Module
1

Power Semiconductor Devices

Lesson
1

Power Electronics

Introduction

This lesson provides the reader the following:

(i)   Create an awareness of the general nature of Power electronic equipment;
(ii)   Brief idea about topics of study involved,
(iii) The key features of the principal Power Electronic Devices;
(iv)   An idea about which device to choose for a particular application.
(v)   A few issues like base drive and protection of PE devices and equipment common to most varieties.

Power Electronics is the art of converting electrical energy from one form to another in an efficient, clean, compact, and robust manner for convenient utilisation.

A passenger lift in a modern building equipped with a Variable-Voltage-Variable-Speed induction-machine drive offers a comfortable ride and stops exactly at the floor level. Behind the scene it consumes less power with reduced stresses on the motor and corruption of the utility mains.

Fig. 1.1 The block diagram of a typical Power Electronic converter

Power Electronics involves the study of

- Power semiconductor *devices* - their physics, characteristics, drive requirements and their protection for optimum utilisation of their capacities,
- Power converter *topologies* involving them,
- *Control* strategies of the converters,
- Digital, analogue and micro*electronics* involved,
- Capacitive and magnetic energy storage elements,
- Rotating and static *electrical devices*,
- *Quality* of waveforms generated,
- Electro Magnetic and Radio Frequency *Interference*,

- *Thermal* Management

The typical converter in Fig. 1.1 illustrates the multidisciplinary nature of this subject.

How is Power electronics distinct from linear electronics?

It is not primarily in their power handling capacities.

While power management IC's in mobile sets working on Power Electronic principles are meant to handle only a few milliwatts, large linear audio amplifiers are rated at a few thousand watts.

The utilisation of the Bipolar junction transistor, Fig. 1.2 in the two types of amplifiers best symbolises the difference. In Power Electronics all devices are operated in the switching mode - either 'FULLY-ON' or 'FULLY-OFF' states. The linear amplifier concentrates on fidelity in signal amplification, requiring transistors to operate strictly in the linear (active) zone, Fig 1.3. Saturation and cutoff zones in the V_{CE} - I_C plane are avoided. In a Power electronic switching amplifier, only those areas in the V_{CE} - I_C plane which have been skirted above, are suitable. On-state dissipation is minimum if the device is in saturation (or quasi-saturation for optimising other losses). In the off-state also, losses are minimum if the BJT is reverse biased. A BJT switch will try to traverse the active zone as fast as possible to minimise switching losses.
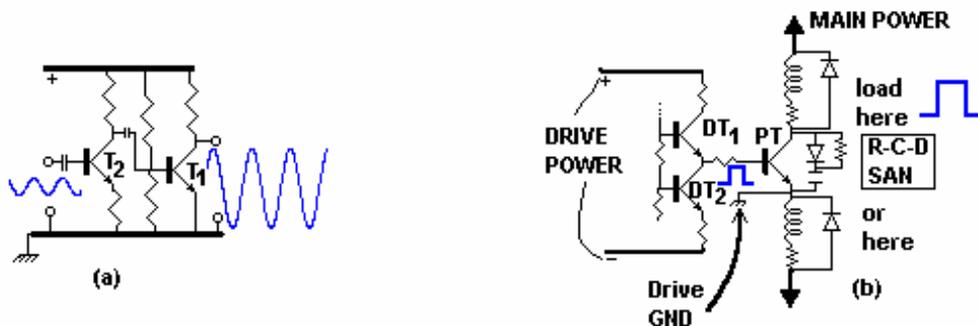
Fig. 1.2 Typical Bipolar transistor based (a) linear (common emitter) (*voltage*) amplifier stage and (b) switching (*power*) amplifier
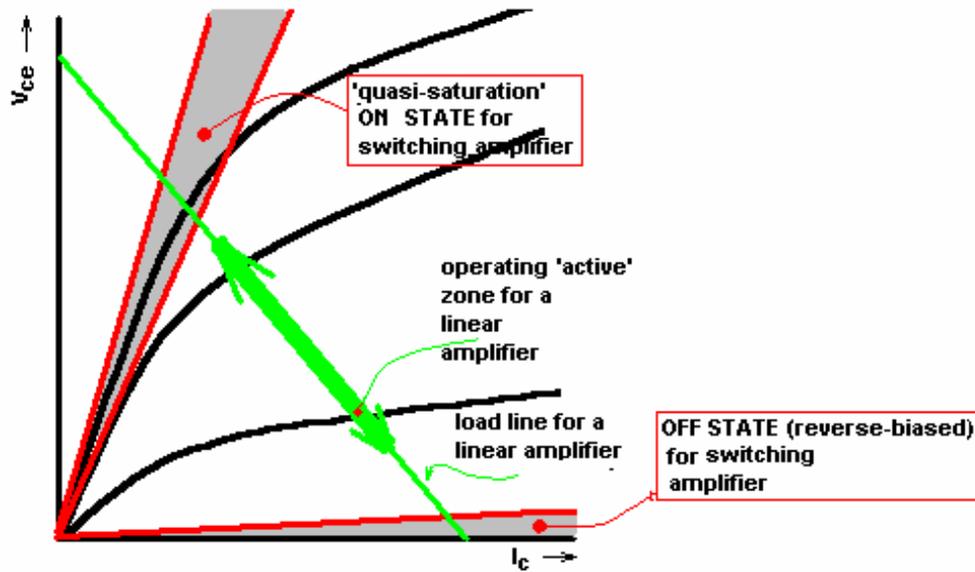
Fig 1.3 Operating zones for operating a Bipolar Junction Transistor as a linear and a switching amplifier

