Power semiconductor devices

Power semiconductor devices constitute the heart of modern power electronic apparatus. The main function of the power semiconductor devices (PSD) in the power converter system are used as on/off switches to control the energy transfer between the source and the load.

The Basic representation of the power semiconductor device can be represented as a traditional switch as shown in Fig. 1.

Figure 2 below shows a simple feature of using PSD as a switch in converting energy between the source and the load.

The difference between ideal switch and practical switch

As mentioned before, PSDs use as switches in PE converters. The switch in practical has different features in practical over its features in ideal case. This can be recognize as described below:
**Ideal Switch**

If the PSD considered working as ideal switch then it should be:

- When switch is OFF, $i = 0$ and $-\infty \leq v \leq +\infty$ which implies that $P_{ON} = 0$

$$i = i_{OFF} = 0$$

$$+ v = V_{OFF} -$$

- When switch is ON, $V = 0$ and $-\infty \leq I \leq +\infty$ which implies that $P_{ON} = 0$

$$i = i_{ON}$$

$$P_{ON} = 0$$

$$+ v = V_{ON} = 0 -$$

It should be possible to easily turn the switch ON and OFF by applying an appropriate control signal.

**Features of Ideal Switch**

- The power required to keep the switch in a particular state, or to switch it ON/OFF should be infinitesimally small.
- Should be able to change state instantaneously which implies that $t_{ON} = 0$, $t_{OFF} = 0$ and $P_{SW} = 0$ (see Fig.3)
- Should be able to withstand infinite temperature that means that its power handling capability is infinite. Requires very low thermal impedance
from internal junction to ambient, RJA=0, so that it transmits heat easily to the ambient

➢ Should be able to withstand infinite value of di/dt during turn ON and infinite value of dv/dt during turn OFF.

➢ Current limitless when on-either direction.

➢ No limit on amount of voltage across switch when off (Blocking voltage infinite (forward or reverse)).

In real life, there exists nothing like that!

For Practical Switches, you have to know that:

**Conduction loss**: $I^2R$ loss, $R$ being the resistance of the switch

\[
R_{on} = 0 \text{ for ideal switch.} \quad R_{on} = \text{its value based on the voltage rating of the switch and its structure. For a good switch, } R_{on} \text{ should be small. Nevertheless, its not ignored.}
\]

**Voltage blocking** – High voltage can be sustained across the switch during OFF state. Surely, it depends on device dimension.
**Terminals of a PSD**

A power electronic device usually has a third terminal — control terminal to control the states of the device.

Control terminal

Control signal from drive circuit must be connected between the control terminal and a fixed power circuit terminal (therefore called common terminal).

Common terminal

A power electronic device must have at least two terminals to allow power circuit current flow through.

**Note:** The difference between PSD and low-power semiconductor device

- Large voltage in the off state, High current capability in the on state, and operate at lower switching speeds

**Important Switch Parameters**

1. Breakdown voltage rating
2. On-resistance/on-state resistance and specific on-resistance
3. Forward conduction drop
4. Forward blocking capability
5. Reverse blocking capability
6. Rise time
7. Fall time

A good way to get more familiar with these things is to look at datasheets of power devices. They can be found on the website of device manufactures like *International Rectifier*, *Infineon Technologies*, *Ixys Corporation* etc.
Classification of PSD

**NOTE:** in general, the power semiconductor devices classified into three switch types:

- **Uncontrolled:** Diodes (a switch controlled by the power circuit)
- **Semi-controlled:** Thyristors, SCR (can be switched on by a signal but only the power circuit can turn it off)
- **Fully Controlled:** Transistors, GTO, SIT, MCT (can be switched on and off by a signal)

First pulse turns it on and stays always on

controlled: Thyristors, SCR (can be switched on by a signal but only the power circuit can turn it off)

Positive voltage turns them on and zero voltage turns them off
**Power Diode**

Power diodes are made of silicon p-n junction with two terminals, anode and cathode. Diode is forward biased when anode is made positive with respect to the cathode. Diode conducts fully when the diode voltage is more than the cut-in voltage (0.7 V for Si). Conducting diode will have a small voltage drop across it.

Diode is reverse biased when cathode is made positive with respect to anode. When reverse biased, a small reverse current known as leakage current flows. This leakage current increases with increase in magnitude of reverse voltage until avalanche voltage is reached (breakdown voltage).

Fig.1 shows V-I Characteristics of diode.

