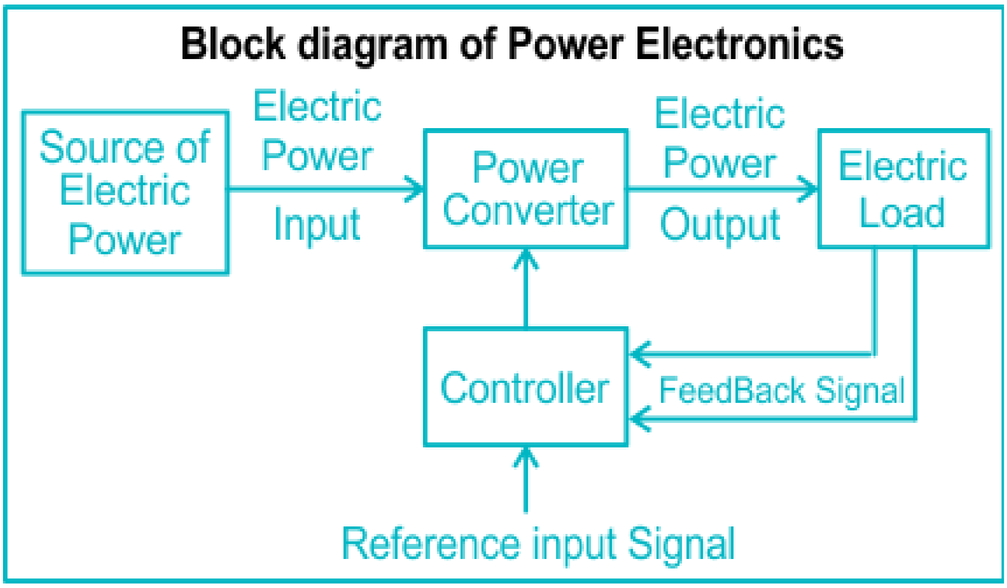
Module 1

POWER SEMICONDUCTOR DEVICES

A Brief Overview of Power Electronics

Power Electronics: What is it?

Electrical engineering's field of power electronics focuses on using electronic devices to convert, control, and condition electrical power. It focuses on using power semiconductor devices like diodes, transistors, and thyristors to effectively convert electric power from one form to another (AC to DC, DC to AC, or changing voltage levels).



Power Electronics' goals

1. load. Power Conversion: Transform electrical energy between AC and DC, DC and AC, AC and AC, or DC and DC.

2. Control the flow of electrical energy with power control.

3. Enhance the quality of power supplied to the load through power conditioning.

Power Converter Types

Rectifiers (AC to DC Converters)

produces a DC output from an AC input.

utilized in DC power supplies, battery chargers, and other devices.

Inverters, or DC to AC converters

produces an AC output from a DC input.

utilized in UPSs and renewable energy systems, among others.

Converters from DC to DC (Choppers)

transforms DC into a different voltage level.

utilized for battery charging, electric cars, etc.

AC to AC Converters (AC Voltage Controllers/Cycloconverters)

transforms AC at one frequency into AC at a different voltage or frequency.

utilized in power systems, AC motor speed control, etc.

USES:

1. Electric automobiles

2. Energy dialogue

3. Systems for renewable energy

4. Automation in Industry

5. Smart and power grids

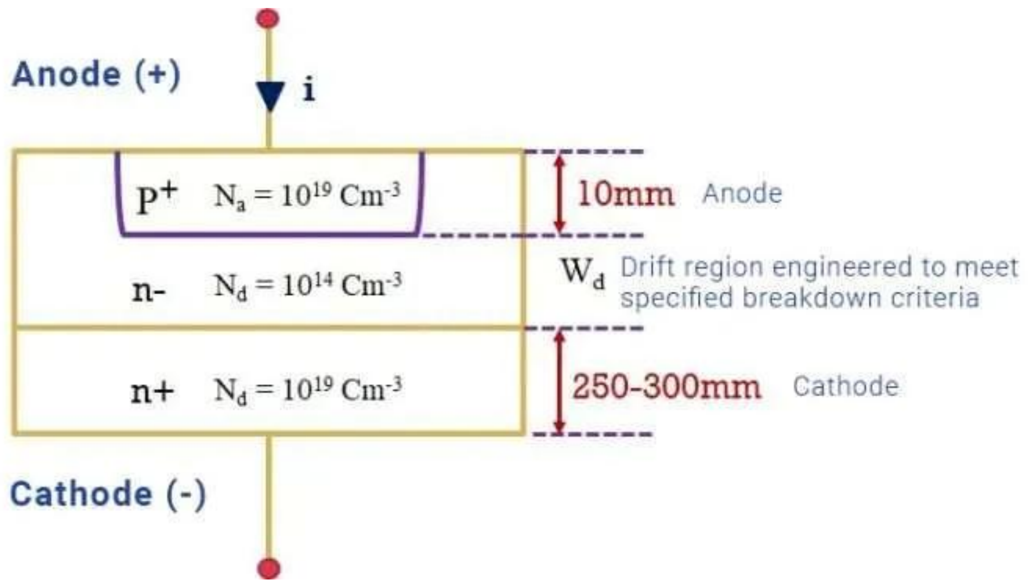
Power Electronics Benefits

- High effectiveness
- Lightweight and small in size
- Accurate management
- Programmability and adaptability
- Integration and conversion of energy
- Less upkeep
- Eco-friendly
- rapid switching

Negative aspects of power electronics include:

- high starting price
- intricate control and design
- Distortion of harmony
- Thermal management and heat dissipation
- Interference from electromagnetic waves (EMI)
- restricted ability to handle overload
- Switching causes energy loss.
- intricate upkeep and repairs
- Environmental condition sensitivity

POWER DIODE



As shown in the diagram with particular values, the P+ layer functions as the anode and has a thickness of 10 µm and a doping level of Na.

With a thickness between 250 and 300 µm and a doping level of Nd, as shown by particular values in the diagram, the N+ layer serves as the cathode.

The diagram also specifies the breakdown voltage and a doping level of Nd, which determine the thickness of the N-layer, which acts as the middle layer or drift region. The breakdown voltage will rise as the N-layer's width increases.

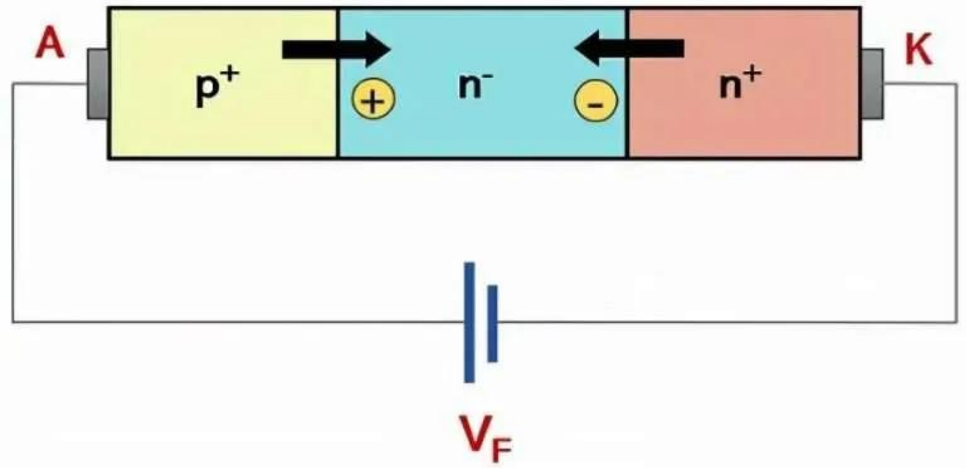
Power Diode Operation Principle:

Power diodes operate on a similar principle as a typical PN-junction diode. The power diode conducts when the anode voltage is greater than the cathode voltage. A power diode's forward voltage drop is usually between 0.5 and 1.2 volts. The power diode functions with forward characteristics in this mode.

