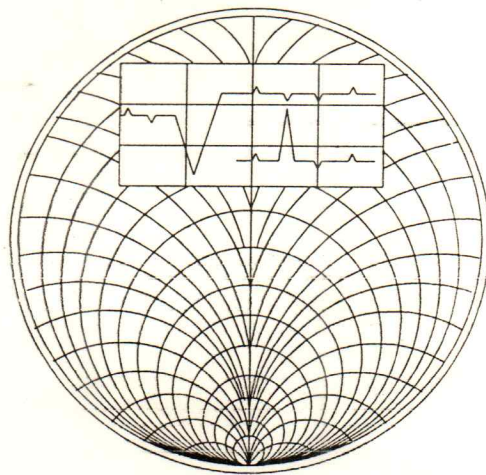


# ***MOSFET/IGBT TRAINER***

***(MODEL: ITB-PEC16)***

***Text-Lab Manual***

***Ver 3.0***



***Vi Microsystems Pvt. Ltd.***  
***Chennai - 600 096.***

# PREFACE

Power Electronics deals with the applications of solid state power semiconductor devices for the control and conversion of electric power. It links the two major traditional divisions of electrical engineering, namely, electric power and electronics.

In recent years, the field of power electronics has experienced large growth, primarily because of the development of semiconductor power devices that can efficiently switch larger currents at higher voltages. The switching speed of the power devices have been significantly improved.

Revolutionary advances in the areas of microelectronics, linear integrated circuits and or digital signal processors have led to the development of effective controllers for the controlled switching operation of the power electronic converters in a simple manner.

All these developments have made it possible to realise efficient and reliable power converters for a variety of applications with power levels ranging from few milli-watts to mega-watts. Such applications include switch mode regulated power supply systems (SMPS), uninterruptable power supplies (UPS), variable speed DC and AC electric motor drives, high voltage DC links between AC power networks etc.

As the applications of power electronics are ever increasing, the need to include power electronics in the undergraduate curriculum for electrical and electronics engineers is now well accepted. It has been taught as a subject for the last one decade, mainly covering the first ever power switching device namely the Silicon Controlled Rectifier (SCR) and its applications in power converters. The topics have been covered under two broad classifications, namely, the line commutated converters and the forced commutated converters. The force commutated converters employing SCRs require separate commutating circuits which are complicated.

The availability of controllable power switching devices such as the Bipolar Junction Power Transistors (Power BJTs), Metal-oxide semiconductor Field-Effect Transistors (Power MOSFETs), Gate-turn off thyristors (GTOs), Insulated Gate Bipolar Transistors (IGBTs), MOS controlled thyristors (MCTs) etc., now, have led to a variety of power converter topologies for various applications. Therefore, it becomes necessary to study the power converters employing these devices and the controllers using modern micro-electronic devices such as Microcontrollers and DSP processors.

In recent times a number of text-books have been published covering the theoretical aspects of the modern power converters and the associated control principles. But a parallel development of laboratory equipments, for teaching power electronics effectively does not seem to have emerged. To augment this lacuna, Vi Microsystems has brought out a number of modules involving SCRs, Power MOSFETs and IGBTs to study the operation of power converters and their control principles.

This text-lab manual explains in detail the characteristics of the modern power semiconductor devices and the operation of power converters employing them. The experiments need to be conducted to understand the operation of the power converters are explained. A step by step procedure to perform the experiments are given. We hope that these modules will help in setting up a good power electronics laboratory in a simple manner.

We, also hope that this would contribute towards an efficient pattern for teaching power electronics and thereby contribute towards effective training of undergraduate engineering and Diploma students in this ever expanding area of practical applications.

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# CHAPTER - 1

## POWER SEMICONDUCTOR SWITCHES (DEVICES)

### Introduction:

Power Electronics is the technology of converting electric power from one form to another using electronic power devices. In the power converter, the power semiconductor devices function as switches, which operate statically, that is, without moving contacts. The time durations, as well as the turn ON and turn OFF operations of these switches are controlled in such a way that an electrical power source at the input terminals of the converter appears in a different form at its output terminals. The output parameters of the converter such as voltage, current and frequency are controlled efficiently.

The increased power capabilities (voltages and current ratings), ease of control, and reduced cost of modern power semiconductor devices have made power converters affordable in a large number of applications. A host of new converter topologies have emerged for a variety of applications.

