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CHAPTER1

1. Introduction

The object of this chapter is to discuss briefly the concept of power electronics, applications of power electronics and the types of power converters described in this lectures.

1.1.CONCEPT OF POWER ELECTRONICS:

Power electronics deals with conversion and control of electrical power with the help of electronic switching devices. The magnitude of power may vary widely, ranging from a few watts to several gigawatts. Power electronics differs from signal electronics, where the power may be from a few nanowatts to a few watts, and processing of power may be by analog (analog electronics) or digital or switching devices (digital electronics). One advantage of the switching mode of power conversion is its high efficiency, which can be 96% to 99%. High efficiency saves electricity. In addition, power electronic devices are more easily cooled than analog or digital electronics devices. Power electronics is often defined as a hybrid technology that involves the disciplines of power and electronics.

Power electronics belongs partly to power engineers and partly to electronics engineers. Power engineering is mainly concerned with generation, transmission, distribution and utilization of electric energy at high efficiency; Electronics engineering, on the other hand, is guided by distortion less production, transmission and reception of data and signals of very low power level of the order of a few watts, or mill watts without much consideration to the efficiency. In addition, apparatus associated with power engineering is based mainly on electromagnetic principles whereas that in electronics engineering is based upon physical phenomena in vacuum, gases/vapors and semiconductors. Power electronics is a subject that concerns the application of electronic-principles into situations that are rated at power level rather than signal level. It may also defined as a subject that deals with the apparatus and equipment working on the principle of electronics but rated at power level rather than signal level. For example, semiconductor power switches such as thyristors, GTOs etc. work on the principle of electronics (movement of holes and electrons), but have the name power attached to them only as a description of their power ratings. Similarly, diodes, mercury-arc rectifiers and thyratrons (gas-filled triode); high-power level devices, form a part of the subject power electronics; because their working" is based on the physical phenomena in gases and

vapors, an electronic process. As the inclusion of all such power-rated electronic equipments would be a voluminous task, the present book is devoted to the study of semi-conductor-based power-electronic components and systems only.

It should be understood that the techniques used in the design of high efficiency and high-energy level power electronic circuits are quite different from the employed in the design of low-efficiency electronic circuits at signal levels.

1.2 APPLICATIONS OF POWER ELECTRONICS:

Some Applications of Power Electronics:

1. Aerospace:

Space shuttle power supplies, satellite power supplies, aircraft power systems.

2. Commercial:

Advertising, heating, air-conditioning, central refrigeration, computer and uninterruptible power supplies, elevators, light dimmers and flashers.

3. Industrial:

Arc and industrial furnaces, blowers and fans, pumps and compressors, industrial lasers, transformer-tap 'changers, rolling mills, textile mills, excavators, cement mills, welding.

4. Residential :

Air-conditioning, cooking, lighting, space heating, refrigerators, electric-door openers, dryers, fans, personal computers, other entertainment equipment, vacuum cleaners, washing and sewing machines, light dimmers, food mixers, electric blankets, food-warmer trays.

5. Telecommunication:

Battery chargers, power supplies (dc and UPS).

6. Transportation:

Battery chargers, traction control of electric vehicles, electric locomotives, street cars~ trolley buses subways, automotive electronics.'

7. Utility systems:

High voltage dc transmission (HVDC), excitation systems, VAR compensation, static circuit breakers, fans and boiler-feed pumps, supplementary energy system (solar, wind).

1.3. ADVANTAGES AND DISADVANTAGES OF POWER ELECTRONIC CONVERTERS

(i) High efficiency due to low loss in power-semiconductor devices. (ii) High reliability of power-electronic converter systems.

(iii) Long life and less maintenance due to the absence of any moving parts.

(iv) Fast dynamic response of the power-electronic systems as compared to electromechanical converter systems.

(v) Small size and less weight result in less floor space and therefore lower installation cost.

(vi) Mass production of power-semiconductor devices has resulted in lower cost

of the, converter equipment Systems based on power electronics, however, suffer

from the following disadvantages;

(a) Power-electronic converter circuits have a tendency to generate harmonics in the supply system, as well as in the load circuit.

In the load circuit, the performance of the load is influenced, for example, a high harmonic content in the load circuit causes commutation problems in dc machines, increased motor heating and more acoustical noise in both dc and ac machines.

So steps must be taken to filter these out from the output side of a converter. In the supply system, the harmonics distort the voltage waveform and seriously influence the performance of other equipment connected to the same supply line. In addition, the harmonics in the supply line can also cause interference with communication lines. It is, therefore necessary to insert filters on the input side of a converter.

(b) Ac to dc and ac to ac converters operate at a low input power factor under certain operating conditions. In order to avoid a low pf, some special measures have to be adopted.

(c) Power-electronic controllers have low overload capacity. These converters must, therefore, be rated for taking momentary overloads. As such, cost of power electronic controller may increase.

(d) Regeneration of power is difficult in power electronic converter systems. The advantages possessed by power electronic converters far outweigh their disadvantages mentioned above. As a consequence, semiconductor-based converters are being extensively employed in systems, where power flow is to be regulated. As already stated, conventional power controllers used in many installations have already been replaced by semiconductor-based power electronic controllers.

1.4. POWER SEMICONDUCTOR DEVICES

Silicon controlled rectifier (SCR) was introduced first in 1957. Since then, several other power semiconductor devices have been developed. All these semiconductor devices are enumerated below along with their ratings. Power diodes are available up to 3000 V, 3500 A, 1 kHz. Thyristors have ratings up to 6000V,3500 A, 1 kHz. SITHs (static induction thyristors) can operate up to 4000 V,2200 A,20 kHz.

GTOs (gate-turn off thyristors) have ratings of 4000V,3000 A, 10 kHz. MCTs (MOS controlled thyristors) can work up to 600 V, 60 A, 20 kHz. Triacs have power ratings of 1200V, 300 A, 400 Hz. BJTs are used up to power ratings of 1200 V, 400 A, 10 kHz. Power MOSFETs (metal oxide semiconductor field effect transistors) and SITs (static induction transistors) have relatively low range of 1000 V,50 A and 1200 V, 300 A respectively .Both these devices can, however, operate satisfactorily up to a frequency range of 100 kHz.

IGBTs (insulated gate bipolar transistors) are available up to 1200 V, 400 A and 20 kHz. Based on (i) turn-on and turn-off characteristics and (ii) gate signal requirements, the power semiconductor devices can be classified as under: (a) Diodes: These are uncontrolled, rectifying devices. Their on and off states are controlled by power- supply.

b) Thyristors : These have controlled turned-on by a gate signal. After thyristors are turned-on, they remain latched-in on-state due to internal regenerative action, (c) Controllable switches: These devices are turned-on and turned-off by the application

of control signals. The devices which behave as controllable switches are BJT, MOSFET, GTO,SITH, IGBT, SIT and MCT.