The power diode goes into blocking mode if the cathode voltage is greater than the anode voltage. The power diode functions similarly to a reverse-biased diode in this mode.

Forward Bias of Power Diodes:

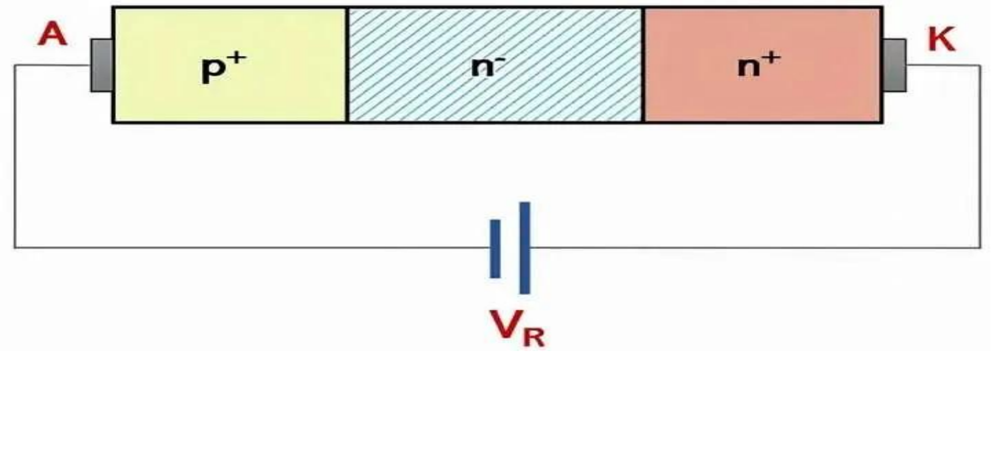
A power diode functions somewhat similarly to a conventional diode. As illustrated below, the forward bias condition of a power diode occurs when the battery's positive terminal connects to the anode and its negative terminal connects to the cathode.



Under these circumstances, the majority of the charge carriers (holes) from the p+ region begin to inject into the n-drift region, and the junction is subjected to forward bias. Electrons in the n-region recombine with holes from the p+ region when the injection rate is low. Nevertheless, holes will enter and recombine with electrons in the n+ region as the injection rate rises. We call this dual injection. Once the threshold is crossed, the diode starts to conduct heavily because of the flow and recombination of charge carriers in the drift region.

Power Diode Reverse Bias:

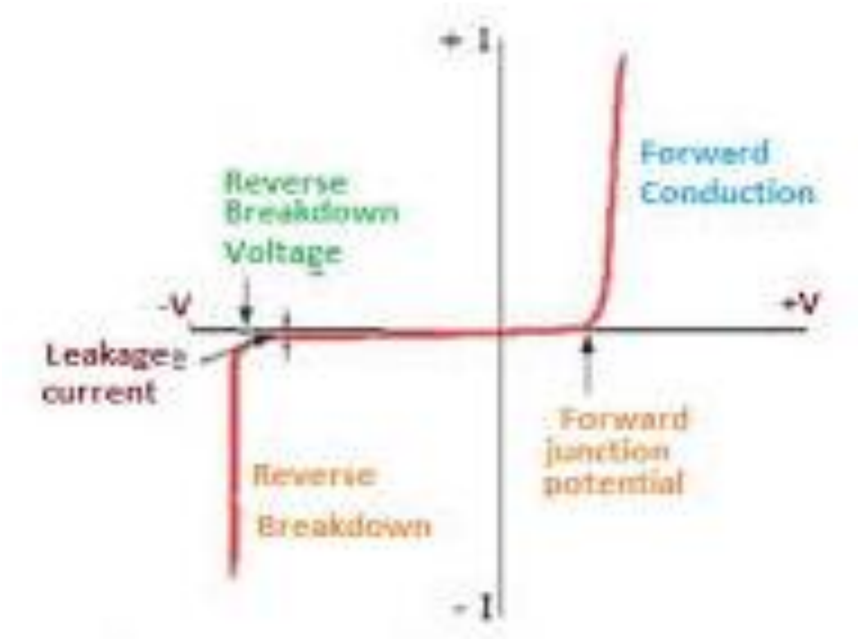
When the battery is in reverse bias, the cathode is connected to the positive terminal and the anode to the negative terminal.



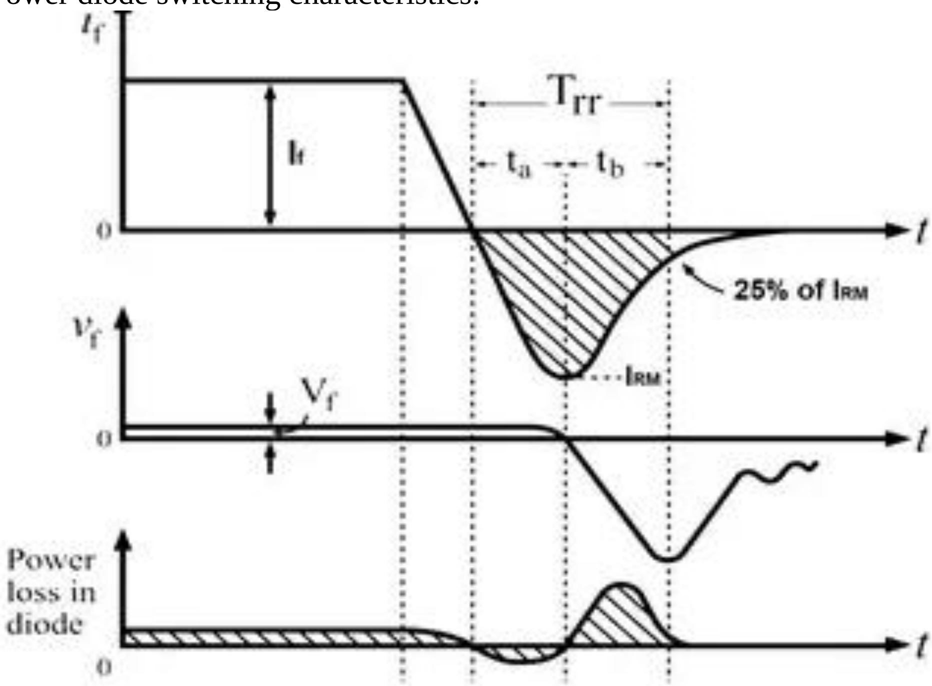
The junction becomes reverse biased in this scenario, and the power diode stops conducting just like a regular diode would. Minority charge carriers find it challenging to pass through the junction because the depletion region stretches into the drift region.

The current flow is not immediately stopped by the abrupt change in the applied voltage polarity. Additionally, a tiny leakage current (roughly 100 mA) flows through the diode in the opposite direction due to the minority charge carriers stored in the junction. Changes in the junction temperature have an impact on this reverse current. Impact ionization happens when the breakdown voltage and the applied potential are equal.