In order to clearly understand the operation of the various converters and their feasibility for various applications, it is essential to study the characteristics of available power semiconductor devices.

Presently available power semiconductor devices can be classified into three groups according to their degree of controllability.

- i) Diodes - ON and OFF states controlled by the power circuit.
- ii) Thyristors - Latched ON by a control signal but must be turned OFF by the power circuit.
- iii) Controllable Switches - Turned ON and OFF by control signals.

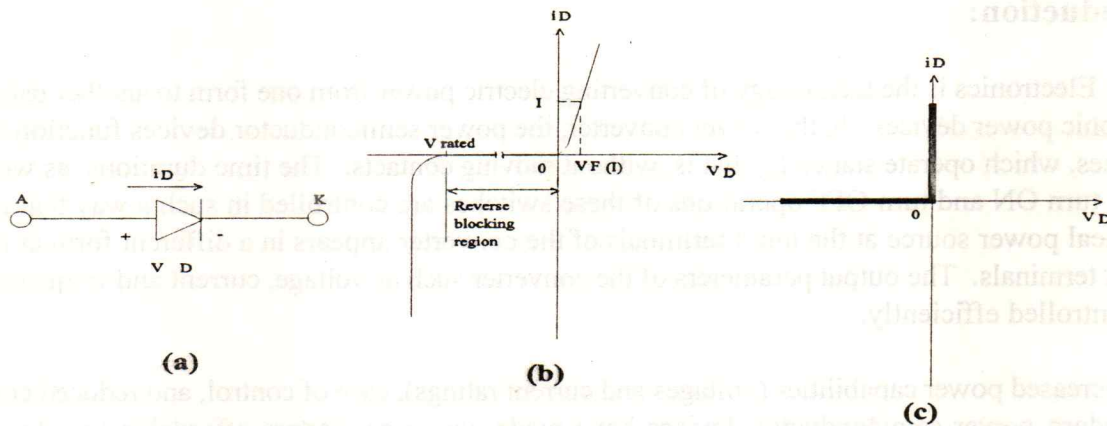
The controllable switches that are available at present are

- i) Bipolar Junction Transistors (BJTs)
- ii) Metal Oxide Semiconductor Field Effect Transistors (MOSFETs)
- iii) Gate Turn Off Thyristors (GTOs)
- iv) Insulated Gate Bipolar Transistors (IGBTs)

The construction and the characteristics of these devices are explained in the following.

**DIODES:**

The circuit symbol for the diode and its steady state  $v$ - $i$  characteristics are shown in figure 1.1(a) and 1.1(b).



**Figure 1.1 Diode: (a) symbol, (b)  $i$ - $v$  characteristics, (c) Idealized characteristics**

When the diode is forward biased, it begins to conduct with only a small forward voltage across it, which is on the order of 1V. When the diode is reverse biased, only a negligibly small leakage current flows through the device until the reverse break-down voltage is reached. In normal operation, the reverse-bias voltage should not reach the breakdown rating.

In view of the very small leakage currents in the blocking (reverse-bias) state and the small voltage in the conducting (forward-bias) state as compared to the operating voltage and currents of the circuit in which the diode is used, the  $i$ - $v$  characteristics for the diode can be idealized, as shown in Figure 1.1c. This idealized characteristic can be used for analysing the converter topology but should not be used for the actual design, when, for example, heat sink requirements for the device are being estimated.

At turn-on, the diode can be considered an ideal switch because it turns on rapidly compared to the transients in the power circuit. However, at turn-off, the diode current reverses for a reverse-recovery time  $t_{rr}$ , as is indicated in Figure 1.2, before falling to zero. This reverse-recovery (negative) current is required to sweep out the excess carriers in the diode and allow it to block a negative polarity voltage. The reverse-recovery current can lead to over voltages in inductive circuits. In most circuits, this reverse current does not affect the converter input/output characteristic and so the diode can also be considered as ideal during the turn-off transient.