SCR, GTO, SITH and MCT require pulse-gate signal for turning them on ; once these devices are on, gate pulse is removed. But BJT, MOSFET, IGBT and SIT require continuous signal for keeping them in turn-on state.

The devices which can withstand unipolar voltage are BJT, MOSFET, IGBT and MCT .Thyristors and GTOs are capable of supporting bipolar voltages.

Triac and RCT (reverse conducting thyristor) possess bidirectional current capability whereas all other remaining devices (diode, SCR, GTO, BJT, MOSFET, IGBT, SIT, SITH,MCT) are unidirectional current devices.

1.5 TYPES OF POWER ELECTRONIC CONVERTERS A power electronic system consists of one or more power electronic converters. A power electronic converter is made up of some power semiconductor devices controlled by integrated circuits. The switching characteristics of power semiconductor devices permit a power electronic converter to shape the input power of one form to output power of some other form. Static

power converters perform these functions of power conversion very efficiently. Broadly speaking, power electronic converters (or circuits) can be classified into six types as under:

1. Diode Rectifiers: A diode rectifier circuit converts ac input voltage into a fixed dc voltage. The input voltage may be single-phase or three phase. Diode rectifiers find wide use in electric traction, battery charging, electroplating, electrochemical processing, power supplies, welding and uninterruptible power supply (UPS) systems.

2. Ac to dc converters (Phase-controlled rectifiers) : These convert constant ac voltage to variable dc output voltage. These rectifiers use line voltage for their commutation as such these are also called line-commutated or naturally-commutated ac to dc converters.

Phase-controlled converters may be fed from 1-phase or 3-phase source. These are used in dc drives, metallurgical and chemical industries, excitation systems for synchronous machines etc.

3. DC to dc converters (DC Choppers) : A dc chopper converts fixed dc input voltage to a controllable dc output voltage. The chopper circuits require forced, or load, commutation to turn-off the thyristors. For lower power circuits, thyristors are replaced by power transistors. Classification of chopper circuits is dependent upon the type of commutation and also on the direction of power flow. Choppers find wide applications in dc drives, subway cars, trolley trucks, battery-driven vehicles etc.

4. DC to ac converters (inverters) : An inverter converts fixed dc voltage to a variable ac voltage. The output may be a variable voltage and variable frequency. These converters use line, load or forced commutation for turning-off the thyristors. Inverters find wide use in induction-motor and synchronous-motor drives, induction heating, UPS, HVDC transmission etc. At present, conventional thyristors are also being replaced by GTOs in high-power applications and by power transistors in low-power applications.

5. AC to ac converters: These convert fixed ac input voltage into variable ac output voltage. These are of two types as under:

a. AC voltage controllers (AC voltage regulators) : These converter" circuits convert fixed ac voltage directly to a variable ac voltage at the same frequency. AC voltage controller

employ two thyristors in ant parallel or a triac. Turn-off of both the devices is obtained by line commutation. Output voltage is controlled by varying the firing angle delay. AC voltage controllers are widely used for lighting control, speed 'control of fans, pumps etc.

b. Cycloconverters : These circuits convert input power at one frequency to output power at a different frequency through one-stage conversion. Line commutation is more common in these converters, though forced and load commutated cycloconverters are also employed.

These are primarily used for slow-speed large ac drives like rotary kiln etc.

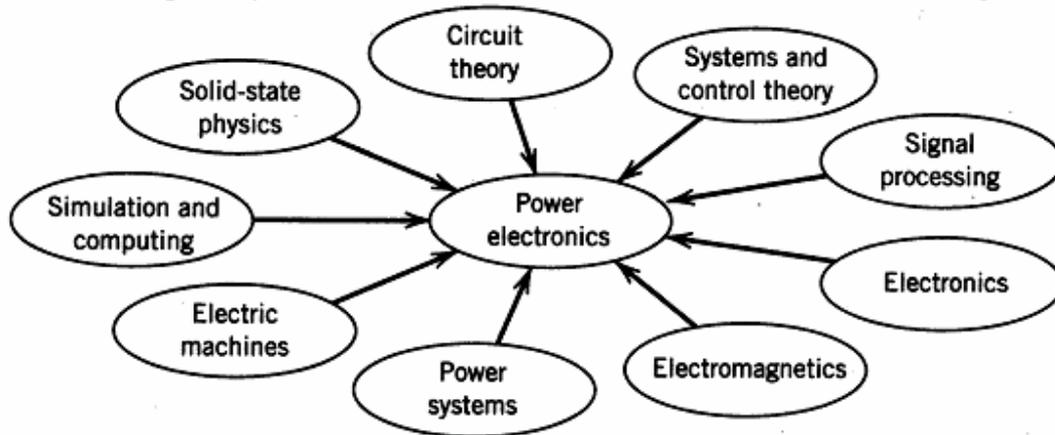
6. Static switches: The power semiconductor devices can operate as static switches or contactors. Static switches possess many advantages over mechanical and electromechanical circuit breakers. Depending upon the input supply, the static switches are called ac static switches or dc static switches.

1-6 POWER ELECTRONIC MODULES

A power electronic converter may require two, four or more semiconductor devices depending upon the circuit configuration. Power modules consisting of two, four or six devices are, at present, available. Thus, a power electronic converter can be assembled from power modules instead of from individual semiconductor devices. A power module has better performance characteristics as compared to conventional devices so far as their switching characteristics, operating speed and losses are concerned. Gate drive circuits for individual devices or power modules are also commercially available. As a result of these developments, now intelligent modules have come in the market.

Intelligent module, also called *smart-power*, is state-of-the-art power electronics and it consists of power module and a peripheral circuit. The peripheral circuit comprises of interfacing of power module with the input/output through proper isolation from low-voltage signal and from high-voltage power circuit, a drive circuit, protection and diagnostic circuitry against maloperation like excess current, over *voltage* etc, microcomputer control and controlled power supply. The user has merely to connect the existing supply and the load terminals to the smart-power. At present, intelligent modules are being used extensively in power electronics. It is reported that there are more than twenty manufacturers of intelligent modules.

Interdisciplinary Nature Of Power Electronics is illustrated in fig. below:



Chapter Two

POWER SEMICONDUCTOR DEVICES

2. Introduction:

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Triac and RCT (reverse conducting thyristor) possess bidirectional current capability whereas all other remaining devices (diode, SCR, GTO, BJT, MOSFET, IGBT, SIT, SITH, MCT) are unidirectional current devices.

The object of this chapter is to describe imported power diode, power transistor and thyristor.

2.1. CHARACTERISTICS OF POWER DIODES

Power diode is a two-layer, two-terminal, p-n semiconductor device. It has one pn-junction formed by alloying, diffusing or epitaxial growth. The two terminals of diode are called anode and cathode, Fig. 2.1 (a). Two important characteristics of power diodes are now described.