The Power Diode's VI Properties



Power diode switching characteristics:



During the AC supply's positive cycle

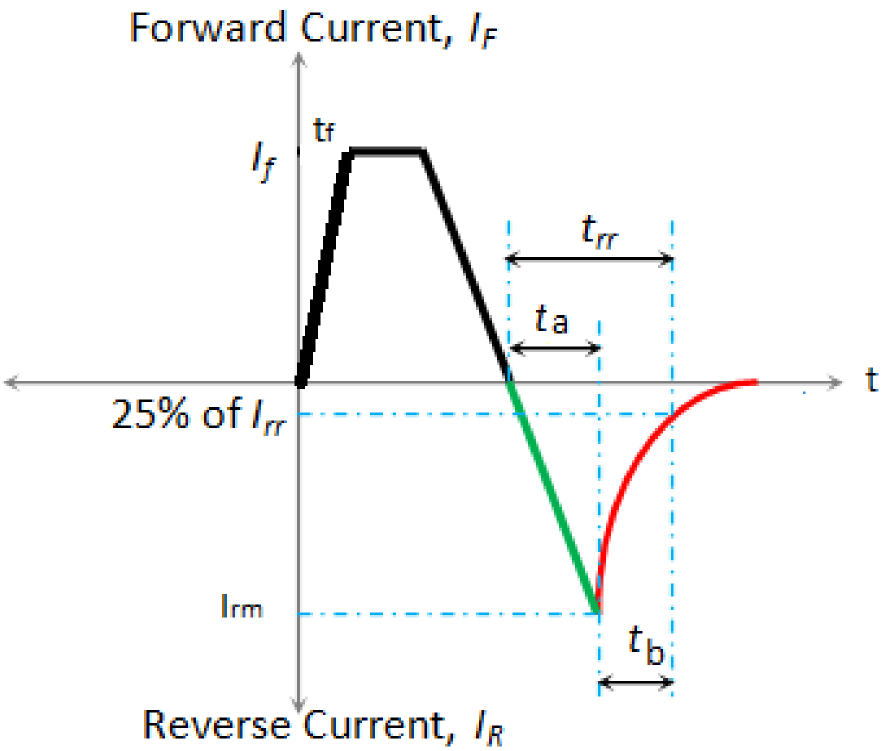
Forward Recovery Time: The diode's current increases linearly when an AC supply is applied, attempting to transition from an OFF to an ON state. This period of time is tf.

During the AC supply's positive cycle

Reverse Recovery Time: Due to the stored charges in the p or n-layer and the depletion layer, the diode continues to conduct in the opposite direction after the forward diode current drops to zero. A reverse-recovery time trr is the duration of the diode current flow.

The time interval between the forward diode current reaching zero and the reverse-recovery current decaying to 25% of its reverse maximum value is known as this factor.

It determines the power diode's switching frequency.



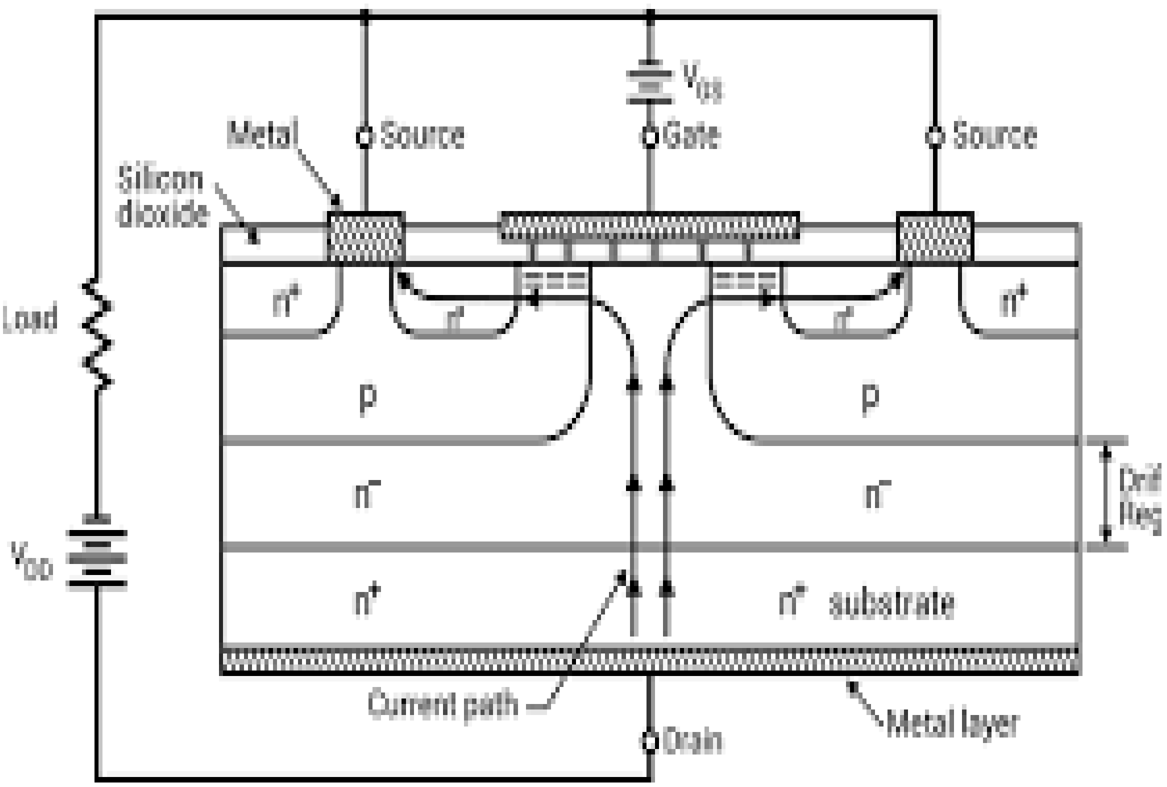
TRANSISTORS OF POWER

MOSFET power

IGBT power

BJT Power

MOSFET(POWER)



Power MOSFET Structure

The layers of a typical power MOSFET are as follows:

a) The terminal where the current enters is called the source (S).

b) The terminal where the current leaves is called the drain (D).

c) Gate (G): The MOSFET's control terminal (similar to a switch).

d) Substrate (Body): The body of the semiconductor that connects to the source, typically silicon.

e) Oxide Layer: The gate is insulated from the rest of the structure by a thin layer of silicon dioxide (SiO_2).

Operating Modes

There are three modes of operation for a Power MOSFET:

Region of Cutoff:

Condition: The threshold voltage (Vth) is greater than the gate-to-source voltage (VGS).

Action: The MOSFET acts as an open switch and no current flows from the drain to the source.

Region of Ohmic (Linear):

The drain-to-source voltage (VDS) is low and VGS is greater than Vth.

Action: The current rises linearly as the VDS rises, and the MOSFET acts similarly to a variable resistor.

Region of Saturation (Active):

Condition: VDS is large and VGS > Vth.

Action: The gate-to-source voltage (V_GS) regulates the constant drain current (I_D). The MOSFET functions as a steady source of current.

Principle of Operation

A Power MOSFET functions similarly to a regular MOSFET but has the capacity to manage higher power.

1 In the OFF State, when VGS < Vth:

There is no channel created between the source and drain.

There is no current flowing from the source to the drain.

The MOSFET functions similarly to an open switch.

2 In the ON State, when VGS > Vth:

The drain and source are separated by a conductive channel, which is N-type for N-channel MOSFETs and P-type for P-channel MOSFETs.

From the drain to the source, current flows.

The voltage applied to the gate regulates the conductivity of the channel.