**Forward Voltage Drop:**

- Is the forward-conducting junction level
- The forward voltage drop is due to the forward resistance of the junction.
- Forward volt drop is across the junction
A typical comparison between different types of diodes is shown in the table below:

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Upto 5000V &amp; 3500A</td>
<td>Upto 3000V and 1000A</td>
<td>Upto 100V and 300A</td>
<td>Upto 600V and 200A</td>
</tr>
<tr>
<td>Reverse recovery time  – High trr ≈25µs.</td>
<td>Reverse recovery time – Low trr ≤5µs.</td>
<td>Reverse recovery time – Extremely low. trr is typically around few ns</td>
<td>have extremely fast switching behaviour with ultra-low trr</td>
</tr>
<tr>
<td>Typically used in rectifiers at power frequencies i.e., at 50Hz or 60 Hz.</td>
<td>Typically operating at higher frequencies as freewheeling diodes.</td>
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<td>Typically operating at higher frequencies as freewheeling diodes.</td>
</tr>
<tr>
<td>$V_F = 0.7V$ to 1.2V</td>
<td>$V_F = 0.8V$ to 1.5V</td>
<td>$V_F = 0.4V$ to 0.6V</td>
<td>$V_F &lt;0.5V$</td>
</tr>
</tbody>
</table>

**SCR**

Thyristor SCR is a general class of a four-layer PNPN semiconducting device, as shown below:

- SCR s have the highest power handling capability. They have a rating of 1200V / 1500A with switching frequencies ranging from 1 KHz to 20 KHz.

- Used as a latching switch that can be turned on by the control terminal but cannot be turned off by the gate.

The structure of the Silicon Controlled Rectifier (SCR also called thyristor) consists of variously doped P and N conducting layers with three external
connections named anode A, cathode K and gate G. It can be represented as two series power diodes:

A typical V-I characteristics of a thyristor is shown Fig.3.

An elementary circuit diagram for obtaining static I-V characteristics of a thyristor.

From SCR characteristic reveals that a thyristor has three basic modes of operation; namely, **Reverse blocking mode**, forward **blocking** (off-state) mode and forward **conduction** (on-state) mode.

In the **reverse direction**, the thyristor appears similar to a reverse biased diode, which conducts very little current until avalanche breakdown occurs.

In the **forward direction** the thyristor has two stable states or modes of operation that are connected together by an unstable mode that appears as a negative
resistance on the V-I characteristics. The low current high voltage region is the forward blocking state or the off state and the low voltage high current mode is the on state. For the forward blocking state the quantity of interest is the forward blocking voltage which is defined for zero gate current. If a positive gate current is applied to a thyristor then the transition or break over to the on state will occur at smaller values of anode to cathode voltage as shown in fig.4. Although not indicated the gate current does not have to be a dc current but instead can be a pulse of current having some minimum time duration. This ability to switch the thyristor by means of a current pulse is the reason for wide spread applications of the device.

However once the thyristor is in the on state the gate cannot be used to turn the device off. The only way to turn off the thyristor is for the external circuit to force the current through the device to be less than the holding current for a minimum specified period.

![Fig.4 Effects on gate current on forward blocking voltage](image)

**Holding and Latching Currents**

**Holding Current** $I_H$

This is the minimum anode current required to maintain the thyristor in the on state. To turn off a thyristor, the forward anode current must be reduced below its holding current for a sufficient time for mobile charge carriers to vacate the junction. If the anode current is not maintained below $I_H$ for long enough, the thyristor will not have returned to the fully blocking state by the time the anode-to-cathode voltage rises again. It might then return to the conducting state without an externally applied gate current.
**Latching Current $I_L$**

This is the minimum anode current required to maintain the thyristor in the on-state immediately after a thyristor has been turned on and the gate signal has been removed. If a gate current, greater than the threshold gate current is applied until the anode current is greater than the latching current $I_L$, then the thyristor will be turned on or triggered.

**Example 1:** The SCR shown has the latching current of 20mA and is fired by the pulse of width 50µs. Determine whether the SCR triggers or not.

![Diagram](image.png)

**Solution:**

When the SCR T1 is turned on, a step of voltage is applied to the RL load. Thus, the current via RL can be obtained as:

$$V_s = i(t)R - L \frac{di(t)}{dt}$$

By applying Laplace transform,

$$V_s = I_s R - Ls I_s$$

Then,

$$I_s = \frac{V_s}{R - Ls} = \frac{V_s/R}{1 - L/R s}$$

By applying inverse Laplace transform, $i(t)$ can be obtained as:

After 50 µsec, $i(t) > I_L$ to trigger the SCR properly (triggered)
\[ i(t) = \frac{V_s}{R} \left( 1 - e^{-t \frac{R}{L}} \right) \]

Here observe that the SCR will be latched if \( i(t) \) is greater than latching current when gate triggering pulse is removed after 50\( \mu \)sec. Hence,

\[
\begin{align*}
  i(t) &= \frac{100}{20} \left( 1 - e^{-50 \times 10^{-6} \times 20} \right) = 10mA
\end{align*}
\]

Hence the SCE will not be triggered since:

\[ i(t) = 10mA < I_L = 20mA \]

**Example 2:** A SCR is connected in series with a 0.5H inductor and 20\( \Omega \) resistance. A 100V DC voltage is applied to this circuit. If the latching current is 4mA, find the minimum width of the gate trigger pulse required to properly turn-on the SCR.