2.1.1. Diode V-I Characteristics

When anode is positive with respect to cathode, diode is said to be forward biased. With increase of the source voltage V_s from zero value, initially diode current is zero. From $V_s = 0$ to cut-in voltage, the forward-diode current is very small. Cut-in voltage is also known as threshold voltage or turn-on voltage. Beyond cut-in voltage, the diode current rises rapidly and the diode is said to conduct. For silicon diode, the cut-in voltage is around 0.7 V. When diode conducts, there is a forward voltage drop of the order of 0.8 to 1 V.

When cathode is positive with respect to anode, the diode is said to be reverse biased. In reverse biased condition of the diode, a small reverse current, called leakage current, of the order of the microamperes or mill amperes (for large diodes) flows. The leakage current increases slowly with the reverse voltage until breakdown or avalanche voltage is reached. At this breakdown voltage, diode is turned on in the reversed direction.

If current in the reversed direction is not limited by a series resistance, the current will become quite high to destroy the diode. The reverse avalanche breakdown of a diode is avoided by operating the diode below specified peak repetitive reverse voltage V_{RRM} . Fig. 2.1 (c) illustrates diode characteristics where V_{RRM} and cut-in voltage are shown.

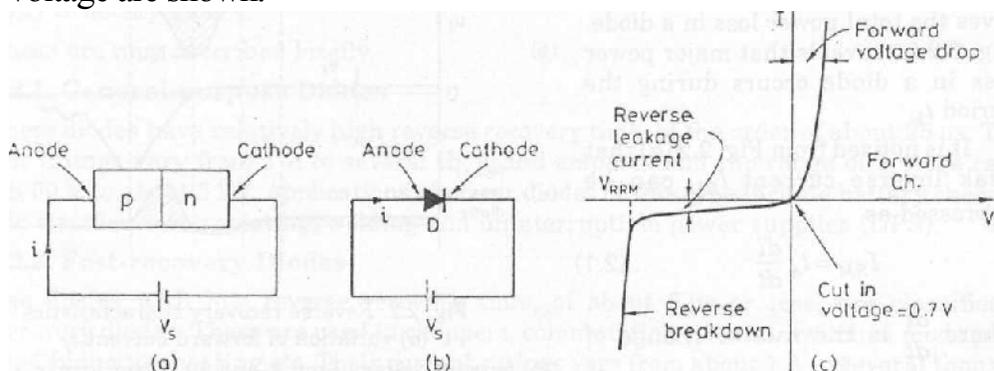


Fig. 2.1. (a) p-n junction (b) diode symbol (c) V-I characteristics of diode.

Diode manufacturers also indicate the value of peak inverse voltage (PIV) of a diode. This is the largest reverse voltage to which a diode may be subjected during its working. PIV is the same as V_{RRM} .

The power diodes are now available with forward current ratings of 1 A to several

thousand amperes and with reverse voltage ratings of 50 V to 3000 V or more.

2.1.2. Diode Reverse Recovery Characteristics

After the forward diode current decays to zero, the diode continues to conduct in the reverse direction because of the presence of stored charges in the two layers. The reverse current flows for a time called reverse recovery time t_{rr} . The diode regains its blocking capability until reverse recovery current decays to zero. The reverse recovery time t_{rr} is defined as the time between the instant forward diode current becomes zero and the instant reverse recovery current decays to 25% of its reverse peak value I_{RM} as shown in Fig. 2.2 (a).

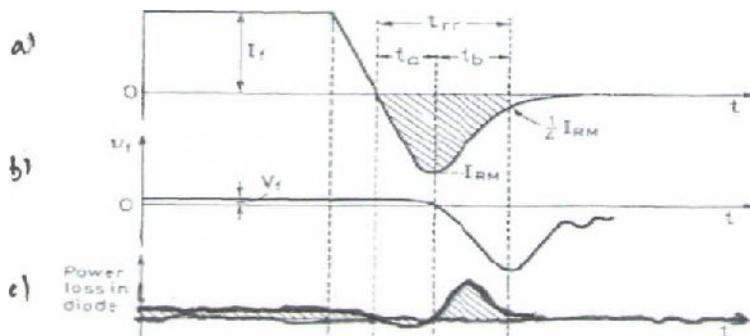


Fig. 2.2. Reverse recovery characteristics (a) variation of forward current **if**

22.2. TYPES OF POWER DIODES

Diodes are classified according to their reverse recovery characteristics. The three types of power diodes are as under :

(i) General purpose diodes (ii) Fast recovery diodes (iii) Schottky diodes.
 These are now described briefly.

2.2.1. General-purpose Diodes

These diodes have relatively high reverse recovery time, of the order of about 25 μ s. Their current ratings vary from 1 A to several thousand amperes and the range of voltage rating is from 50 V to about 5 kV. Applications of power diodes of this type include battery charging, electric traction, electroplating, welding and uninterruptible power supplies (UPS).

2.2.2. Fast-recovery Diodes

The diodes with low reverse recovery time, of about 5 μ s or less, are classified as fast-recovery diodes. These are used in choppers, commutation circuits, switched

mode power supplies, induction heating etc. Their current ratings vary from about 1 A to several thousand amperes and voltage ratings from 50 V to about 3 kV.

For voltage ratings below about 400 V, the epitaxial process is used for diode fabrication. These diodes have fast recovery time, as low as 50 ns.

For voltage ratings above 400 V, diffusion technique is used for the fabrication of diodes. In order to shorten the reverse-recovery time, platinum or gold doping is carried out. But this doping may increase the forward voltage drop in a diode.

2.2.3. Schottky Diodes

This class of diodes use metal-to-semiconductor junction for rectification purposes instead of p-n junction. Schottky diodes are characterised by very fast recovery time and low forward voltage drop. Rectified current flow is by majority carriers only and this avoids the turn-off delay accompanied with minority carrier recombination. Their reverse voltage ratings are limited to about 100 V and forward current ratings vary from 1 A to 300 A. Applications of Schottky diodes include high-frequency instrumentation and switching power supplies.

The electrical and thermal characteristics of power diodes are similar to those of thyristors .

2.3. POWER TRANSISTORS

Power diodes are uncontrolled devices. In other words, their turn-on and turn-off characteristics are not under control. Power transistors, however, possess controlled characteristics. These are turned on when a current signal is given to base, or control, terminal. The transistor remains in the on-state so long as control signal is present. When this control signal is removed, a power transistor is turned off.

Power transistors are of three types as under :

- (i) Bipolar junction transistors (BJTs).
- (ii) Metal-oxide-semiconductor field-effect transistors (MOSFETs).
- (iii) Insulated gate bipolar transistors (IGBTs) .

2.3.1. Bipolar Junction Transistors

A bipolar transistor is a three-layer, two junction *npn* or *pnp* semiconductor device. With one p-region sandwiched by two n-regions, Fig. 2.3 (a), *npn* transistor is obtained. With two p-regions sandwiching one n-region, Fig. 2.3 (b), *pnp* transistor is obtained. The term 'bipolar' denotes that the current flow in the device is due to the movement of both holes and electrons. A BJT has three terminals named collector, emitter and base. An emitter is indicated by an arrowhead indicating the direction of emitter current. No arrow is associated with base or collector.