Linear operation	Switching operation
Active zone selected: Good linearity between input/output	Active zone avoided : High losses, encountered only during transients
Saturation & cut-off zones avoided: poor linearity	Saturation & cut-off (negative bias) zones selected: low losses
Transistor biased to operate around quiescent point	No concept of quiescent point
Common emitter, Common collector, common base modes	Transistor driven directly at base - emitter and load either on collector or emitter
Output transistor barely protected	Switching-Aid-Network (SAN) and other protection to main transistor
Utilisation of transistor rating of secondary importance	Utilisation of transistor rating optimised

An example illustrating the linear and switching solutions to a power supply specification will emphasise the difference.

Spec: Input : 230 V, 50 Hz, Output: 12 V regulated DC, 20 W
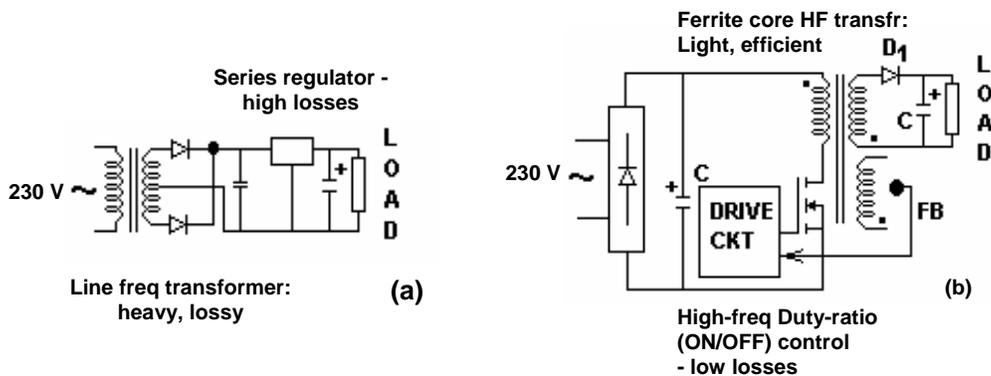
Fig. 1.4 (a) A Linear regulator and (b) a switching regulator solution of the specification above

The linear solution, Fig. 1.4 (a), to this quite common specification would first step down the supply voltage to 12-0-12 V through a power frequency transformer. The output would be rectified using Power frequency diodes, electrolytic capacitor filter and then series regulated using a chip or a audio power transistor. The tantalum capacitor filter would follow**.** The balance of the voltage between the output of the rectifier and the output drops across the regulator device which also carries the full load current. The power loss is therefore considerable. Also, the step-down iron-core transformer is both heavy, and lossy. However, only twice-line-frequency ripples appear at the output and material cost and technical know-how required is low.

In the switching solution Fig. 1.4 (b) using a MOSFET driven flyback converter, first the line voltage is rectified and then isolated, stepped-down and regulated. A ferrite-core high-frequency (HF) transformer is used. Losses are negligible compared to the first solution and the converter is extremely light. However significant high frequency (related to the switching frequency) noise appear at the output which can only be minimised through the use of costly 'grass' capacitors.

