Lecture 2.
Power semiconductor devices (Power switches)

Power semiconductor switches are the work-horses of power electronics (PE). There are several power semiconductors devices currently involved in several industrial applications. PE switches works in two states only: Fully on (conducting, and Fully off (blocking). Switches are very important and crucial components in power electronic systems

- What is a good power switch:
  » No power loss when ON
  » No power loss when OFF
  » No power loss during turning ON or OFF
  » Little power required to turn it ON or OFF
  » Bi-directional?
  » Adequate voltage and current ratings
  » Low Turn-on and Turn-off times

- Basic ratings:
  » carrying current, blocking voltage.
  » Speed. Any real device requires a definite time to switch.
  » Second-order ratings: di/dt, dv/dt, momentary capabilities.
  » Power loss
  » Thermal ratings –from power switching devices to heat sink
  » Control ratings: how to operate the switch

TYPES OF POWER SEMICONDUCTOR SWITCHES

The main types of power semiconductor switches in common use are

1. Power Diodes

2. Thyristor devices

   a. Silicon controlled rectifier (SCR)
   b. Static induction thyristor (SITH)
   c. Triac (Triode ac switch)
d. Gate turn-off thyristor (GTO)
e. Mos- controlled thyristor (MCT)
f. integrated gated-commutated thyristor (IGCTs)

3. Power transistors
   a. Bipolar junction transistor (BJT)
   b. Metal oxide semiconductor field effect transistor (MOSFET)
   c. Insulated gate bipolar transistor (IGBT)
   d. Static induction transistor (SIT)

2.1 Power Diodes:

These are two terminal switches, as shown in Fig. 2.1 -a, formed of a pn junction. It is not controllable and its operating states are determined by the circuit operating point. When diode is forward biased, it conducts current, i.e a forward positive voltage Vo will turn it on. When it reversed biased (a reverse negative current from Cathode to Anode) will turn it off. With forward biasing a small forward voltage (V_F) will appear across it (0.2-0.3V). Practically, the diode characteristic consists of two regions, as shown in Fig. 2.1 -b; a forward bias region (ON state) where both v_D and i_D are positive and the current in this region increases exponentially with the increase in the voltage, and a reversed bias region (OFF state) where both v_D and i_D, are negative and very small leakage current (μA to mA) flows through the diode until the applied reverse voltage reaches the diode’s breakdown voltage limit VBR. Ideally, the diode is represented by a short circuit when forward biased and as an open circuit when reversed biased with the ideal characteristic shown in Fig. 2.1-c.

![Diode Characteristic](image)

Fig.2.1 Diode: a) symbol, b) characteristic, and c) ideal characteristic.
Types of Power Diodes:

1. Line frequency (general purpose):
   - on state voltage very low (below 1 V)
   - large reverse recovery time $t_{rr}$ (about 25μs).
   - very high current (up to 6 kA) and voltage (8 kV) ratings
   - used in line-frequency (50/60Hz) applications such as rectifiers.
   - Slow recovery (Fig. 2.2)

![Diode Recovery Time Diagram](image)

$t_{rr}$ = reverse recovery time

2. Fast recovery:
   - very low $t_{rr}$ (<1 μs).
   - power levels at several hundred volts and several hundred amps.
   - normally used in high frequency circuits.

3. Schottky:
   - very low forward voltage drop (typical 0.3V)
   - limited blocking voltage (50-100V).
   - used in low voltage, high current application such as switched mode power supplies.

2.2 Thyristors (Silicon Controlled Rectifiers “SCRs”)

The thyristor, it is also called silicon controlled rectifier (SCR), is a four-layer, three terminal switching semiconductor device, with each layer consisting of an alternately N or P-type material, for example N-P-N-P. The main terminals, labeled anode and cathode, are across the full four layers, and the control
terminal, called the gate, is attached to one of the middle layers as shown in Fig.2.3.

![Fig.2.3: The thyristor and its equivalent 2-transistor circuit.](image)

SCRs are mainly used where high currents and voltages are involved, and are often used to control alternating currents, where the change of sign of the current causes the device to automatically switch off. Like a diode, an SCR conducts only in one direction. The SCR symbol and its ideal characteristic are shown in Fig.2.4.