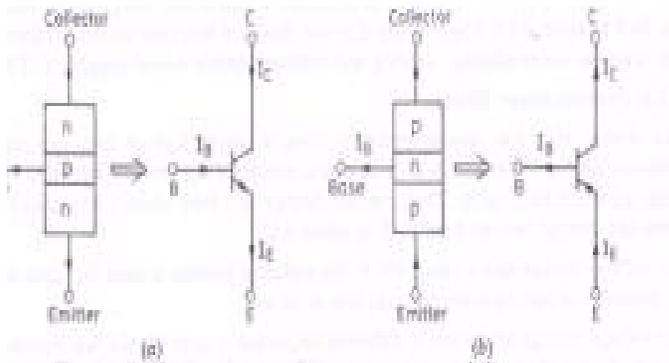


Fig. 2.3. Bipolar junction transistors (a) npn type and (b) pnp type.

2.3.1.1. Steady-state Characteristics. Out of the three possible circuit configurations for a transistor, common-emitter arrangement is more common in switching applications. So, henceforth, *npn* transistors will only be considered.

Input characteristics. A graph between base current I_B and base-emitter voltage V_{BE} gives input characteristics. As the base-emitter junction of a transistor is like a diode, I_B versus V_{BE} graph resembles a diode curve. When collector-emitter voltage V_{CE2} is more than V_{CE1} , base current decreases as shown in Fig. 2.4(b).

Output characteristics. A graph between collector current I_C and collector-emitter voltage V_{CE} gives output characteristics of a transistor. For zero base current, i.e. for $I_B = 0$, as V_{CE} is increased, a small leakage (collector) current exists as shown in Fig. 2.4 (c). As the base current is increased from $I_B = 0$ to $751 I_{B2}$ etc, collector current also rises as shown in Fig. 2.4 (c).

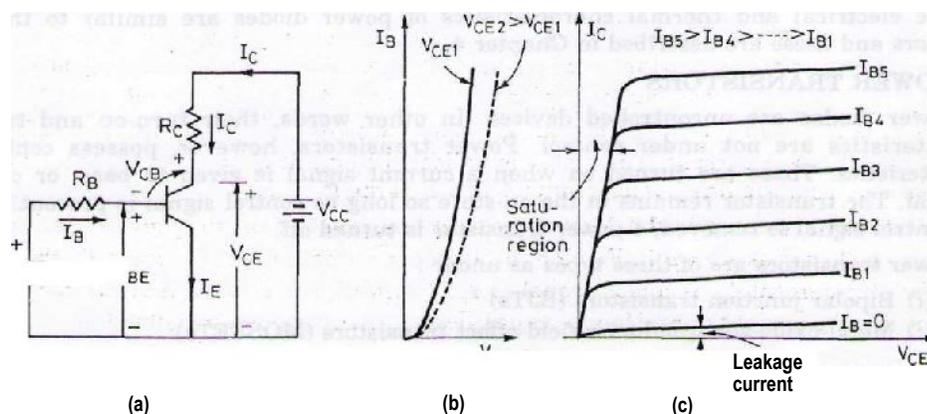


Fig.2.4

2.4. POWER MOSFETs

A metal-oxide-semiconductor field-effect transistor (MOSFET) is a recent device developed by combining the areas of field-effect concept and MOS technology.

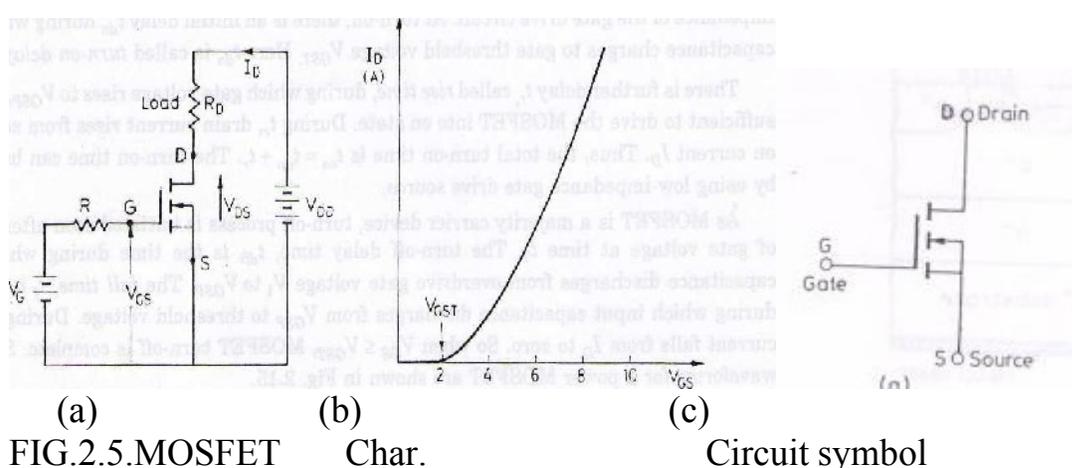
A power-MOSFET has three terminals called drain, source and gate in place of the corresponding three terminals collector, emitter and base for BJT. The circuit symbol of power MOSFET is as shown in Fig. 2.5 (a). Here arrow indicates the direction of electron flow. A BJT is a current controlled device whereas a power MOSFET is a voltage-controlled device. As its operation depends upon the flow of majority carriers only, MOSFET is a unipolar device. The control signal, or base current in BJT is much larger than the control signal (or gate current) required in a MOSFET. This is because of the fact that gate circuit impedance in MOSFET is extremely high, of the order of 10 ohm. This large impedance permits the MOSFET gate to be driven directly from microelectronic circuits. BJT suffers from second breakdown voltage whereas MOSFET is free from this problem. Power MOSFETs are now finding increasing applications in low-power high frequency converters.

2.4.1. MOSFET Characteristics

The static characteristics of power MOSFET are now described briefly. The basic circuit diagram for n-channel power MOSFET is shown in Fig. 2.5 (a) where voltages and currents are as indicated.

(a) *Transfer characteristics.* This characteristic shows the variation of drain

current I_D as a function of gate-source voltage V_{GS} . Fig. 2.5 (b) shows typical transfer characteristic for n-channel power MOSFET. It is seen that there is threshold voltage V_{GST} below which the device is off. The magnitude of V_{GST} is of the order of 2 to 3 V.



(b) Output characteristics. Power MOSFET output characteristics shown in Fig. 2.6 indicate the variation of drain current I_D as a function of drain-source voltage V_{DS} as a parameter. For low values of V_{DS} the graph between $I_D - V_{DS}$ is almost linear ; this indicates a constant value of on-resistance $R_{DS} = V_{DS}/I_D$. For given V_{GS} , if V_{DS} is increased, output characteristic is relatively flat indicating that drain current is nearly constant. A load line intersects the output characteristics at **A** and **B**. Here **A** indicates fully-on condition and **B** fully-off state. Power MOSFET operates as a switch either at **A** or at **B** just like a BJT.