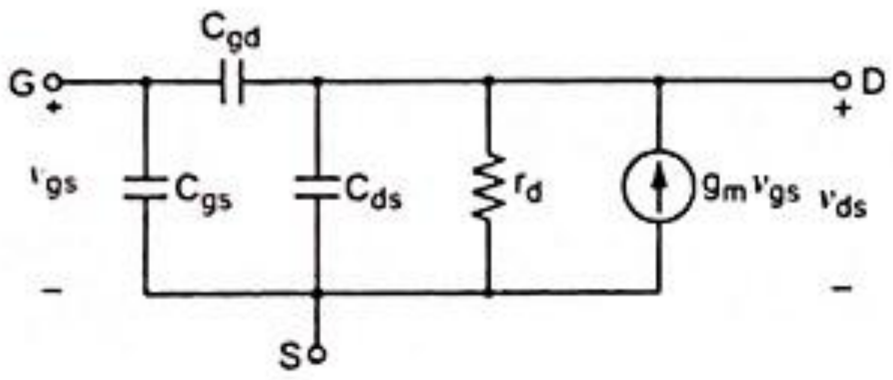
3 Flow of Current (Drain to Source)

The electric field produced by the gate voltage (VGS) determines the drain-to-source current (ID).

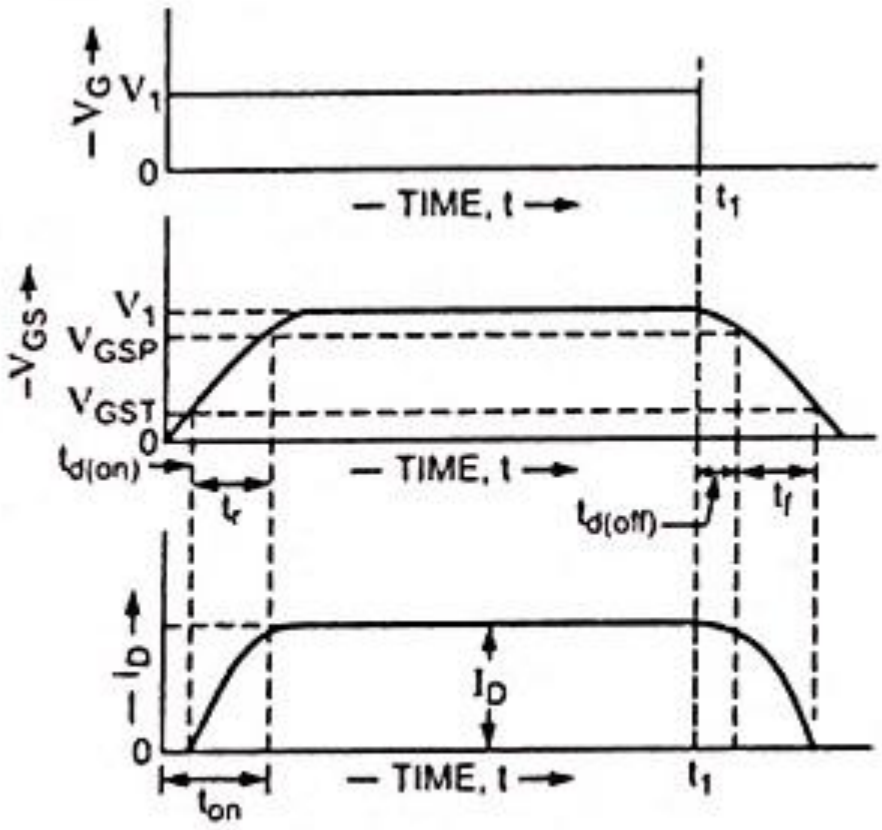
More electrons (for N-channels) or holes (for P-channels) form a channel when VGS is raised, which lowers the channel's resistance.

The channel's width and the drain current (ID) are proportionate.

MOSFET switching characteristics

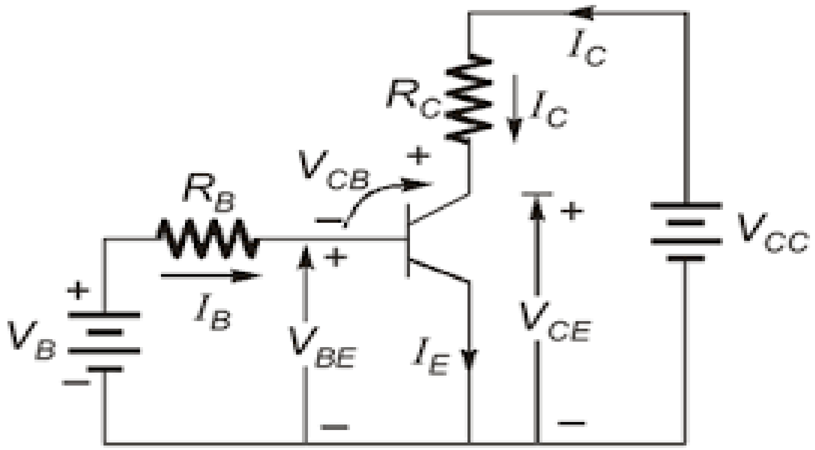


(a) Switching Model of MOSFETs



(b) Switching waveforms

POWER BJT



Bipolar Junction Transistor (BJT) operation

A semiconductor device with three terminals that can function as an amplifier or switch is called a bipolar junction transistor (BJT). There are three regions in it:

Emitter (E)

Base (B)

Gatherer (C)

Two categories of BJTs exist:

Transistor NPN

Transistor PNP

Operational Principle:

1. Current Control: A much larger current between the collector and the emitter is managed by the tiny current at the base terminal.

2. Biasing :

The collector-base junction is reverse biased for NPN, while the base-emitter junction is forward biased.

The polarities are inverted for PNP.

Many charge carriers can move from the emitter to the collector when the base receives enough voltage because it lowers the barrier at the base-emitter junction.

Characteristics of BJT Switching

A BJT functions as a switch in two primary states:

State of Cut-off (OFF state)

State of Saturation (ON state)

The base current regulates the change between these states. The following are the main phases of BJT switching:

Cut-off Region (OFF State)

Reverse bias is present at the base-emitter junction.

Between the emitter and collector, there is no current flow.

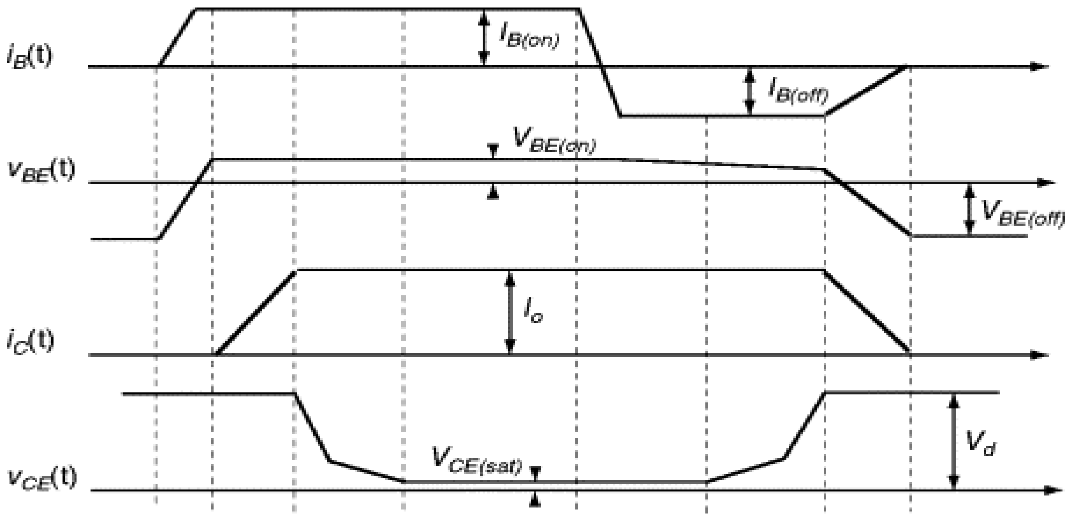
Emitter and collector currents are practically zero.