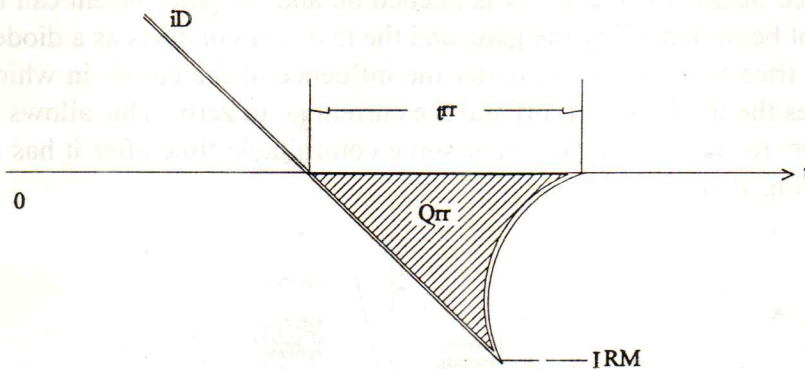


Figure 1.2. Diode turn-off

Depending on the application requirements, various types of diodes are available:

1. **Schottky diodes.** These diodes are used where a low forward voltage drop (typically 0.3V) is needed in very low output voltage circuits. These diodes are limited in their blocking voltage capabilities to 50-100V.
2. **Fast-recovery diodes.** These are designed to be used in high-frequency circuits in combination with controllable switches where a small reverse-recovery time is needed. At power levels of several hundred volts and several hundred amperes, such diodes have  $t_{rr}$  ratings of less than a few microseconds.
3. **Line-Frequency Diodes.** The on-state voltage of these diodes is designed to be as low as possible and as a consequence have larger  $t_{rr}$ , which are acceptable for line-frequency applications. These diodes are available with blocking voltage ratings of several kilovolts and current ratings of several kiloamperes. Moreover, they can be connected in series and parallel to satisfy any voltage and current requirement.

### 1.3 THYRISTORS

The circuit symbol for the thyristor and its  $i-v$  characteristics are shown in Figure 1.3(a) and 1.3(b). The main current flows from the anode (A) to the cathode (K). In its off-state, the thyristor can block a forward polarity voltage and not conduct, as is shown in Figure 1.3(b) by the off-state portion of the  $i-v$  characteristic.

The thyristor can be triggered into the on state by applying a pulse of positive gate current for a short duration provided that the device is in its forward-blocking state. The resulting  $i-v$  relationship is shown by the on-state portion of the characteristics shown in Figure 1-3(b). The forward voltage drop in the on state is only a few volts (typically 1-3V depending on the device blocking voltage rating).

Once the device begins to conduct, it is latched on and the gate current can be removed. The thyristor cannot be turned off by the gate, and the thyristor conducts as a diode. Only when the anode current tries to go negative, under the influence of the circuit in which the thyristor is connected, does the thyristor turn off and the current go to zero. This allows the gate to regain control in order to turn the device on at some controllable time after it has again entered the forward-blocking state.

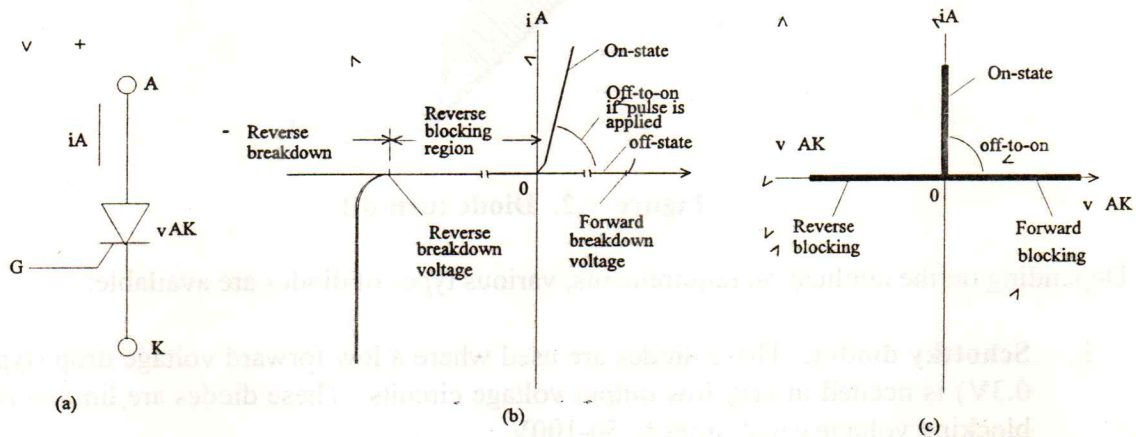


Figure 1.3 Thyristor: (a) Symbol (b) i-v Characteristics (c) idealized characteristics

In reverse bias at voltages below the reverse breakdown voltage, only a negligibly small leakage current flows in the thyristor, as is shown in Figure 1.3(b). Usually the thyristor voltage ratings for forward and reverse blocking voltages are the same. The thyristor current ratings are specified in terms of maximum rms and average currents that is capable of conducting. The idealized v-i characteristics of the SCR operating as a switch is shown in figure 1.3(c).