Fig.2.6

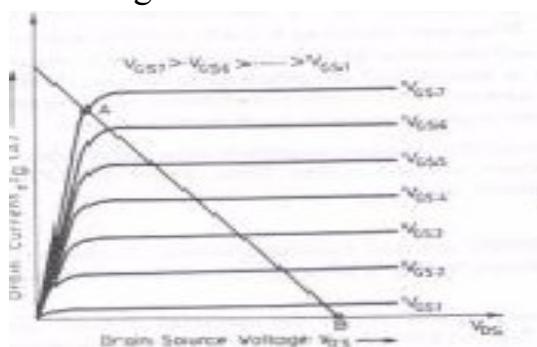


Fig. 2.14. Output characteristics of a power MOSFET.

2.4.2. Comparison of MOSFET with BJT

Power MOSFET has several features different from those of BJT. These are outlined as under :

(i) Power MOSFET has lower switching losses but its on-resistance and conduction losses are more. A BJT has higher switching losses but lower conduction loss. So at high frequency applications, power MOSFET is the obvious choice. But at lower operating frequencies (less than about 10 to 30 kHz), BJT is superior.

(ii) MOSFET is voltage controlled device whereas **BJT** is current controlled device.

(iii) MOSFET has positive temperature coefficient for resistance. This makes parallel operation of MOSFET easy. If a MOSFET shares increased current initially, it heats up faster, its resistance rises and this increased resistance causes this current to shift to other devices in parallel. A BJT has negative temperature coefficient, so current-sharing resistors are necessary during parallel operation of BJTs.

(iv) In MOSFET, secondary breakdown does not occur, because it has positive temperature coefficient. As BJT has negative temperature coefficient, secondary breakdown occurs. In BJT, with decrease in resistance, the current increases. This increased current over the same area results in hot spots and breakdown of the BJT.

(v) Power MOSFETs in higher voltage ratings have more conduction loss.

(vi) The state of the art MOSFETs are available with ratings upto 500 V, 140 A whereas BJTs are available with ratings up to 1200 V, 800 A.

2.5. INSULATED GATE BIPOLAR TRANSISTOR (IGBT)

IGBT is a new development in the area of power MOSFET technology. This device combines into it the advantages of both MOSFET and BJT. So an IGBT has high input impedance like a MOSFET and low-on-state power loss as in a BJT. Further, IGBT is free from second breakdown problem present in BJT. IGBT is also known as metal-oxide insulated gate transistor (MOSIGT), conductively-modulated field effect transistor (COMFET) or gain-modulated FET (GEMFET). It was also initially called insulated gate transistor (IGT).

2.5.1. IGBT Characteristics

The circuit of Fig. 2.7(a) shows the various parameters pertaining to IGBT characteristics.

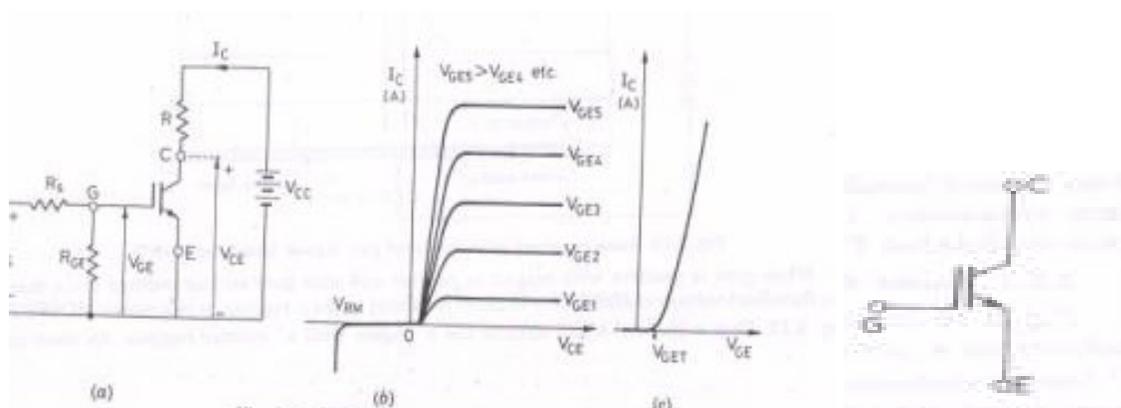


FIG.2.7 .IGBT.(a) Circuit digram ,(b)static V-I char. And (c)transfer char. IGBT symbol)

2.5.2. Applications of IGBT

IGBTs are widely used in medium power applications such as dc and ac motor drives, UPS systems, power supplies and drives for solenoids, relays and contactors. Though IGBTs are somewhat more expensive than BJTs, yet they are becoming popular because of lower gate-drive requirements, lower switching losses and smaller snubber circuit requirements. IGBT converters are more efficient with less size as well as cost, as compared to converters based on BJTs. Recently, IGBT inverter induction-motor drives using 15-20 kHz switching frequency are finding favour where audio-noise is objectionable. In most applications, IGBTs will eventually push out BJTs. At present, the state of the art IGBTs are available up to 1200 V, 500 A. Table below shows the comparisons of transistors.

TABLE 4.1 Comparisons of Power Transistors

Switch Type	Base/Gate Control Variable	Control Characteristic	Switching Frequency	On-State Voltage Drop	Max. Voltage Rating V_s	Max. Current Rating I_s	Advantages	Limitations
BJT	Current	Continuous	Medium 20 kHz	Low	1.5 kV $S_s = V_s I_s$ = 1.5 MVA	1 kA $S_s = V_s I_s$ = 1.5 MVA	Simple switch Low on-state drop Higher off-state voltage capability High switching loss	Current controlled device and requires a higher base current to turn-on and sustain on-state current Base drive power loss Charge recovery time and slower switching speed Secondary breakdown region High switching losses Unipolar voltage device High on-state drop as high as 10 V Lower off-state voltage capability Unipolar voltage device
MOSFET	Voltage	Continuous	Very high	High	1 kV $S_s = V_s I_s$ = 0.1 MVA	150 A $S_s = V_s I_s$ = 0.1 MVA	Higher switching speed Low switching loss Simple gate drive circuit Little gate power. Negative temperature coefficient on rain current and facilitates parallel operation	Low power device Low voltage and current ratings Lower off-state voltage capability Unipolar voltage device Higher on-state voltage drop Lower current ratings
COOLMOS	Voltage	Continuous	Very high	Low	1 kV	100 A	Low gate drive requirement and low on-state power drop	Low power device Low voltage and current ratings
IGBT	Voltage	Continuous	High	Medium	3.5 kV $S_s = V_s I_s$ = 1.5 MVA	2 kA $S_s = V_s I_s$ = 1.5 MVA	Low on-state voltage Little gate power	Lower off-state voltage capability Unipolar voltage device Higher on-state voltage drop Lower current ratings
SIT	Voltage	Continuous	Very high	High			High-voltage rating	Higher on-state voltage drop Lower current ratings

2.6 Thyristor

A thyristor has characteristics similar to a thyratron tube. But from the construction view point, a thyristor (a *pnpn* device) belongs to transistor (*pnp* or *nnp* device) family. The name 'thyristor', is derived by a combination of the capital letters from THYRatron and transISTOR. This means that thyristor is a solid state device like a transistor and has characteristics similar to that of a thyratron tube. The present-day reader may not be familiar with thyratron tube as this is not being taught these days.