Power Semiconductor device - history

Power electronics and converters utilizing them made a head start when the first device the Silicon Controlled Rectifier was proposed by Bell Labs and commercially produced by General Electric in the earlier fifties. The Mercury Arc Rectifiers were well in use by that time and the robust and compact SCR first started replacing it in the rectifiers and cycloconverters. The necessity arose of extending the application of the SCR beyond the line-commutated mode of action, which called for external measures to circumvent its turn-off incapability via its control terminals. Various turn-off schemes were proposed and their classification was suggested but it became increasingly obvious that a device with turn-off capability was desirable, which would permit it a wider application. The turn-off networks and aids were impractical at higher powers.

The Bipolar transistor, which had by the sixties been developed to handle a few tens of amperes and block a few hundred volts, arrived as the first competitor to the SCR. It is superior to the SCR in its turn-off capability, which could be exercised via its control terminals. This permitted the replacement of the SCR in all forced-commutated inverters and choppers. However, the gain (power) of the SCR is a few decades superior to that of the Bipolar transistor

and the high base currents required to switch the Bipolar spawned the Darlington. Three or more stage Darlingtons are available as a single chip complete with accessories for its convenient drive. Higher operating frequencies were obtainable with a discrete Bipolars compared to the 'fast' inverter-grade SCRs permitting reduction of filter components.   But the Darlington's operating frequency had to be reduced to permit a sequential turn-off of the drivers and the main transistor. Further, the incapability of the Bipolar to block reverse voltages restricted its use.

The Power MOSFET burst into the scene commercially near the end seventies. This device also represents the first successful marriage between modern integrated circuit and discrete power semiconductor manufacturing technologies. Its voltage drive capability – giving it again a higher gain, the ease of its paralleling and most importantly the much higher operating frequencies reaching upto a few MHz saw it replacing the Bipolar also at the sub-10 KW range mainly for SMPS type of applications. Extension of VLSI manufacturing facilities for the MOSFET reduced its price vis-à-vis the Bipolar also. However, being a majority carrier device its on-state voltage is dictated by the $R_{DS(ON)}$ of the device, which in turn is proportional to about $V_{DSS}^{2.3}$ rating of the MOSFET. Consequently, high-voltage MOSFETS are not commercially viable.

Improvements were being tried out on the SCR regarding its turn-off capability mostly by reducing the turn-on gain. Different versions of the Gate-turn-off device, the Gate turn-off Thyristor (GTO), were proposed by various manufacturers - each advocating their own symbol for the device. The requirement for an extremely high turn-off control current via the gate and the comparatively higher cost of the device restricted its application only to inverters rated above a few hundred KVA.

The lookout for a more efficient, cheap, fast and robust turn-off-able device proceeded in different directions with MOS drives for both the basic thysistor and the Bipolar. The Insulated Gate Bipolar Transistor (IGBT) – basically a MOSFET driven Bipolar from its terminal characteristics has been a successful proposition with devices being made available at about 4 KV and 4 KA. Its switching frequency of about 25 KHz and ease of connection and drive saw it totally removing the Bipolar from practically all applications. Industrially, only the MOSFET has been able to continue in the sub – 10 KVA range primarily because of its high switching frequency. The IGBT has also pushed up the GTO to applications above 2-5 MVA.

Subsequent developments in converter topologies – especially the three-level inverter permitted use of the IGBT in converters of 5 MVA range. However at ratings above that the GTO (6KV/6KA device of Mitsubishi) based converters had some space. Only SCR based converters are possible at the highest range where line-commutated or load-commutated converters were the only solution. The surge current, the peak repetition voltage and I^2t ratings are applicable only to the thyristors making them more robust, specially thermally, than the transistors of all varieties.
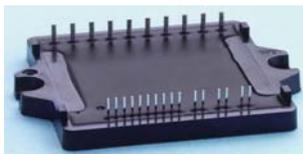
1200V Version 3 ASIPM

Presently there are few hybrid devices and Intelligent Power Modules (IPM) are marketed by some manufacturers. The IPMs have already gathered wide acceptance. The 4500 V, 1200 A

IEGT (injection-enhanced gate transistor) of Toshiba or the 6000 V, 3500 A IGCT (Integrated Gate Commutated Thyristors) of ABB which are promising at the higher power ranges. However these new devices must prove themselves before they are accepted by the industry at large.