In an application such as the simple circuit shown in Figure 1.4(a) control can be exercised over the instant of current conduction during the positive half cycle of source voltage. When the thyristor current tries to reverse itself when the source voltage goes negative, the idealized thyristor would have its current become zero immediately after  $t = \frac{1}{2}T$ , as is shown in the waveform in Figure 1.4(b).

However, as specified in the thyristor data sheets and illustrated by the waveforms in Figure 1.4(c), the thyristor current reverses itself before becoming zero. The important parameter is not the time it takes for the current to become zero from its negative value, but rather the turn-off time interval  $t_q$  defined in Figure 1.4(c) from the zero crossover of the current to the zero crossover of the voltage across the thyristor. During  $t_q$  a reverse voltage must be maintained across the thyristor, and only after this time is the device capable of blocking a forward voltage without going into its on state. If a forward voltage is applied to the thyristor before this interval has passed, the device may prematurely turn on, and damage to the device and/or circuit could result. Thyristor data sheets specify  $t_q$  with a specified reverse voltage applied during this interval as well as a specified rate of rise of voltage beyond this interval. This interval  $t_q$  is sometimes called the circuit-commutated recovery time (circuit turn-off time) of the thyristor.

Depending on the application requirements, various types of thyristors are available. In addition to voltage and current ratings, turn-off time  $t_q$ , and the forward voltage drop, other characteristics that must be considered include the rate of rise of the current ( $di/dt$ ) at turn-on and the rate of rise of voltage ( $dv/dt$ ) at turn-off.

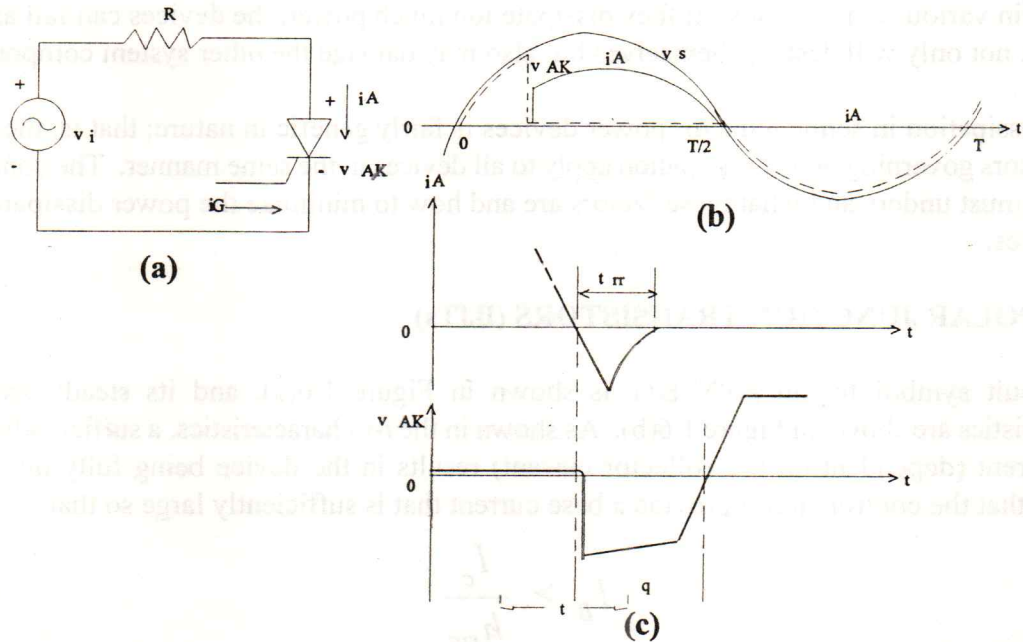


Figure 1.4 Thyristor: (a) Circuit, (b) Waveforms, (c) turn-off time interval  $t_q$ .