2.6.1 TERMINAL CHARACTERISTICS OF THYRISTORS: Thyristor is a four layer, three-junction, *p-n-p-n* semiconductor switching device. It has three terminals; anode, cathode and gate. Fig. 2.8(a) gives constructional details of a typical thyristor. Basically, a thyristor consists of four layers of alternate *p-type* and *n-type* silicon semiconductors forming three junctions J_1 , J_2 and J_3 as shown in Fig. 2.8 (a). The threaded portion is for the purpose of tightening the thyristor to the frame or heat sink with the help of a nut. Gate terminal is usually kept near the cathode terminal Fig. 2.8 (a). Schematic diagram and circuit symbol for a thyristor are shown respectively in Figs. 2.8 (b) and (c). The terminal connected to outer *p* region is called anode (*A*), the terminal connected to outer *n* region is called cathode and that

connected to inner p region is called the gate (G). For large current applications, thyristors need better cooling; this is achieved to a great extent by mounting them onto heat sinks. SCR rating has improved considerably since its introduction in 1957. Now SCRs of voltage rating 10 kV and an rms current rating of 3000 A with corresponding power-handling capacity of 30 MW are available. Such a high power thyristor can be switched on by a low voltage supply of about 1 A and 10 W and this gives us an idea of the immense power amplification capability ($= 3 \times 10^6$) of this device. As SCRs are solid state devices, they are compact, possess high reliability and have low loss. Because of these useful features, SCR is almost universally employed these days for all high power-controlled devices. An SCR is so called because *silicon* is used for its construction and its operation as a *rectifier* (very low resistance in the forward conduction and very high resistance in the reverse direction) can be *controlled*. Like the diode, an SCR is an unidirectional device that blocks the current flow from cathode to anode. Unlike the diode, a thyristor also blocks the current flow from anode to cathode until it is triggered into conduction by a proper gate signal between gate and cathode terminals. For engineering applications of thyristors, their terminal characteristics must be known.

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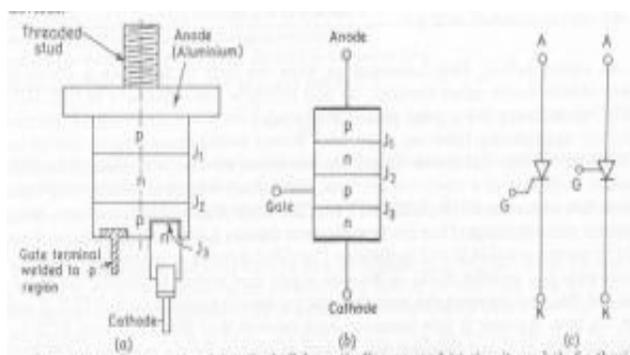


Fig.2.8

2.6.2. Static V-I Characteristics of a Thyristor:

An elementary circuit diagram, for obtaining static $V-I$ characteristics, of a thyristor is shown in Fig. 2.9 (a). The anode and cathode are connected to main source through the load. The gate and cathode are fed from a source E_s which provides positive gate current from. Gate to cathode.

Fig.2.9 (b) shows static $V-I$ charact. of a thyristor. Here V_a is the anode voltage across, thyristor terminals A, K and I_a is the anode current. Typical SCR $V-I$ characteristic shown in Fig. 2.7 (b) 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.

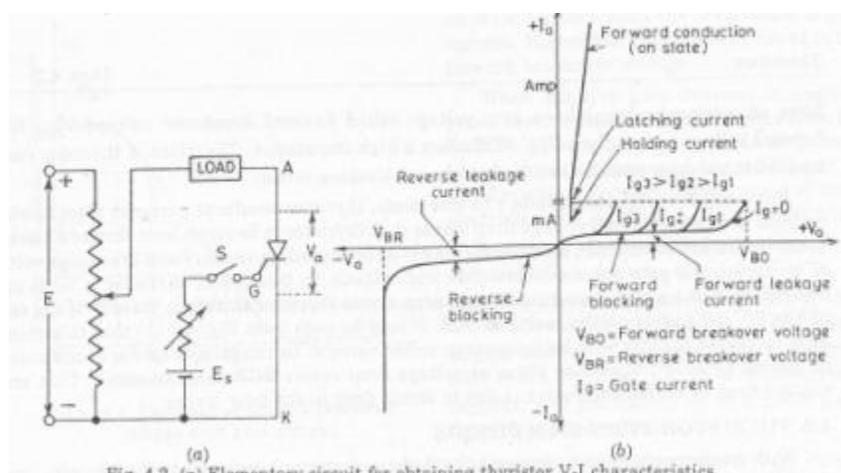


Fig.2.9

2.6.3 THYRISTOR TURN-ON METHODS

With anode positive with respect to cathode, a thyristor can be turned on by anyone of the following techniques:

- (a) Forward voltage triggering. (b) gate triggering. (c) dv/dt triggering.
 (d) Temperature triggering. (e) Light triggering.

2.6.4 TWO-TRANSISTOR MODEL

The principle of thyristor operation can be explained with the use of its two-transistor model (or two-transistor analogy), Fig. 2.10 (a) shows schematic diagram of a thyristor. From this figure, two-transistor model is obtained by bisecting the two middle layers, along the dotted line, in two separate halves

as shown in Fig. 2.10 (b). In this figure, junctions $J1 - J2$ and $J2 - J3$ can be considered to constitute pnp and nnp transistors separately. The circuit representation of the two-transistor model of a thyristor is shown in Fig. 2.10(c).

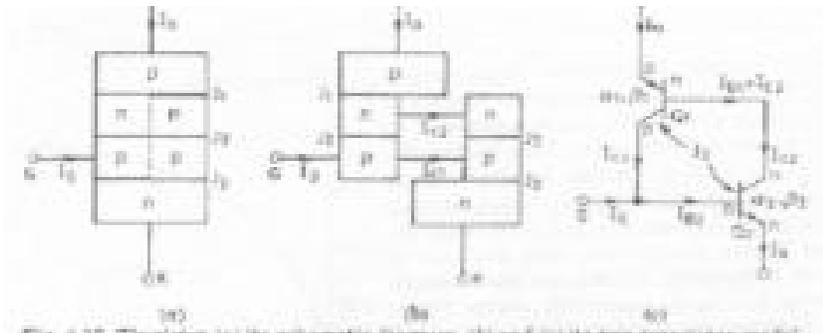


Fig. 2.10. Thyristor (a) its schematic diagram, (b) and (c) its two-transistor model

2.7. THYRISTOR PROTECTION

Reliable operation of a thyristor demands that its specified ratings are not exceeded. In practice, a thyristor may be subjected to over voltages or over currents. During SCR turn-on, di/dt may be prohibitively large. There may be false triggering of SCR by high value of dv/dt . A spurious signal across gate-cathode terminals may lead to unwanted turn-on. A thyristor must be protected against all such abnormal conditions for satisfactory and reliable operation of SCR circuit and the equipment. SCRs are very delicate devices, their protection against abnormal operating conditions is, therefore, essential. The object of this section is to discuss various techniques adopted for the protection of SCRs.