Silicon carbide is a wide band gap semiconductor with an energy band gap wider than about 2 eV that possesses extremely high thermal, chemical, and mechanical stability. Silicon carbide is the only wide band gap semiconductor among gallium nitride (GaN, E_G = 3.4 eV), aluminum nitride (AlN, E_G = 6.2 eV), and silicon carbide that possesses a high-quality native oxide suitable for use as an MOS insulator in electronic devices The breakdown field in SiC is about 8 times higher than in silicon. This is important for high-voltage power switching transistors. For example, a device of a given size in SiC will have a blocking voltage 8 times higher than the same device in silicon. More importantly, the on-resistance of the SiC device will be about two decades lower than the silicon device. Consequently, the efficiency of the power converter is higher. In addition, SiC-based semiconductor switches can operate at high temperatures (~600 C) without much change in their electrical properties. Thus the converter has a higher reliability. Reduced losses and allowable higher operating temperatures result in smaller heatsink size. Moreover, the high frequency operating capability of SiC converters lowers the filtering requirement and the filter size. As a result, they are compact, light, reliable, and efficient and have a high power density. These qualities satisfy the requirements of power converters for most applications and they are expected to be the devices of the future.

Ratings have been progressively increasing for all devices while the newer devices offer substantially better performance. With the SCR and the pin-diodes, so called because of the sandwiched intrinsic 'i'-layer between the 'p' and 'n' layers, having mostly line-commutated converter applications, emphasis was mostly on their static characteristics - forward and reverse voltage blocking, current carrying and over-current ratings, on-state forward voltage etc and also on issues like paralleling and series operation of the devices. As the operating speeds of the devices increased, the dynamic (switching) characteristics of the devices assumed greater importance as most of the dissipation was during these transients. Attention turned to the development of efficient drive networks and protection techniques which were found to enhance the performance of the devices and their peak power handling capacities. Issues related to paralleling were resolved by the system designer within the device itself like in MOSFETS, while the converter topology was required to take care of their series operation as in multi-level converters.

The range of power devices thus developed over the last few decades can be represented as a tree, Fig. 1.5, on the basis of their controllability and other dominant features.
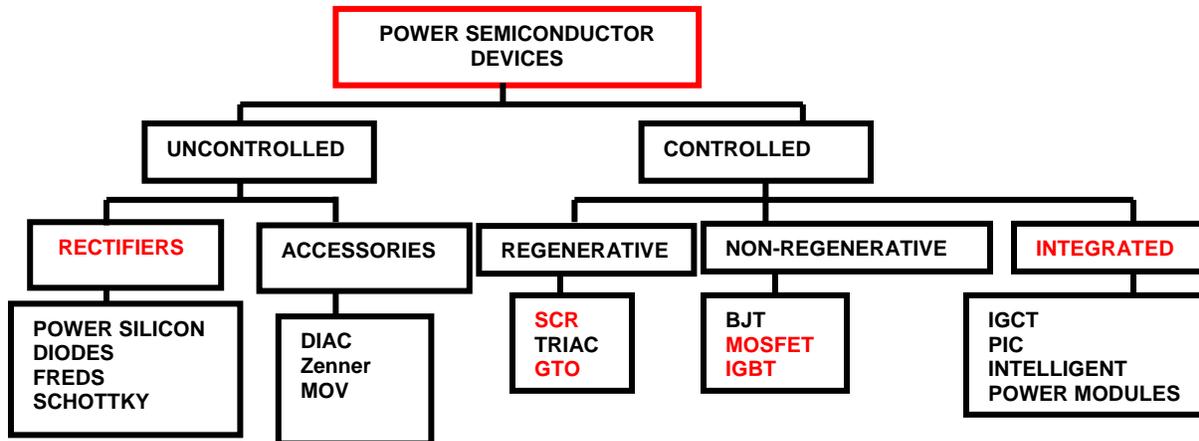
Fig. 1.5 Power semiconductor device variety
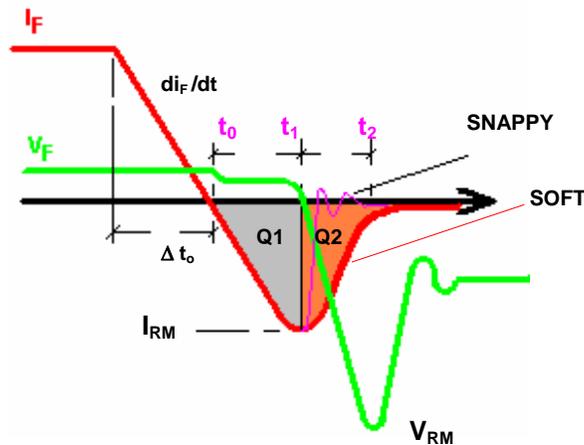
Power Diodes