Saturation Region (ON State)

The base-emitter junction is biased forward.

Forward-biased collector-base junction.

The emitter receives the maximum current from the collector.



Changing BJT Stages

A BJT experiences a number of transient states when it transitions from OFF to ON or the other way around. The following are the stages of switching:

1 Delay in Turning On (td)

The amount of time it takes for the BJT to begin conducting after the input signal forward biases the base-emitter junction.

The base current increases from zero to its maximum value during this period.

2 Time of Rise (tr)

When the collector current rises from 10% to 90% of its ultimate value
The transistor moves from the cut-off region to the saturation region during this phase.

3 Saturation (On-State)

The collector current reaches its maximum when the transistor is fully ON.

For silicon BJTs, the voltage across the collector-emitter (Vce) is very low, near 0.2V.

4 Delay for Turning Off (td)

Reverse biasing the base-emitter junction and bringing the base current down to zero takes time.

Fall (tf)

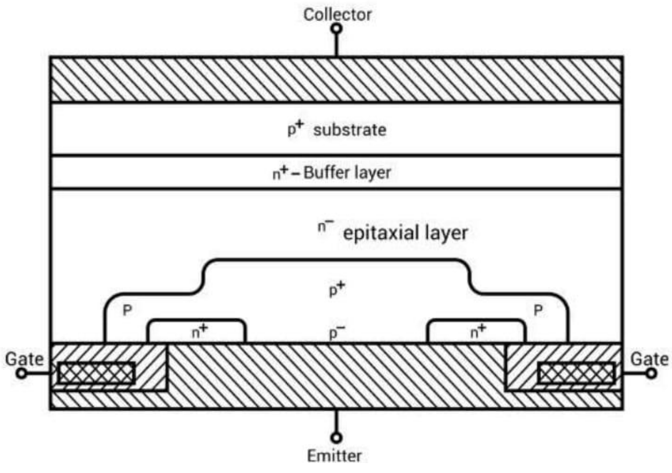
The amount of time it took for the collector current to decrease from 90% to 10% of its maximum value.

The transistor transitions between cut-off and saturation.

5 Cut-off (off-state)

The transistor is in the OFF state when the collector-emitter current drops to zero.

POWER IGBT



There are three terminals on the IGBT:

Gatherer (C)

Gate (G)

Emitter (E)

Principle of Operation

Voltage-Controlled Device: The voltage at the gate regulates the IGBT. The IGBT uses a very small amount of gate current in contrast to BJTs, which are current-controlled.

Operation Switching:

Current can move from the collector to the emitter when a positive voltage is applied to the gate terminal (in relation to the emitter), creating an N-channel (inversion layer) underneath the gate.

The device shuts off and the channel vanishes when the gate voltage is removed.

IGBT Operating Modes

OFF-State (Remote Cut-off)

VGEV_{GE}VGE (gate-emitter voltage) = 0V.

There is no current flowing from the collector to the emitter, and there is no conduction path.

The voltage between the emitter and collector is blocked by the IGBT.

Conduction Region (ON-State)

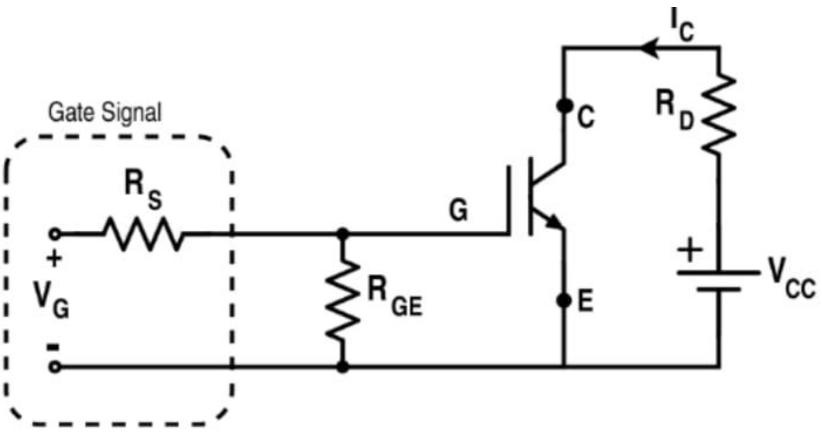
The gate forms an N-channel when a positive voltage (VGEV_{GE}VGE) is applied to it.

The injection of holes in the PNP structure causes current to flow from the collector to the emitter.

With only a slight voltage drop across the collector-emitter terminals, the IGBT permits a high current to flow.

Region of Activity

Since IGBTs are usually used as switches, the active region, where the IGBT functions as an amplifier, is rarely utilized.



Phases of Transitioning

Time of Turn-On Delay (td)

This is the interval of time between applying the gate pulse and the collector current beginning.

The inversion layer (N-channel) forms and the gate capacitance charges during this period.

Time of Rise (tr)

Between 10 and 90 percent of its maximum value, the collector current rises.

The collector-emitter voltage (VCEV_{CE}VCE) decreases as the IGBT switches to conduction mode.

Delay Time Turned Off (tdoff)

After the gate voltage is lowered to zero, the time it takes to remove the channel.

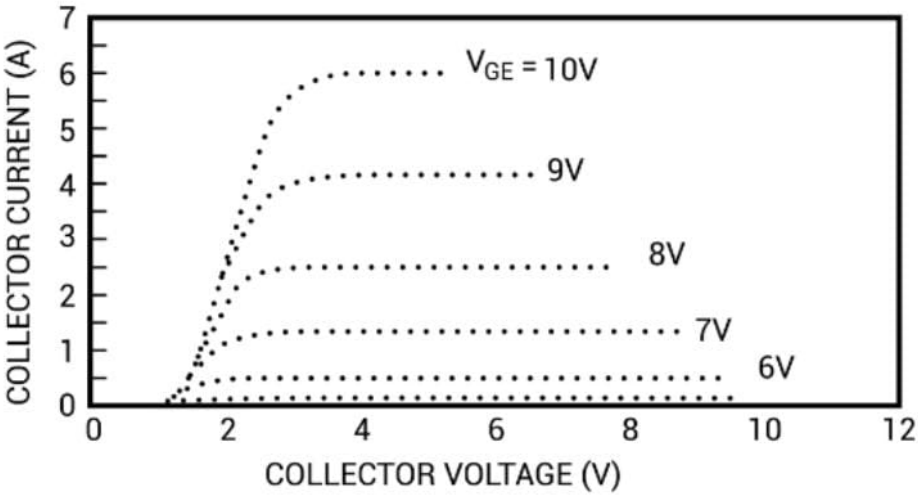
To fully turn off the IGBT, the stored charges in the base of the PNP portion must be eliminated.