#### 1.4 DESIRED CHARACTERISTICS OF CONTROLLABLE SWITCHES:

As mentioned in the introduction, most types of semiconductor power devices including BJTs, MOSFETs, GTO, and IGBTs can be turned on and off by control signals applied to the control terminal of the device. These devices we term *controllable switches* and are represented in a generic manner by the circuit symbol shown in Figure 1.5. No current flows when the switch is off, and when it is on, current can flow in the direction of the arrow only. The ideal controllable switch has the following characteristics:

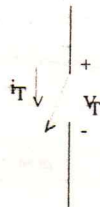


Figure 1.5. Generic Controllable Switch

1. Block arbitrarily large forward and reverse voltages with zero current flow when off.
2. Conduct arbitrarily large currents with zero voltage drop when on.
3. Switch from on to off or vice versa instantaneously when triggered.
4. Vanishingly small power required from control source to trigger the switch.

Real devices, do not have these ideal characteristics and hence will dissipate power when they are used in various applications. If they dissipate too much power, the devices can fail and, in doing so, not only will destroy themselves but also may damage the other system components.

Power dissipation in semiconductor power devices is fairly generic in nature; that is, the same basic factors governing power dissipation apply to all devices in the same manner. The converter designer must understand what these factors are and how to minimize the power dissipation in the devices.

### 1.5 BIPOLAR JUNCTION TRANSISTORS (BJTs)

The circuit symbol for an NPN BJT is shown in Figure 1.6(a), and its steady-state  $i-v$  characteristics are shown in Figure 1.6(b). As shown in the  $i-v$  characteristics, a sufficiently large base current (dependent on the collector current) results in the device being fully on. This requires that the control circuit provide a base current that is sufficiently large so that

$$I_B > \frac{I_c}{h_{FE}}$$

where  $h_{FE}$  is the dc current gain of the device.

The on-state voltage  $V_{CE(sat)}$  of the power transistors is usually in the 1-2V range, so that the conduction power loss in the BJT is quite small. The idealized  $i-v$  characteristics of the BJT operating as a switch are shown in Figure 1.6(c).

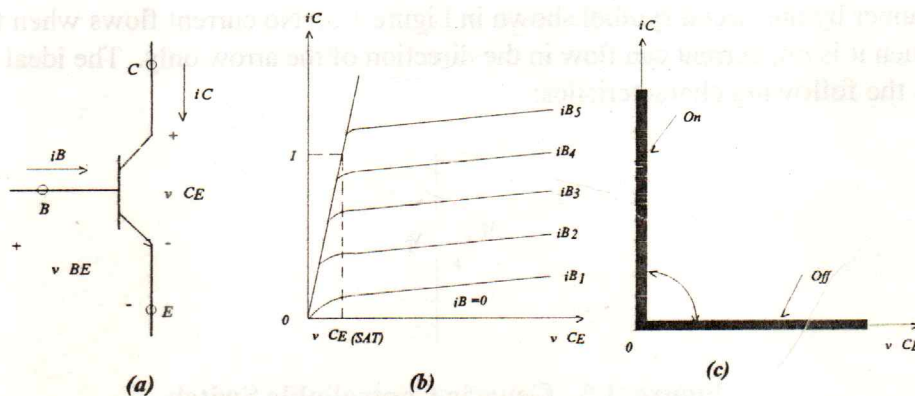


Figure 1.6 A BJT: (a) Symbol, (b)  $i-v$  Characteristics, (c) idealized characteristics

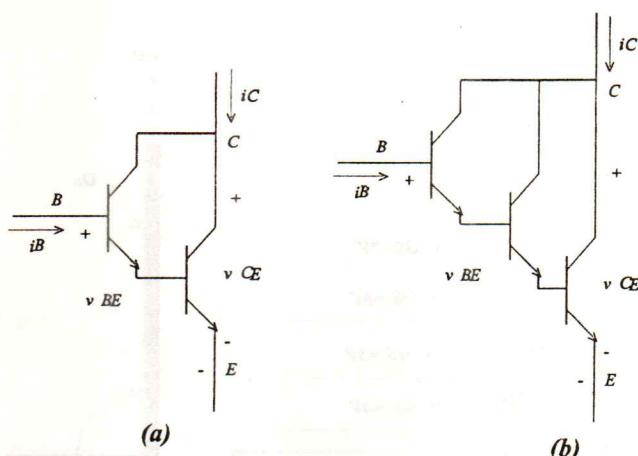


Figure 1.7 Darlington Configurations: (a) Darlington (b) Triple Darlington

Bipolar junction transistors are current-controlled devices, and base current must be supplied continuously to keep them in the on state: The dc current gain  $h_{FE}$  is usually only 5-10 in high-power transistors, and so these devices are sometimes connected in a Darlington or triple Darlington configuration, as is shown in Figure 1.7, to achieve a larger current gain. Some disadvantages accrue in this configuration including slightly higher overall  $V_{CE(sat)}$  values and slower switching speeds.