Modern SCRs can switch large amounts of power (up to megawatts). In the realm of very high power applications, they are still the primary choice.

SCR is a controllable switch that usually required to be latched to conduct. This latching (triggering) process is carried out by injecting current to the gate terminal ($i_g$), Fig.2.5, at the required latching instant provided that the device is forward biased ($v_{Ak}$ is positive). Practically, the thyristor characteristic has three main regions as shown in Fig. 2.6:

- the Conduction Region where the thyristor is operating in its ON state,
- the Forward Blocking Region where the thyristor is forward biased but not yet triggered or the voltage didn’t reach the forward breakover voltage, and
- the Reverse Region that consists of the reverse blocking region and the reverse avalanche region similar to the diode characteristic.
Fig. 2.4 Thyristor: (a) symbol, (b) ideal characteristic,

Fig. 2.5 Thyristor gate circuit

Fig. 2.6 Thyristor (SCR) characteristic
Thyristors can only be turned on with three conditions:
1. The device must be forward biased, i.e., the anode should be more positive than the cathode.
2. A positive gate current \((I_g)\) should be applied at the gate.
3. The current through the thyristor should be more than the latching current.

Once conducting, the anode current is LATCHED (continuously flowing).

Important points for the SCR characteristic:

- **Latching Current:** This is the minimum current required to turn on the SCR device and convert it from the Forward Blocking State to the ON State.
- **Holding Current:** This is the minimum forward current flowing through the thyristor in the absence of the gate triggering pulse.
- **Forward Breakover Voltage:** This is the forward voltage required to be applied across the thyristor to turn it ON without the gate signal application.
- **Max Reverse Voltage:** This is the maximum reverse voltage to be applied across the thyristor before the reverse avalanche occurs.

Ideally, SCRs are represented by a short circuit when operating within the conduction region and as an open circuit when operating within the blocking region. The ideal characteristic is shown in Fig. 2-b. It is also worth mentioning that once the SCR is triggered and turned ON the gate signal can be removed without turning it OFF. SCRs are turned OFF when reversing the terminal voltage and current.

**Turning on/off mechanism**

- **Thyristor (SCR) Conduction**
  
- In reverse-biased mode, the SCR behaves like a diode. It conducts a small leakage current which is almost dependent on the voltage, but increases with temperature. When the peak reverse voltage is exceeded, avalanche breakdown occurs, and the large current will flow.

- In the forward biased mode, with no gate current present (i.e. in the untriggered state, the device exhibits a leakage current. If the forward breakover voltage \((V_{bo})\) is exceeded, the SCR “self-triggers” into the conducting state and the voltage collapses to the normal forward volt-drop, typically 1.5-3V. The presence of any gate current \(i_g\) will reduce the forward breakover voltage and will trigger the thyristor at any required instant \((\alpha)\), see Fig.2.7.
- Thyristor turn off

The process of turning OFF SCR is defined as "Commutation". Thyristor cannot be turned off by applying negative gate current. It can only be turned off if the current $I$ through it goes negative (reverse). In all commutation techniques, a reverse voltage is applied across the thyristor during the turn OFF process. There are two methods by which a thyristor can be turned OFF.

i. Natural Commutation
ii. Forced Commutation

**Natural Commutation**

In AC circuit, the current always passes through zero for every half cycle. As the current passes through natural zero, a reverse voltage will simultaneously appear across the device. This will turn OFF the device immediately. This happens when negative portion of the sine-wave occurs. This process is called as "natural commutation" since no external circuit is required for this purpose.

**Forced Commutation**

Another method of turning off is known as "forced commutation". The anode current is "diverted" to another circuitry. To turn OFF a thyristor, the forward anode current should be brought to zero for sufficient time to allow the removal of charged carriers. In case of DC circuits the forward current should be forced to zero by means of some external circuits.
Forced commutation circuit

Fig. 2.8 shows one typical thyristor commutation circuit. Thyristor $T_m$ is the main Thyristor through which the flow of power is controlled. Capacitor $C$ and the four Thyristors ($T_1, T_2, T_3, T_4$) is the commutation circuit. The function of the commutation circuit is to switch off the main thyristor at the end of each ON period. During ON period of the thyristor, the two auxiliary thyristors $T_2$ and $T_4$ are triggered so that the capacitor $C$ is charged such as plate $a$ is positive. To switch OFF, $T_m$ thyristors ($T_1, T_3$) are triggered ON. This results in applying reverse polarity voltage across $T_m$ and hence it will be switched OFF. Also the capacitor polarity will be reversed; i.e. plate $b$ will now be positive. Thyristor $T_m$ is switched ON for the next ON period, and now to switch OFF $T_m$, Thyristors ($T_2, T_4$) are switched ON, and so the cycle is repeated.