(a) di/dt protection. When a thyristor is forward biased and is turned on by a gate pulse, conduction of anode current begins in the immediate neighborhood of the gate-cathode junction. Thereafter, the current spreads across the whole area of junction. The thyristor design permits the spread of conduction to the whole junction area as rapidly as possible. However, if the rate of rise of anode current, i.e. di/dt , is large as compared to the spread velocity of carriers, local hot spots will be formed near the gate connection on account of high current density. This localised heating may destroy the

thyristor. Therefore, the rate of rise of anode current at the time of turn-on must be kept below the specified limiting value. The value of di/dt can be maintained below acceptable limit by using a small inductor, called di/dt inductor, in series with the anode circuit. Typical di/dt limit values of SCRs are 20—500 A/ μ sec.

Local spot heating can also be avoided by ensuring that the conduction spreads to the whole area as rapidly as possible. This can be achieved by applying a gate current nearer to (but never greater than) the maximum specified gate current.

(b) dv/dt protection. With forward voltage across the anode and cathode of a thyristor, the two outer junctions are forward biased but the inner junction is reverse biased. This reverse biased junction J_2 , Fig2.8(b), has the characteristics of a capacitor due to charges existing across the junction. In other words, space-charges exist in the depletion region around junction J_2 and therefore junction J_2 behaves like a capacitance. If the entire anode to cathode forward voltage V_a appears across J_2 junction and the charge is denoted by Q , then a charging current i given by Eq. (2.7) flows :

$$\begin{aligned} i &= \frac{dQ}{dt} = \frac{d}{dt} (C_j \cdot V_a) \\ &= C_j \frac{dV_a}{dt} + V_a \frac{dC_j}{dt} \end{aligned} \quad (2.7a)$$

As C_j , the capacitance of junction J_2 , is almost constant the current is given by

$$i = C_j \frac{dV_a}{dt}$$

If the rate of rise of forward voltage dV_a/dt is high, the charging current i will be more. This charging current plays the role of gate current and turns on the SCR even when gate signal is zero. Such phenomena of turning-on a thyristor, called dv/dt turn-on must be avoided as it leads to false operation

of the thyristor circuit. For controllable operation of the thyristor, the rate of rise of forward anode to cathode voltage dV_a/dt must be kept below the specified rated limit. Typical values of dv/dt are 20 - 500 V/usec. False turn-on of a thyristor by large dv/dt can be prevented by using a snubber circuit in parallel with the device.

2.7.1. Design of Snubber Circuits A snubber circuit consists of a series combination of resistance R_s and capacitance C_s in parallel with the thyristor as shown in Fig. 2. 11. Strictly speaking, a capacitor C_s in parallel with the device is sufficient to y

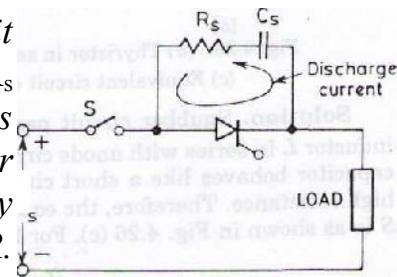


Fig. 2.11 Snubber circuit across SCR.

prevent unwanted dv/dt triggering of the SCR. When switch S is closed, a sudden voltage appears across the circuit. Capacitor C behaves like a short circuit, at a slow rate such that dv/dt across C_s and therefore across SCR is less than the specified maximum dv/dt rating of the device. Here the question arises that if C_s is enough to prevent accidental turn-on of the device by dv/dt , what is the need of putting R_s in series with C_s ? The answer to this is as under.

Before SCR is fired by gate pulse, C_s charges to full voltage V_s . When the SCR is turned on, capacitor discharges through the SCR and sends a current equal to $V_s/$ (resistance of local path formed by C_s and SCR). As this resistance is quite low, the turn-on di/dt will tend to be excessive and as a result, SCR may be destroyed. In order to limit the magnitude of discharge current, a resistance R_s is inserted in series with C_s as shown in Fig. 2.11. Now when SCR is turned on, initial discharge current V_s/R_s is relatively small and turn-on di/dt is reduced.

In actual practice ; R_s , C_s and the load circuit parameters should be such that dv/dt across C_s during its charging is less than the specified dv/dt rating of the SCR and discharge current at the turn-on of SCR is v/within reasonable limits. Normally, R_s C_s and load circuit parameters form an underdamped circuit so that dv/dt is limited to acceptable values.

In practice, designed snubber parameters are adjusted up or down in the final assembled power circuit so as to obtain a satisfactory performance of the power electronics system therefore voltage across SCR is zero. With the passage of time, voltage across C_s builds up.

2.8. HEATING, COOLING AND MOUNTING OF THYRISTORS

Some power loss occurs in a thyristor during its working. The various components of this power loss in the junction region of a thyristor are as under :

- (i) Forward conduction loss .
- (ii) Loss due to leakage current during forward and reverse blocking.
- (iii) Switching losses at turn-on and turn-off
- (iv) Gate triggering loss

At industrial power frequencies between zero and 400 Hz, the forward conduction loss, or on-state conduction loss, is usually the major component. But switching losses become dominant at high operating frequencies. These electrical losses produce thermal heat which must be removed from the junction region. The thermal losses and hence the temperature rise of the device increase with the thyristor rating. The cooling of thyristors, therefore, becomes more difficult as the SCR rating increases.

The heat produced in a thyristor by electrical loss is dissipated to ambient fluid (air or water) by mounting the device on a heat sink. When heat due to losses is equal to that dissipated by the heat sink, steady junction temperature is reached. Thyristor heating and hence its junction temperature rise is dependent primarily on current handled by the device during its working. As such, current rating of thyristors is often based on thermal considerations.

2.9. GATE TURN OFF (G.T.O.) THYRISTOR:

A gate turn-off thyristor, a *pnpn* device, can be turned on like an ordinary thyristor by a pulse of positive gate current. In inverter and chopper circuits, a thyristor can be turned off by forced commutation. For such applications, a GTO is, however, a more versatile device ; it can be easily turned off by a negative gate pulse of appropriate amplitude. GTOs were developed

sometimes in the late 1960s but these could not find commercial use because of certain performance problems. Only recently, modern technology has helped in the improved performance of GTOs and these are now being used in several commercial inverters.