Whether in single units or made as a Darlington configuration on a single chip [a monolithic Darlington (MD)], BJTs have a significant storage time during the turn-off transition. Typical switching times are in the range of a few hundred nanoseconds to a few microseconds.

Including MDs, BJTs are available in voltage ratings upto 1400V and current ratings of a few hundred amperes. In spite of a negative temperature coefficient of on-state resistance, modern BJTs fabricated with good quality control can be paralleled provided that care is taken in the circuit layout and that some extra current margin is provided, that is, where theoretically four transistors in parallel would suffice based on equal current sharing, five may be used to tolerate a slight current imbalance.

## 1.6 METAL-OXIDE-SEMICONDUCTOR FIELD EFFECT TRANSISTORS: (MOSFETs)

The circuit symbol of an n-channel MOSFET is shown in Figure 1.8(a). It is a voltage controlled device, as is indicated by the  $i$ - $v$  characteristics shown in Figure 1.8(b). The device is fully on and approximates a closed switch when the gate-source voltage is below the threshold value,  $V_{GS(th)}$ . The idealized characteristics of the device operating as a switch are shown in Figure 1.8(c).

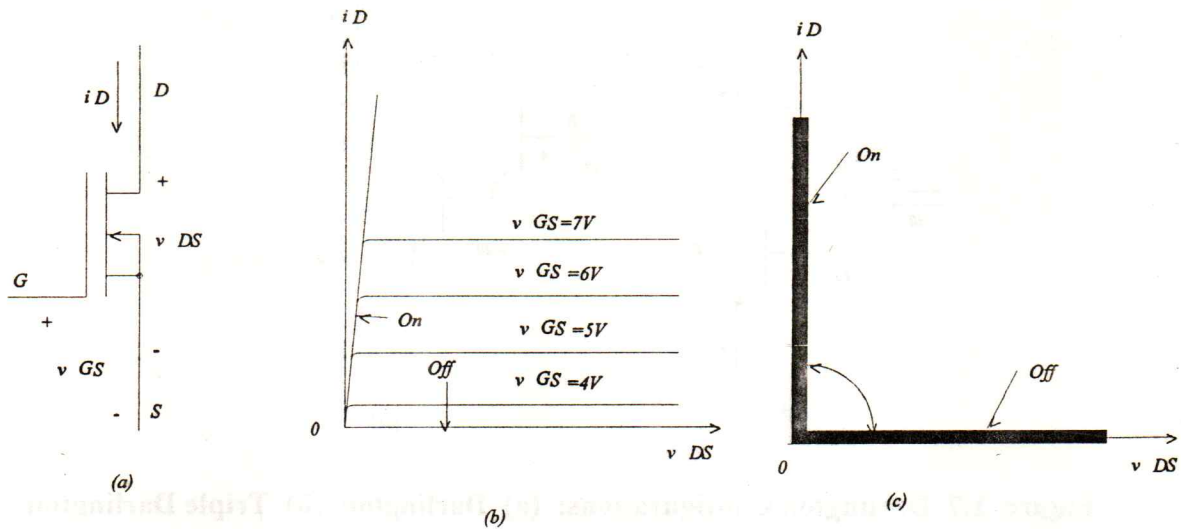


Figure 1.8: N channel MOSFET:

- (a) Symbol,
- (b)  $i$ - $v$  Characteristics,
- (c) idealized characteristics

Metal-oxide-semiconductor field effect transistors require the continuous application of a gate-source voltage of appropriate magnitude in order to be in the on state. No gate current flows except during the transitions from on to off or vice versa when the gate capacitance is being charged or discharged. The switching times are very short, being in the range of a few tens of nanoseconds to a few hundred nanoseconds depending on the device type.

The on-state resistance  $r_{DS(on)}$  of the MOSFET between the drain and source increases rapidly with the device blocking voltage rating. Because of this, only devices with small voltage ratings are available that have low on-state resistance and hence small conduction losses.