Time for Fall (tf)

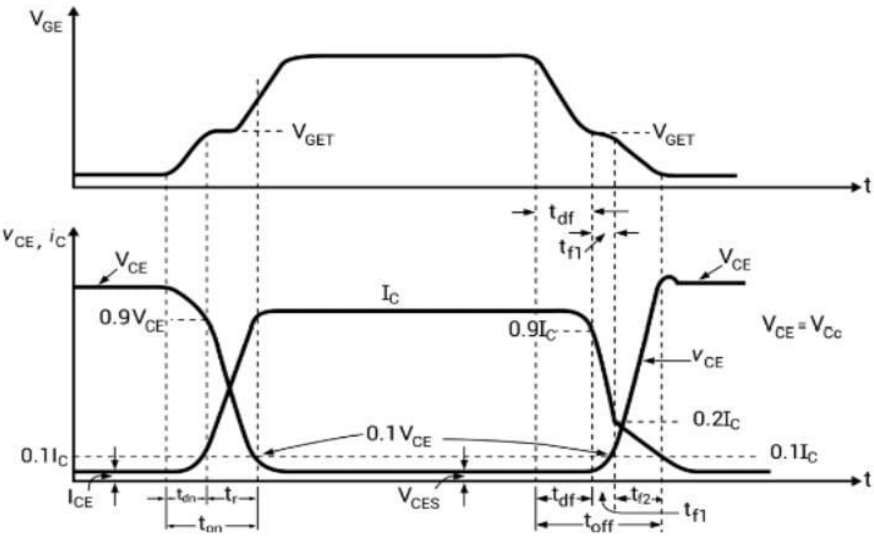
The collector current drops from 90% to 10% of its maximum value during this period.

Current flow is stopped when the IGBT switches from the ON to the OFF state.

IGBT's forward characteristics

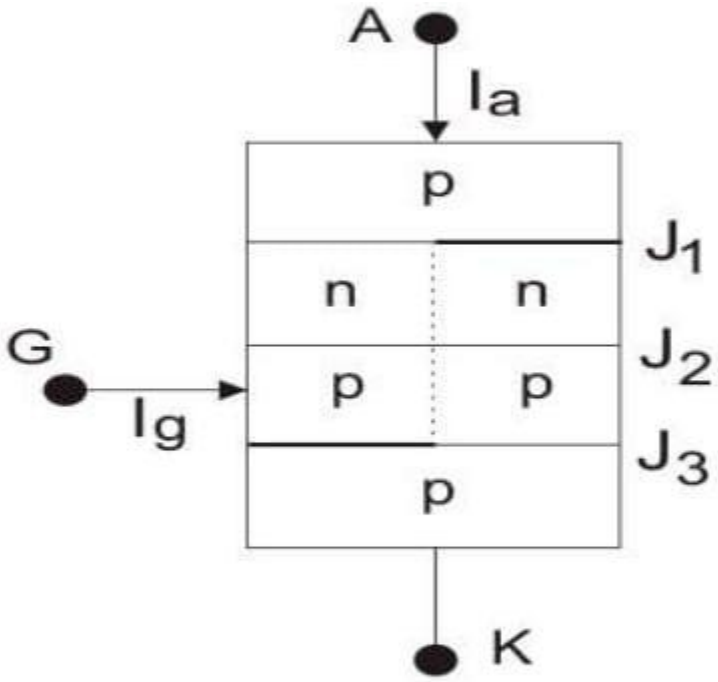


IGBT switching characteristics



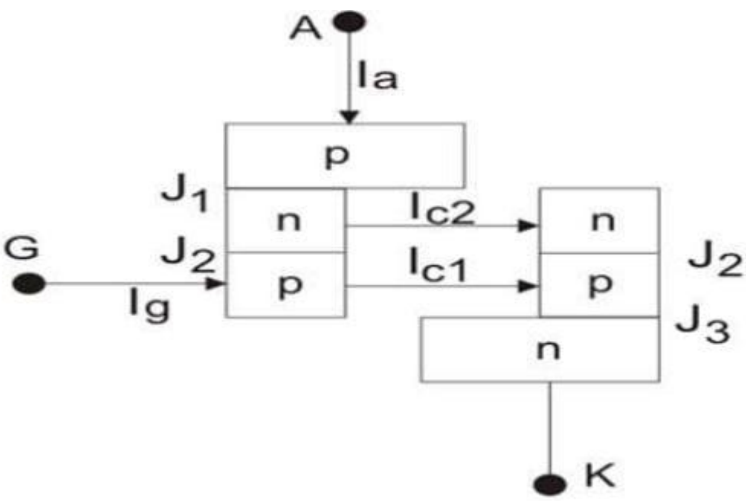
TWO TRANSISTOR ANALOGY OD SCR

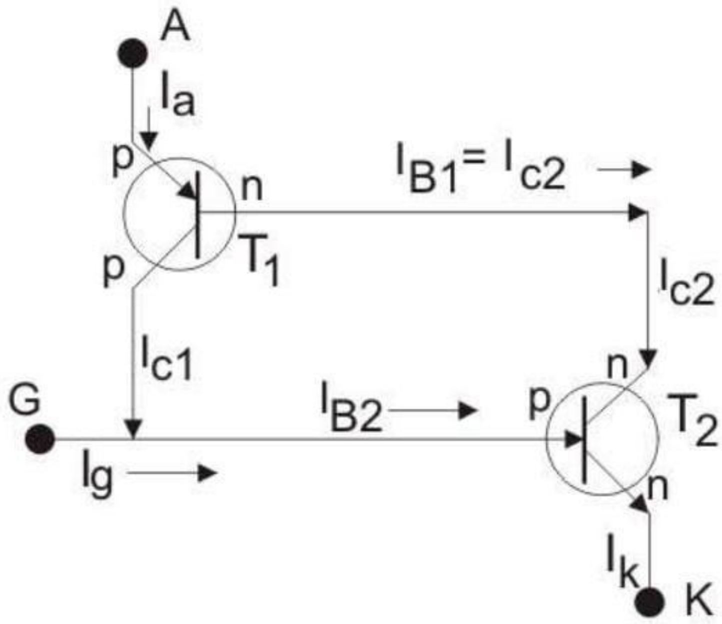
The two transistor model of SCR, which is an analogy of a silicon controlled rectifier and also a combination of P and N layers, makes it easy to understand the basic working principle of SCR. This is illustrated in the figure below.



This thyristor is a pnpn. One pnp transistor with J1 and J2 junctions and another with J2 and J3 junctions, as seen in the figure below, will result from cutting it in half along the dotted line.

The relationship between the collector and emitter currents when the transistors are off is displayed below.





SCR TURN ON METHODS

Triggering is the process by which the SCR turns on. To put it another way, turning the SCR off. Here, several SCR triggering techniques are covered, ranging from the Forward-Blocking state to the Forward-Conduction state. is referred to as Triggering.

The different ways to trigger SCRs are

1. Triggering Forward Voltage

2. Temperature or Thermodynamic Triggering

3. Light triggering or radiation

4. Triggering dv/dt

5. Triggering the Gate

(1) Triggering Forward Voltage:

An extra forward voltage is applied between the anode and cathode in this mode.

when there is a positive anode terminal relative to the cathode (VAK). Junction J2 is reverse biased, while junctions J1 and 13 are forward biased.

With the exception of leakage current, there is no current flow because the depletion region in J2 is reverse biased.

When VAK is increased further, the junction J2 experiences avalanche breakdown at a voltage Vao (Forward Break Over Voltage), causing a current to flow and the device to tend to turn on (even when the gate is open).

2. Temperature (or Thermo) Triggering:

As the junction temperature rises, the SCR's depletion layer's width falls.