As no forced commutation circuitry is required for GTOs, inverters using these devices are compact and cost less. The negative gate current required to turn off a GTO is quite a large percentage (20 to 30%) of anode current prior to commutation. For example, an 800 A GTO will require a negative current pulse of 200 A peak for turning it off. Fig. 2.12(a) gives the circuit symbols of a GTO. The symbols shown in (a) (i) and (ii) are self explanatory, gate

current can go in for turning on and out for turning off. But the symbol a (iii) looks easy when circuit configurations using GTOs are to be drawn.

2.9.1 Static V-I Characteristics of GTOs

Typical static V - I characteristics for a GTO thyristor are shown in Fig. 2.12 (b). It is seen from these characteristics that latching current for large power GTOs is several amperes (here 2A) as compared to 100—500 mA for conventional thyristors of the

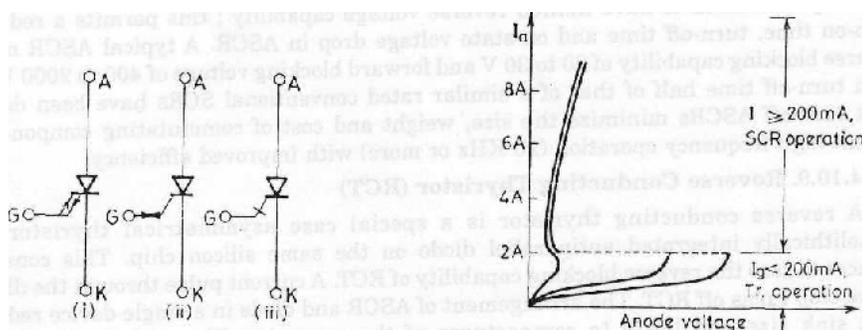


Fig. 2.12. Gate turn-off thyristor (a) circuit symbol and (b) its static V-I

same rating. If gate current is not able to turn on the GTO, it behaves like a high voltage, low gain transistor with considerable anode current. This leads to a noticeable power loss under such conditions.

A GTO has the following disadvantages as compared to a conventional thyristor :

- (i) Magnitude of latching and holding currents is more in a GTO.
- (ii) On state voltage drop and the associated loss is more in a GTO.
- (iii) Due to the multi

cathode structure of GTO, triggering gate current is higher than that required for a conventional SCR. (iv) Gate drive circuit losses are more. (v) Its reverse-voltage blocking capability is less than its forward-voltage blocking capability. But this is no disadvantage so far as inverter circuits are concerned.

In spite of all these demerits, GTO has the following advantages over an SCR :

(i) GTO has faster switching speed. (ii) Its surge current capability is comparable with an SCR. (iii) It has more di/dt rating at turn-on. (iv) GTO circuit configuration has lower size and weight as compared to SCR circuit unit. (v) GTO unit has higher efficiency because an increase in gate-drive power loss and on-state loss is more than compensated by the elimination of forced commutation losses. (vi) GTO unit has reduced acoustical and electromagnetic noise due to elimination of commutation chokes.

In view of the above facts, GTO devices are now being used for (a) high-performance drive systems, such as the field-oriented control scheme used in rolling mills, robotics and machine tools, (b) traction purposes because of their lighter weight and (c) adjustable-frequency inverter drives. At present, GTOs with ratings up to 2500 V and 1400 A are available.

2.10 The Diac (Bidirectional Thyristor Diode)

A cross-sectional view of a diac showing all its layers and junctions is depicted in Fig. 2.13 (a). If voltage V_{12} , with terminal 1 positive with respect to terminal 2, exceeds break-over voltage V_{B01} then structure $pn\ pn$ conducts. In case terminal 2 is positive with respect to terminal 1 and when V_{21} exceeds breakover voltage V_{B02} , structure $pn\ pn'$ conducts. The term 'diac' is obtained from capital letters, Diode that can work on AC. Fig. 2.13 (b) gives the circuit symbol and Fig. 2.13(c) the $V-I$ characteristics of a diac. It is seen that diac has symmetrical breakdown characteristics. Its leads are interchangeable. Its turn-on voltage is about 30 V. When conducting, it acts like a low resistance with about 3 V drop across it. When not conducting, it acts like an open switch. A diac is sometimes called a gateless triac

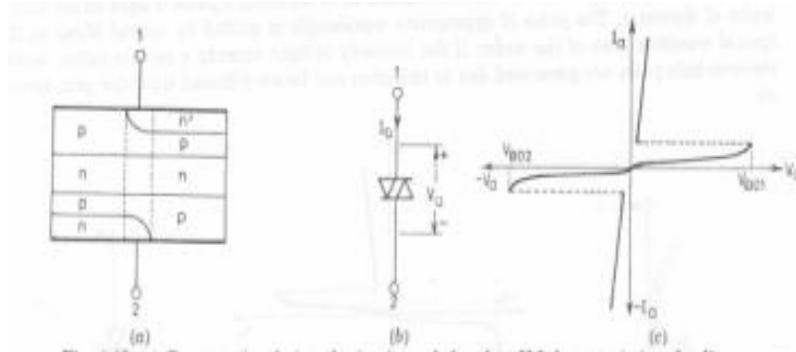


Fig. 2.13. (a) Cross-sectional view (b) circuit symbol and (c) V - I characteristics of a diac.

2.11. The Triac

An SCR is a unidirectional device as it can conduct from anode to cathode only and not from cathode to anode. A triac can, however, conduct in both the directions. A triac is thus a bidirectional thyristor with three terminals. It is used extensively for the control of power in ac circuits. Triac is the word derived by combining the capital letters from the words TRIode and AC. When in operation, a triac is equivalent to two SCRs connected in antiparallel. The circuit symbol and its characteristics are shown in Fig. 2.14 (a) and (b) respectively. As the triac can conduct in both the directions, the terms anode and cathode are not applicable to triac. Its three terminals are usually designated as MT1 (main terminal 1), MT2 and the gate by **G** as in a thyristor.

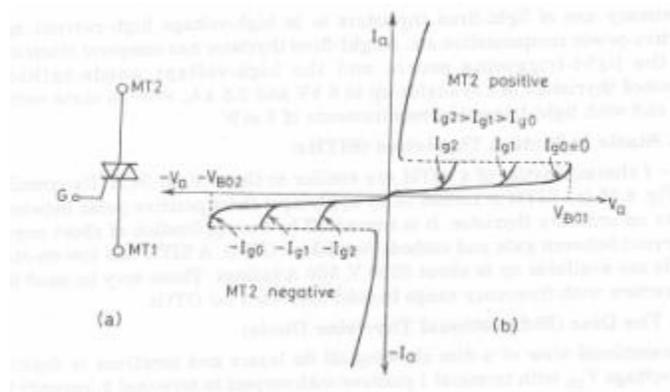


Fig2.14. (a) Circuit symbol and (b) static V-I characteristics of a triac.

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