Metal-oxide-semiconductor field effect transistors are available in voltage ratings in excess of 1000V but with small current ratings and with up to 100 A at small voltage ratings. The maximum gate-source voltage is  $\pm 20V$ , although MOSFETs that can be controlled by 5-V signals are available.

## 1.7 GATE TURN-OFF THYRISTORS: (GTOs)

The circuit symbol for the GTO is shown in Figure 1.9(a) and its steady-state  $i$ - $v$  characteristics is shown in Figure 1.9(b).

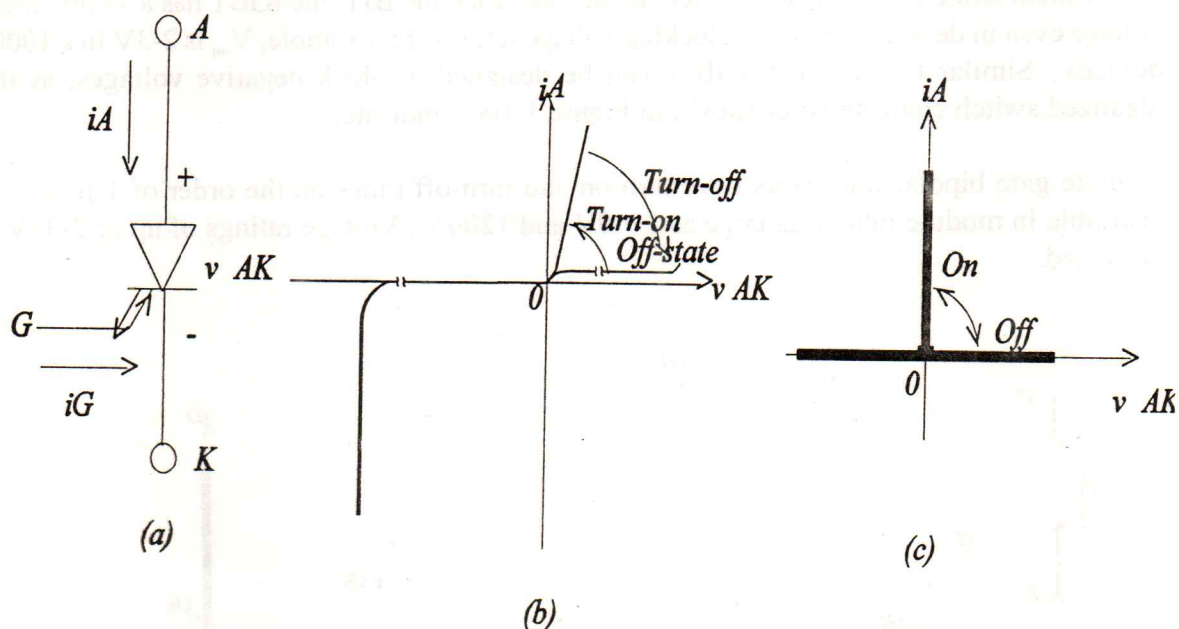


Figure 1.9: Gate turn-off transient characteristics

- (a) snubber circuit,  
(b) GTO turn-off characteristic.

Like the thyristor, the GTO can be turned on by a short-duration gate current pulse, and once in the on-state, the GTO may stay on without any further gate current. However, unlike the thyristor, the GTO can be turned off by applying a negative gate-cathode voltage, therefore causing a sufficiently large negative gate current to flow. This negative gate current need only flow for a few microseconds (during the turn-off time), but it must have a very large magnitude, typically as large as one-third the anode current being turned off. The GTOs can block negative voltages whose magnitude depends on the details of the GTO design. The idealized characteristics of the device operating as a switch are shown in Figure 1.9(c).

The on-state voltage (2-3V) of a GTO is slightly higher than those of thyristors. The GTO switching speeds are in the range of a few microseconds to 25  $\mu$ s. Because of their capability to handle large voltages (up to 4.5 kV) and large currents (up to a few kilo-amperes), the GTO is used when a switch is needed for high voltages and large currents in a switching frequency range of a few hundred hertz to 10 kHz.

1.8 INSULATED GATE BIPOLAR TRANSISTORS:

The circuit symbol for an IGBT is shown in Figure 1.10(a) and its  $i$ - $v$  characteristics are shown in Figure 1.10(b). The IGBT's have some of the advantages of the MOSFET, the BJT, and the GTO combined. Similar to the MOSFET, the IGBT has a high impedance gate, which requires only a small amount of energy to switch the device. Like the BJT, the IGBT has a small on-state voltage even in devices with large blocking voltage ratings (for example,  $V_{on}$  is 2-3V in a 1000-V device). Similar to the GTO, IGBTs can be designed to block negative voltages, as their idealized switch characteristics shown in Figure 1.10(c) indicate.