Fig. 1.6 Typical turn-off dynamics of a soft and a 'snappy' diode'

Silicon Power diodes are the successors of Selenium rectifiers having significantly improved forward characteristics and voltage ratings. They are classified mainly by their turn-off (dynamic) characteristics Fig. 1.6. The minority carriers in the diodes require finite time - t_{rr} (reverse recovery time) to recombine with opposite charges and neutralise. Large values of Q_{rr} (= $Q_1 + Q_2$) - the charge to be dissipated as a negative current when the and diode turns off and t_{rr} (= t_2 - t_0) - the time it takes to regain its blocking features, impose strong current stresses on the controlled device in series. Also a 'snappy' type of recovery of the diode effects high di/dt voltages on all associated power device in the converter because of load or stray inductances present in the network. There are broadly three types of diodes used in Power electronic applications:

Line-frequency diodes: These PIN diodes with general-purpose rectifier type applications, are available at the highest voltage (~5kV) and current ratings (~5kA) and have excellent over-current (surge rating about six times average current rating) and surge-voltage withstand capability. They have relatively large Q_{rr} and t_{rr} specifications.

Fast recovery diodes: Fast recovery diffused diodes and fast recovery epitaxial diodes, FRED's, have significantly lower Q_{rr} and t_{rr} (~ 1.0 μ sec). They are available at high powers and are mainly used in association with fast controlled-devices as free-wheeling or DC-DC choppers and rectifier applications. Fast recovery diodes also find application in induction heating, UPS and traction.

Schottky rectifiers: These are the fastest rectifiers being majority carrier devices without any $Q_{rr..}$ However, they are available with voltage ratings up to a hundred volts only though current ratings may be high. Their conduction voltages specifications are excellent (~0.2V). The freedom from minority carrier recovery permits reduced snubber requirements. Schottky diodes face no competition in low voltage SPMS applications and in instrumentation.

Silicon Controlled Rectifier (SCR)

The Silicon Controlled Rectifier is the most popular of the thyristor family of four layer regenerative devices. It is normally turned on by the application of a gate pulse when a forward bias voltage is present at the main terminals. However, being regenerative or 'latching', it cannot be turned off via the gate terminals specially at the extremely high amplification factor of the gate. There are two main types of SCR's**.**

Converter grade or Phase Control thyristors These devices are the work horses of the Power Electronics. They are turned off by natural (line) commutation and are reverse biased at least for a few milliseconds subsequent to a conduction period. No fast switching feature is desired of these devices. They are available at voltage ratings in excess of 5 KV starting from about 50 V and current ratings of about 5 KA. The largest converters for HVDC transmission are built with series-parallel combination of these devices. Conduction voltages are device voltage rating dependent and range between 1.5 V (600V) to about 3.0 V (+5 KV). These devices are unsuitable for any 'forced-commutated' circuit requiring unwieldy large commutation components.

The dynamic di/dt and dv/dt capabilities of the SCR have vastly improved over the years borrowing emitter shorting and other techniques adopted for the faster variety. The requirement for hard gate drives and di/dt limting inductors have been eliminated in the process.

Inverter grade thyristors: Turn-off times of these thyristors range from about 5 to 50 μsecs when hard switched. They are thus called fast or 'inverter grade' SCR's. The SCR's are mainly used in circuits that are operated on DC supplies and no alternating voltage is available to turn them off. Commutation networks have to be added to the basic converter only to turn-off the SCR's. The efficiency, size and weight of these networks are directly related to the turn-off time, t_q of the SCR. The commutation circuits utilised resonant networks or charged capacitors. Quite a few commutation networks were designed and some like the McMurray-Bedford became widely accepted.

Asymmetrical, light-activated, reverse conducting SCR's Quite a few varieties of the basic SCR have been proposed for specific applications. The Asymmetrical thyristor is convenient when reactive powers are involved and the light activated SCR assists in paralleling or series operation.