![Fig. 2.8 Typical forced commutation circuit for a thyristor.](image)

Types of Thyristors

1. **Phase controlled**
   - rectifying line frequency voltage and current for ac and dc motor drives.
   - large voltage (up to 7 kV) and current (up to 5 kA) type 1 capability.
   - low on-state voltage drop (1.5 to 3V).

2. **Inverter grade**
   - used in inverter and chopper
   - Quite fast. Can be turned-on using “force commutation” method.

3. **Light activated**
   - Similar to phase controlled, but triggered by pulse of light.
   - Normally very high power ratings.
SCR ratings for voltage and current approach those of diodes. Devices for high-voltage dc (HVDC) conversion have been built with simultaneous 12 kV and 6 kA type 2 ratings. Figure 2.9 below shows types of thyristors in practice.

Fig . 2.9 Power semiconductor switches (thyristors).
2.3 The Triac

The triac is a two thyristors connected back – to – back, used for high or medium power control for both a.c and d.c applications, as shown in Fig.2.10. Either of the electrodes MT1 and MT2 can act as anode and either is cathode. The device can be triggered by either positive or negative voltage on the gate with respect to MT1. This device is effectively two thyristors (SCR s) back-to-back in construction with an external n-region which is the gate.

![Triac construction diagram](image)

The four possible mode of operation of triac are

(a) MT2+, G+ (both relative to MT1) Gate current flows into gate terminal.
(b) MT2+, G– Gate current opposite to (a).
(c) MT2–, G+ Gate current as (a)
(d) MT2–, G– Gate current as (b)
2.4 Gate Turn Off Thyristors (GTO Thyristors).

GTO behaves like normal thyristor, but can be turned off using gate signal. However turning off is difficult. Need very large reverse gate current (normally 1/5 of anode current). GTO symbol and characteristics are shown in Fig.2.11.

Fig.2.11 Gate turn off thyristor

- Ratings: Voltage: \( V_{ak} < 6 \text{kV} \), Current: \( I_a < 2 \text{kA} \) -
- Frequency < 5 kHz.
- Gate drive design is very difficult. Need very large reverse gate current to turn off.
- GTO normally requires snubbers. High power snubbers are expensive.
- In very high power region (> 6kV, > 2kA), development in gate-controlled thyristor (GCT) may effectively end the future of GTO.
### 2.5 Power transistors

Can be turned “ON” and “OFF” by relatively very small control signals. Operated in SATURATION and CUT OFF modes only. No “linear region” operation is allowed due to excessive power loss.

Traditional devices: Bipolar junction transistors (BJT), Metal oxide silicon field effect transistor (MOSFET), Insulated gate bipolar transistors (IGBT).

Emerging (new) devices: Gate controlled thyristors (IGCT).

#### 1- Bipolar Junction Transistor (BJT)

![BJT Power Transistor](image)

BJT: symbol (npn) v-i characteristics

- Ratings: Voltage: $V_{CE} < 1600$ V, Current $I_C < 1000$ A.
- Switching frequency up to 5 kHz.
- Low on-state voltage $V_{CE}$: 2-3V, hence low on-state loss.
- Low current gain ($\beta$) Need high base current to obtain reasonable $I_C$.
- Expensive and complex base drive circuit.
- Not popular in new products.

**BJT Power Transistor Characteristics**

- To turn on/off the device, a base drive circuit is connected to the base and emitter terminal.
- To turn on, current is injected into the base terminal. When turned on, conventional current passes from collector to emitter.
- To turn-off, the base current is removed.
- The current gain of a BJT ends to be low when operated in the saturated ON condition. $\beta < 10$ is common. It deteriorates as voltage ratings increases.
- It is normal to use Darlington connection for higher current gain.
2- Metal Oxide Semiconductor Field Effect Transistors
“MOSFETs”
These are three terminal switches as shown in Fig. 2.13.