Insulate gate bipolar transistors have turn-on and turn-off times on the order of  $1 \mu s$  and are available in module ratings as large as 1700V and 1200A., Voltage ratings of up to 2-3kV are projected.

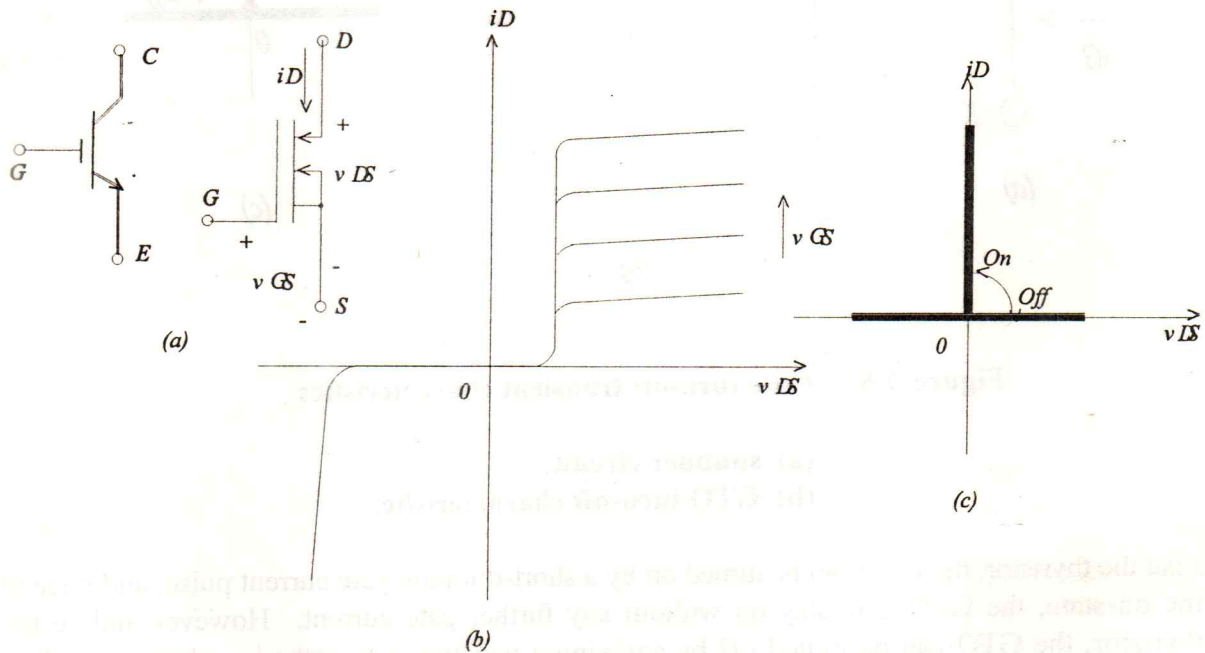


Figure 1.10. An IGBT:

- (a) symbol,
- (b)  $i$ - $v$  characteristics,
- (c) idealized characteristics

1.9 COMPARISON OF CONTROLLABLE SWITCHES:

Only a few definite statements can be made in comparing these devices since a number of properties must be considered simultaneously and because the devices are still evolving at a rapid pace. However, the qualitative observations given in Table 1.1 can be made.

It should be noted that in addition to the improvements in these devices, new devices are being investigated. The progress in semiconductor technology will undoubtedly lead to higher power ratings, faster switching speeds, and lower costs.

On the other hand, the forced-commutated thyristor, which was once widely used in circuits for controllable switch applications, is no longer being used in new converter designs with the possible exception of power converters in multi-MVA ratings. This is a pertinent example of how the advances in semiconductor power devices have modified converter design.

Table 1-1. Relative Properties of Controllable Switches

Device	Power Capability	Switching Speed
BJT/MD	Medium	Medium
MOSFET	Low	Fast
GTO	High	Slow
IGBT	Medium	Medium

CONCLUSION:

Characteristics and capabilities of various power semiconductor devices are presented in, this chapter. The various power converter modules control modules developed for laboratory experimental studies are explained in the following chapters.