**Solution:**

The equivalent circuit is shown aside:

The latching current \( I_L = 4mA \)

\[ i(t) = \frac{V_s}{R} \left( 1 - e^{-t \frac{R}{L}} \right) \]

When \( i(t) \) is equal to latching current \( I_L \), SCR must be turned ON. Hence, if \( i(t) = I_L \)

\[
I_L = \frac{V_s}{R} \left( 1 - e^{-t \frac{R}{L}} \right)
\]

\[
4 \times 10^{-3} = \frac{100}{20} \left( 1 - e^{-t \frac{20}{0.5}} \right)
\]

Solving above equation by taking the \( \ln \) of two sides, the required width to trigger the SCR is equal to: \( t = 20\mu sec \)
Pulsed Gate Drive

Instead of applying a continuous (DC) gate drive (see Fig.6 a), the pulsed gate drive is used (see Fig.6 b&c). The gate voltage and current are applied in the form of high frequency pulses. The frequency of these pulses is up to 10 kHz. Hence, the width of the pulse can be up to 100 microseconds. The pulsed gate drive is applied for following reasons (advantages):

i) The thyristor has small turn-on time i.e. up to 5 microseconds. Hence, a pulse of gate drive is sufficient to turn-on the thyristor.

ii) Once thyristor turns-on, there is no need of gate drive. Hence, gate drive in the form of pulses is suitable.

iii) The DC gate voltage and current increases losses in the thyristor. Pulsed gate drive has reduced losses.

iv) The pulsed gate drive can be easily passed through isolation transformers to isolate thyristor and trigger circuit.

Usually, a train of pulses is used rather than single pulse as shown in Fig.6b. This is to insure the SCR turned-on. If the first pulse fails to turn on the SCR, then the second and successive pluses are available to turn on the SCR. This is can be clarified as shown in fig.7
**Triac**

**SCR** can be used to control lamps, motors, or heaters etc. However, one of the problems of using a SCR for controlling such circuits is that like a diode, the “SCR” is a unidirectional device, meaning that it passes current in one direction only, from **Anode** to **Cathode**.

Circuits like shown below can be used to obtain full-wave power control in two-directions but this increases both the complexity and number of components used in the switching circuit.

A “Triode AC Switch” or **Triac** for short which is also a member of the thyristor family that be used as a solid state power switching device but more importantly it is a “bidirectional” device. In other words, a **Triac** can be triggered into conduction by both positive and negative voltages applied to its Anode and with both positive and negative trigger pulses applied to its Gate terminal making it a two-quadrant switching Gate controlled device.

A Triac behaves just like two conventional thyristors connected together in inverse parallel (back-to-back) with respect to each other and because of this arrangement the two thyristors share a common Gate terminal all within a single three-terminal package.
A “Triac” is a 4-layer, PNPN in the positive direction and a NPNP in the negative direction, three-terminal bidirectional device that blocks current in its “OFF” state acting like an open-circuit switch, but unlike a conventional thyristor, the Triac can conduct current in either direction when triggered by a single gate pulse.

Four modes in which a Triac can be operated are shown using the Triacs I-V characteristics curves.

- **I + Mode** = MT2 current positive (+ve), Gate current positive (+ve)
- **I – Mode** = MT2 current positive (+ve), Gate current negative (-ve)
- **III + Mode** = MT2 current negative (-ve), Gate current positive (+ve)
- **III – Mode** = MT2 current negative (-ve), Gate current negative (-ve)

In Quadrant I, the Triac is usually triggered into conduction by a positive gate current, labelled above as mode I+. But it can also be triggered by a negative gate current, mode I–. Similarly, in Quadrant III, triggering with a negative gate current, –IG is also common, mode III– along with mode III+. Modes I– and III+ are, however, less sensitive configurations requiring a greater gate current to cause triggering than the more common Triac triggering modes of I+ and III–.

**Triac Applications**

A common type of Triac switching circuit uses phase control to vary the amount of voltage, and therefore power applied to a load, in this case a motor, for both the positive and negative halves of the input waveform. This type of AC motor speed control gives a fully variable and linear
control because the voltage can be adjusted from zero to the full applied voltage as shown.

This basic phase triggering circuit uses the Triac in series with the motor across an AC sinusoidal supply. The variable resistor, VR1 is used to control the amount of phase shift on the gate of the Triac which in turn controls the amount of voltage applied to the motor by turning it ON at different times during the AC cycle.