This is considered the fastest power switching device (200 kHz) for rating voltages < 500V, current \( I_{DS} < 300A \), or at 100 kHz, < 1500 V, 300 A.

MOSFET characteristics
- Turning on and off is very simple. Only need to provide \( V_{GS} = +15V \) to turn on and 0V to turn off. Gate drive circuit is simple.
- Basically low voltage device. High voltage device are available up to 600V but with limited current. Can be paralleled quite easily for higher current capability.
- Dominant in high frequency application (>100 kHz). Biggest application is in switched-mode power supplies.
- On state loss relatively high. \( V_{DS} > 3 \) V.

Practically, MOSFET’s characteristic consists of three regions, as shown in Fig.2.13:
- Cut OFF region (OFF state) when \( V_{GS} < V_{Th} \).
- Linear region when \( V_{DS} < V_{GS} - V_{Th} \), and
- Active region when \( V_{DS} > V_{GS} - V_{Th} \).

Ideally, MOSFETs are represented by a short circuit when operating within the ON State and as an open circuit when operating within the OFF State.
3 - Insulated Gate Bipolar Transistor “IGBT”

This is also a three terminal switch as shown in Fig. 2.14. Its operation modes and characteristics are almost similar to those for MOSFETs, shown in Fig. 2.13, except for the operating ranges.

IGBT: symbol

Fig.2.14: IGBT

IGBT has a combination of BJT and MOSFET characteristics. Compromises include:

- Gate behavior similar to MOSFET - easy to turn on and off.
- Low losses like BJT due to low on-state Collector-Emitter voltage $V_{CE} = (2-3V)$.
- Ratings: Voltage: $V_{CE} < 6000V$, Current 2500A currently available.
- Good switching capability (up to 100 kHz) for newer devices.
- Typical application, IGBT is used at 20-50 kHz.
- For very high power devices and applications, frequency is limited to several kHz -
- Very popular in new products; practically replacing BJT in most new applications
- "Snubberless" operation is possible. Most new IGBTs do not require snubber.
Other switching devices:

There are several other power switching devices available such as: Diac, Static Induction Transistors (SITs), Static Induction Thyristors (SITHs), and MOS-Controlled Thyristors (MCT).

MCTs (MOS Controlled Thyristor)

An effort to combine the advantages of bipolar junction and field-effect structures has resulted in hybrid devices:
- The IGBT is an improvement over a BJT.
- The MCT is an improvement over a thyristor.

MCT characteristics

- MCT can be switched on or off by negative or positive gate voltage, respectively.
- It has fast TURN-ON and then OFF times, with high-speed switching capability.
- Low conduction losses, low switching losses, and high current density.
- The gating requirements of an MCT are easier than those of the GTO since it needs smaller gate turn-off current due to its high gate input impedance.
- Compared with the power MOSFET, it has higher current density and lower forward drop. It has great potential in high-power, high-voltage applications. A peak power of 1 MW can be switched off in 2 ns by a single MCT.

Therefore, the MCT overcomes several of the limitations of the existing power devices and promises to be a better switch for the future. The MCT symbol and equivalent circuit are shown in Fig.2.15. The MCT characteristics are shown in Fig.2.16.
New Emerging Devices

The Power Silicon Carbide Semiconductors

Silicon Carbide (SiC) semiconductors are a new option for power electronic designers looking to improve system efficiency, its features are:

** Extremely low Switching losses**
- Zero reverse recovery charge - improves system efficiency

** High Power Density**
- Smaller footprint device reduces system size and weight
**High thermal conductivity**  
- 2.5 x more thermally conductive than silicon  

**Reduced Sink requirements**  
- results in lower cost and smaller size  

**High temperature operation**  
- increased power density and improved reliability.

Figure 2.17 shows a summary of power semiconductor device capabilities by the year 2016.

Figure 2.17: Summary of power semiconductor device capabilities. All devices except the MCT have a relatively mature technology, and only evolutionary improvements in the device capabilities are anticipated in the next few years. However, MCT technology is in a state of rapid expansion, and significant improvements in the device capabilities are possible as indicated by the expansion arrow in the diagram.