$ voltage applied to charging current R_C
- * Capacitor C charges through R until it reaches the UJT trigger voltage V_p .
- * The UJT then turns ON & C discharges through UJT

Emitter. during discharging p-n-p-n UJT provides pulses & passes through pulse transformer.

- * At the Secondary of pulse Transformer Triggering pulses are appear to turn on the SCR.
 - * Rate of rise of Capacitor voltage can be controlled by varying R. It can be controlled upto 180° . This is called ramp control, open loop control.

Problems:

- Problems:

① If $R_E = 1\text{k}\Omega$, & $I_V = 5\text{mA}$, $V_V = 2\text{V}$, determine the value of V_{EE} which will cause the VJT to turn off.

Soln. At valley point $V_E = V_V = 2V$,

$$I_E = I_V = 5mA$$

$$V_{EE} = I_E R_E + V_E = 5mA \times 1k\Omega + 2V = 7V$$

- ② Design the UJT relaxation oscillator using UJT2N264
 for triggering an SCR. The UJT has the following characteristics:
 $n = 0.7$, $I_p = 50\text{mA}$, $V_v = 2\text{V}$, $I_V = 6\text{mA}$, $V_{BB} = 20\text{V}$, $R_{BB} = 7\text{k}\Omega$,
 $I_{EO} = 2\text{mA}$. Also determine the limits for the op frequency
 of the oscillator.

Soln Let C = 0.1 eff

$$R_{max} = \frac{V_{BB} - V_p}{I_p} = \frac{V_{BB} - (n V_{BB})}{I_p} = \frac{20 - (0.7 \times 20)}{50 \mu A} = 120 \text{ k}\Omega$$

$$R_{on} = \frac{V_{BB} - V_v}{I_v} = \frac{20V - 2V}{6mA} = 3k\Omega$$

$$R_2 = \frac{10^4}{n \cdot V_{BB}} = \frac{10^4}{0.7 \times 20} = 714.29 \text{ k}\Omega \quad \text{OR} \quad \frac{0.7 R_{BB}}{n \cdot V_{BB}}$$

$$R_1 = \frac{V_{BB}}{I_{E0}} - R_2 - R_{BB} = \frac{20}{2m} - 714.29 - 7k = 2.28k\Omega$$

Comments on the d.p frequency, are

$$T_{max} = R C_{max} \ln\left(\frac{1}{1-n}\right) = 120 \text{ k}(0.1\mu) \ln\left(\frac{1}{1-0.7}\right)$$

$$T_{max} = 14.4 \text{ msec.}$$

$$f_{min} = \frac{1}{T_{max}} = 69.2 \text{ kHz}$$

$$T_{min} = R_{min} C \ln\left(\frac{1}{1-n}\right) = 3 \text{ k}(0.1\mu) \ln\left(\frac{1}{1-0.7}\right)$$

$$T_{min} = 0.36 \text{ msec}$$

$$f_{max} = \frac{1}{T_{min}} = \frac{1}{0.36 \text{ msec}} = 2.76 \text{ kHz}$$