Consequently, raising the junction temperature in an SCR activates the device when the VA is extremely close to its breakdown voltage.

The device begins to conduct when the reverse biased junction collapses due to an increase in junction temperature.

3. Light Triggering or Radiation Triggering:

In place of a gate terminal, a unique terminal niche is created inside the inner player for light-triggered SCRs.

This terminal generates free charge carriers when light is allowed to strike it.

The thyristor begins to conduct when the light intensity exceeds a typical value.

We refer to these SCRs as LASCRs.

4. Triggering dv/dt:

J2 is reverse biased when the device is forward biased, while 11 and 13 are forward biased.

Because of the charges across the junction, Junction 12 acts like a capacitor.

If the device's capacitance is C and its charge is Q, and the voltage across it is V, then

$Q = CV$

$i=dQ/dt$

$i=d(CV)/dt$

$CdV/dt + VdC/dt$

since $dC/dt = 0$.

$CdV/dt = i$

Therefore, even if the voltage across the device is low, it may turn on when the rate of change of the voltage across the device increases.

5. Triggering the gate:

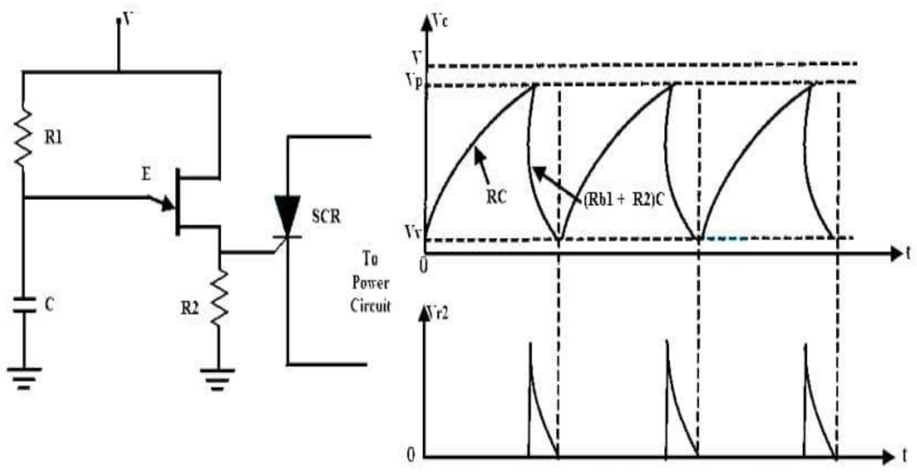
The most popular SCR triggering technique is this one.

A forward biased thyristor can be turned on by applying a positive voltage between the gate and the cathode.

The thickness of the depletion layer is decreased by injecting charge carriers into the inner P-layer when a positive voltage is applied at the gate terminal.

The voltage at which forward break-over takes place falls as the applied voltage rises because the carrier injection rises as well.

UJT FIRINIG CIRCUIT



Using a Uni Junction Transistor (UJT) as a triggering device limits power loss by producing a train of pulses. This is the most popular method of triggering the SCR because the prolonged pulses at the gate using R and RC triggering methods cause more power dissipation at the gate.

The timing circuit is formed by connecting the RC network to the UJT's emitter terminal. Since the resistance is variable and the capacitor is fixed, the charging rate of the capacitor is dependent on the variable resistance, which indicates that the RC time constant is being controlled.

The capacitor begins charging through the variable resistance when the voltage is applied. The voltage across the capacitor can be changed by altering the resistance value. When the capacitor voltage reaches the UJT's peak value, it begins to conduct and generate a pulse output until the voltage across the capacitor reaches the UJT's valley voltage V. At base terminal 1, this process is repeated, creating a train of pulses.

The SCR is turned on at preset intervals using the pulse output at base terminal 1.

SCR PARALLEL OPERATION AND SERIES

The necessary voltage and current ratings in many power control applications are higher than what a single SCR can supply. In these circumstances, the SCRs must be connected in parallel or series to satisfy the specifications. For economic reasons and the convenience of using SCRs with lower ratings, multiple connections are occasionally used even when the necessary rating is available. Two SCRs of the same make and rating never have the same characteristics or properties, just like any other electrical equipment, and this can cause issues in the circuit. SCR mismatching results from variations in

(1) Time of turn-on

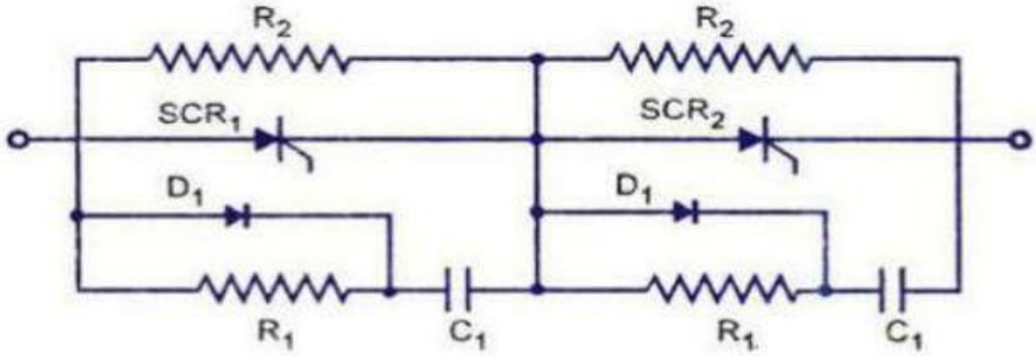
(ii) time of turn-off

(ii) Forward-moving leakage current

(iv) Reverse-directional leakage current and

Recovery voltage (V).

SCR operation in series



(i) Inequitable voltage distribution throughout SCRS

(ii) Variations in the features of recovery.

It's important to distribute the voltage evenly. Voltage sharing is accomplished for steady-state conditions by connecting each SCR in parallel with a Zener diode or a resistance. As illustrated in the figure, a low non-inductive resistor and capacitor are connected in series across each SCR to provide transient voltage sharing. Dynamic stabilization is aided by diodes D1 connected in parallel with resistor RI. Within allowable bounds, this circuit lessens the disparity between the two devices' blocking voltages. Furthermore, the R-C circuit can also be used as a "snubber circuit." The snubber circuit can be used to determine the values of R1 and C1, and equalization can be checked. If AV is the allowable difference in blocking voltage and AQ is the difference in recovery charge of two devices resulting from different recovery currents for different times, then

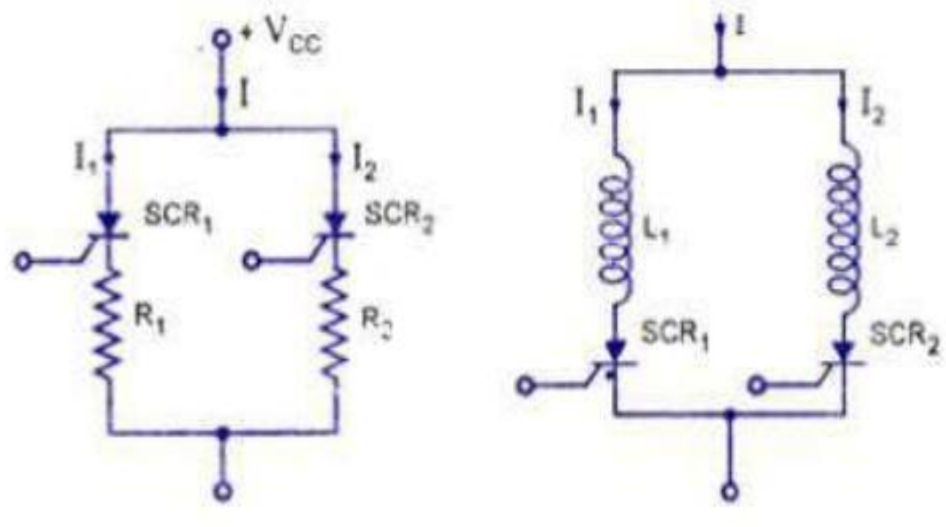
C1 = Q/V

The resistance Rx should be high enough to cause the circuit to become overly damp. Excessive power dissipation may occur during turn-on because the capacitor Cl may discharge through the SCR; however, the resistor RI limits the switching current from CI and also prevents "ringing," or oscillation of Cl with the circuit inductance during commutation. When signals are applied to their gates simultaneously, all of the SCRs connected in series should turn on simultaneously.