The Triac’s triggering voltage is derived from the $V_{R1} – C_1$ combination via the Diac (The diac is a bidirectional semiconductor device that helps provide a sharp trigger current pulse to fully turn-ON the triac).

At the start of each cycle, C1 charges up via the variable resistor, VR1. This continues until the voltage across C1 is sufficient to trigger the diac into conduction which in turn allows capacitor, C1 to discharge into the gate of the triac turning it “ON”. Once the triac is triggered into conduction and saturates, it effectively shorts out the gate triggering phase control circuit connected in parallel across it and the triac takes control for the remainder of the half-cycle.

As we have seen above, the triac turns-OFF automatically at the end of the half-cycle and the VR1 – C1 triggering process starts again on the next half cycle.

**Power Transistors Characteristics**

Power transistors are devices that have controlled turn-on and turn-off characteristics. These devices are used as switching devices and are operated in the saturation region resulting in low on-state voltage drop. They are turned on when a current signal is given to base or control terminal. The transistor remains on so long as the control signal is present. The switching speed of modern transistors is much higher than that of Thyristors and are used extensively in dc-dc and dc-ac converters. However, their voltage and current ratings are lower than those of thyristors and are therefore used in low to medium power applications.

Power transistors are classified as follows

- Bipolar junction transistors (BJTs)
- Metal-oxide semiconductor filed-effect transistors (MOSFETs)
Insulated-gate bipolar transistors (IGBTs)

Steady State Characteristics

The power transistor has steady state characteristics almost similar to signal level transistors except that the V-I characteristics has a region of quasi saturation as shown by Fig. 2.

Three regions of operation for a BJT can be recognised:

- **Cutoff Region**: When the base current ($I_B$) is zero, the collector current ($I_C$) is insignificant and the transistor is driven into the cutoff region. The transistor is now in the **OFF state**. The collector–base and base–emitter junctions are reverse-biased in the cutoff region or OFF state, and the transistor behaves as an *open switch*. In this region:

  $I_C = 0$ and the collector–emitter voltage $V_{CE}$ is equal to the supply voltage $V_{CC}$

- **Saturation Region**: When the base current is sufficient to drive the transistor into saturation. During saturation, both junctions are forward-biased and the transistor acts like a *closed switch*. In the quasi saturation and hard saturation, the base drive is applied and transistor is said to be on. In this region:
Active Region: In the active region, the collector–base junction is reversed-biased and the base–emitter junction is forward-biased. The active region of the transistor is mainly used for \textit{amplifier applications} and should be avoided for switching operation.

\textit{The power BJT is never operated in the active region (i.e. as an amplifier) it is always operated between cut-off and saturation.}

\textbf{ADVANTAGES OF BJT'S}

- BJT’s have high switching frequencies since their turn-on and turn-off time is low.
- The turn-on losses of a BJT are small.
- BJT has controlled turn-on and turn-off characteristics since base drive control is possible.
- BJT does not require commutation circuits.

\textbf{DEMERITS OF BJT}

- Drive circuit of BJT is complex.
- It has the problem of charge storage which sets a limit on switching frequencies.
- It cannot be used in parallel operation due to problems of negative temperature coefficient.

\textbf{POWER MOSFETS}

Unlike the devices discussed so far, a power MOSFET is a \textit{unipolar}, majority carrier, “zero junction,” \textit{voltage-controlled device}. Figures (a) and (b) below show the symbol of an N-type and P-type MOSFETs.
The linearized transfer characteristic of the MOSFET is shown in Fig. 5a, and the output, or drain-source, characteristic is shown in Fig. 5b.

**POWER IGBTs**

IGBTs (Insulated Gate Bipolar Transistors) combine the simplicity of drive and the excellent fast switching capability of the MOSFET structure with the ability to handle high current values typical of a bipolar device. IGBTs also offer good behavior in terms of voltage drop. Many designers view IGBT as a device with MOS input characteristics and bipolar output characteristic that is a voltage-controlled bipolar device. It combines the best attributes of both Power MOSFET and BJT devices to achieve optimal device characteristics.
A simplified view of the semiconductor arrangement is shown in Fig. 6.

With gate and emitter at the same polarity and the collector positive, junction 2 is reverse-biased and no current flows from emitter to collector. With the gate positive with respect to the emitter and greater than the threshold voltage, the MOSFET channel is formed for current flow. This current is the base current for a pnp transistor, allowing current to flow from emitter to collector, turning the switch on. A simplified equivalent circuit of the IGBT is given in Fig. 7.

The IGBT combines the easy gating requirements of the MOSFET with its high input impedance, and the power handling capability of the BJT.