This phenomenon decreases the use of each SCR while increasing the string's reliability. As a result, string efficiency declines. The derating factor (DRF), which is provided, is used to measure string reliability. by the phrase

Efficiency of DRF 1-string

SCR PARALLEL CONNECTION



SCRs are connected in parallel to share the load current when it surpasses their current rating. However, the current sharing between SCRs may not be appropriate when they are operated in parallel. More current will typically be shared by the device with the lower dynamic resistance. This will cause that specific device's temperature to rise relative to others, which will further lower its dynamic resistance and increase the current flowing through it. This process keeps going until the device is punctured and is cumulative. Other elements that either directly or indirectly contribute to this issue include variations in turn-on and delay times, finger voltage, and loop inductance.

SCR placement in the cubicle is also very important. It is important to make sure that when SCRs are connected in parallel, their latching current levels are such that when a gate pulse is applied, every SCR turns on and stays on when the gate pulse is removed. Additionally, the devices' holding currents shouldn't differ so much that, when the load current is reduced, one of the devices shuts off due to a drop in current that exceeds its holding current value. This is especially crucial because without a gate pulse, the device that has stopped conducting cannot restart when the load current increases.

The on-state voltage across the device should also be taken into account. The voltage drop across the parallel paths must be equal for the devices to share currents equally. It becomes essential to use a common heat sink for their mounting in order for all of the SCRS connected in parallel to operate at the same temperature, as shown in the figure. The figure illustrates the resistance compensation used for de circuits. The resistors Rx and R2 in this circuit are selected to produce an equal voltage drop in each arm. Figure illustrates the use of inductive compensation for ac circuits. This technique can reduce the variations in characteristics caused by variations in turn-on time, delay time, finger voltage, latching current, and holding current. High rate of rise firing circuits can be used to decrease delay time and gate characteristic mismatch. Circuits that share current must be built to distribute current evenly at maximum anode current and maximum temperature. In the worst operating circumstances, this is done to guarantee that the devices share current equally. SCRs' mechanical configuration is also crucial for minimizing mismatching. From this perspective, cylindrical construction is possibly the best. Protection against di/dt and dv/dt

Techniques for DV/DT Security

1 Circuit Snubber (RC or RCD Snubber)

How it operates: A resistor (R), capacitor (C), or a resistor, capacitor, and diode (RCD) combination connected in parallel with the device makes up a snubber circuit.

Its function is to prevent significant voltage fluctuations by absorbing excess energy during switching.

Effectiveness: The resistor dissipates excess energy, and the capacitor limits the rate of voltage change.

Design: Based on the necessary dv/d limit, determine the resistor RRR and capacitor CCC values.

2 RC Low-Pass Filter

How it operates: Devices such as IGBTs, SCRs, or MOSFETs have a basic RC network connected across their gate terminal.

Its goal is to lessen the effect of high dv/dt by slowing down the input signal and filtering out high-frequency components.

3 Resistance of the Gate (Rg)

How it works: The gate terminal of an IGBT or MOSFET is connected in series with a resistor.

Its function is to regulate the device's turn-on speed, which in turn regulates the dv/dtdv/dtdv/dt across the device.

Effectiveness: The dv/dt can be regulated by adjusting the gate voltage's rate of rise.

Trade-off: High Rg lowers stress while increasing switching delay.

4. Appropriate Shielding and Grounding

Reduce stray capacitive coupling and noise to avoid unintentional device triggering.

Techniques for Preventing di/dtdi/dtdi/dt

Circuit Snubber (L or RC Snubber)

To limit di/dtdi/dtdi/dt in the circuit, an RCD snubber is made up of a resistor (R), a diode (D), and a capacitor (C).

L Snubber (Inductive Snubber): To reduce the rate of change in current, an inductor (L) is connected in series with the load.

Working: The inductor slows down the current change by opposing the rapid change in current due to its property $V=L\cdot(di/dt)$.

Soft-Switching Methods

By ensuring that switching takes place at zero current, techniques such as Zero Current Switching (ZCS) reduce di/dt stress.

Zero current switching, in which current naturally drops to zero before the switch shuts off, is how resonant converters work.

Turn-On and Turn-Off Control

Smoother transitions are ensured by using devices such as gate drivers with turn-on/turn-off delay features.

By doing this, high di/dt during switching events are avoided.

SNUBBER CIRCUIT DESIGN

Circuit snubber

Switching devices and circuit components may malfunction as a result of overheating, excessive voltage, overcurrent, or excessive voltage or current changes. By putting fuses in the right places, they can be protected from overcurrent. Fans and heat sinks can be used to remove extra heat from components, such as switching devices. To limit the rate of change in voltage or current (di/dt or dv/dt) and overvoltage during turn-on and turn-off, sniffer circuits are required. These are positioned across semiconductor devices to enhance performance and provide protection. The ability of a thyristor to maintain a blocking state when subjected to a voltage transient is measured by its static dv/dt. To avoid arcing, these are also utilized across the switches and relays.

Use of the Snubber Circuit Is Required

These are positioned across a variety of switching devices, including thyristors and transistors. When the device is turned from the ON to the OFF state, its impedance abruptly rises to a high value. However, this permits a tiny current to pass through the switch. A high voltage is induced across the device as a result. The induced voltage across the device increases if this current decreases more quickly, and the switch burns out if it cannot withstand this voltage. In order to avoid this high induced voltage, an auxiliary path is required.

Similar to this, when the switch is going from the OFF to the ON state, an uneven current distribution causes overheating and ultimately burns the switch. In this case as well, a snubber is required to lower the current at first by creating a different path.

When in switching mode, sniffers perform one or more of the following tasks.

A bipolar switching transistor's load line should be shaped to maintain it within its safe operating range.

lowering the currents and voltages under transient turn-ON and turn-OFF conditions.

lowers the junction temperature by removing energy from a switching transistor and dispersing it in a resistor.

restricting the voltage and current change rates during transients.

A switching transistor's peak voltage can be limited by reducing ringing and lowering its frequency.

RC Snubber circuit design:

The most widely used type of snubber is the RC snubber circuit, though there are other types as well, such as diode and solid state snubbers. This holds true for damping as well as rate of rise control.

A capacitor and a series resistor are connected across a switch in this circuit. for the Snubber circuit design. The amount of energy stored in the capacitors is equal to the amount of energy that must be released through the snubber resistance. To lamp the ring and lower the peak voltage at turn-off, place an RC Snubber across the switch. There are two types of RC snubber circuits: polarized and non-polarized. The worst-case peak current in the snubber circuit, assuming the source has very little impedance, is

I=C.dv/dt and I=Vo/Rs