MOSFET

The Power MOSFET technology has mostly reached maturity and is the most popular device for SMPS, lighting ballast type of application where high switching frequencies are desired but operating voltages are low. Being a voltage fed, majority carrier device (resistive behaviour) with a typically rectangular Safe Operating Area, it can be conveniently utilized. Utilising shared manufacturing processes, comparative costs of MOSFETs are attractive. For low frequency applications, where the currents drawn by the equivalent capacitances across its terminals are small, it can also be driven directly by integrated circuits. These capacitances are the main hindrance to operating the MOSFETS at speeds of several MHz. The resistive characteristics of its main terminals permit easy paralleling externally also. At high current low voltage applications the MOSFET offers best conduction voltage specifications as the $R_{DS(ON)}$ specification is current rating dependent. However, the inferior features of the inherent anti-parallel diode and its higher conduction losses at power frequencies and voltage levels restrict its wider application.
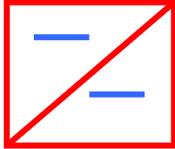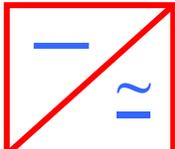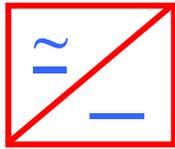
The IGBT

It is a voltage controlled four-layer device with the advantages of the MOSFET driver and the Bipolar Main terminal. IGBTs can be classified as punch-through (PT) and non-punch-through (NPT) structures. In the punch-through IGBT, a better trade-off between the forward voltage drop and turn-off time can be achieved. Punch-through IGBTs are available up to about 1200 V. NPT IGBTs of up to about 4 KV have been reported in literature and they are more robust than PT IGBTs particularly under short circuit conditions. However they have a higher forward voltage drop than the PT IGBTs. Its switching times can be controlled by suitably shaping the drive signal. This gives the IGBT a number of advantages: it does not require protective circuits, it can be connected in parallel without difficulty, and series connection is possible without dv/dt snubbers. The IGBT is presently one of the most popular device in view of its wide ratings, switching speed of about 100 KHz a easy voltage drive and a square Safe Operating Area devoid of a Second Breakdown region.

The GTO

The GTO is a power switching device that can be turned on by a short pulse of gate current and turned off by a reverse gate pulse. This reverse gate current amplitude is dependent on the anode current to be turned off. Hence there is no need for an external commutation circuit to turn it off. Because turn-off is provided by bypassing carriers directly to the gate circuit, its turn-off time is short, thus giving it more capability for highfrequency operation than thyristors. The GTO symbol and turn-off characteristics are shown in Fig. 30.3. GTOs have the I^2t withstand capability and hence can be protected by semiconductor fuses. For reliable operation of GTOs, the critical aspects are proper design of the gate turn-off circuit and the snubber circuit.

Power Converter Topologies

A Power Electronic Converter processes the available form to another having a different frequency and/or voltage magnitude. There can be four basic types of converters depending upon the function performed:

CONVERSION FROM/TO	NAME	FUNCTION	SYMBOL
DC to DC	Chopper	Constant to variable DC or variable to constant DC	
DC to AC	Inverter	DC to AC of desired voltage and frequency	
AC to DC	Rectifier	AC to unipolar (DC) current	
AC to AC	Cycloconverter, AC-PAC, Matrix converter	AC of desired frequency and/or magnitude from generally line AC	
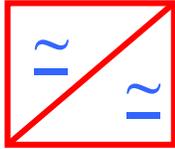
Base / gate drive circuit

All discrete controlled devices, regenerative or otherwise have three terminals. Two of these are the Main Terminals. One of the Main Terminals and the third form the Control Terminal. The amplification factor of all the devices (barring the now practically obsolete BJT) are quite high, though turn-on gain is not equal to turn-off gain. The drive circuit is required to satisfy the control terminal characteristics to efficiently tun-on each of the devices of the converter, turn them off, if possible, again optimally and also to protect the device against faults, mostly over-currents. Being driven by a common controller, the drives must also be isolated from each other as the potentials of the Main Terminal which doubles as a Control terminal are different at various locations of the converter. Gate-turn-off-able devices require precise gate drive waveform for optimal switching. This necessitates a wave-shaping amplifier. This amplifier is located after the isolation stage.

Thus separate isolated power supplies are also required for each Power device in the converter (the ones having a common Control Terminal - say the Emitter in an IGBT - may require a few less). There are functionally two types of isolators: the pulse transformer which can transmit after isolation, in a multi-device converter, both the un-shaped signal and power and optical isolators which transmit only the signal. The former is sufficient for a SCR without isolated power supplies at the secondary. The latter is a must for practically all other devices. Fig. 1.7 illustrates to typical drive circuits for an IGBT and an SCR.
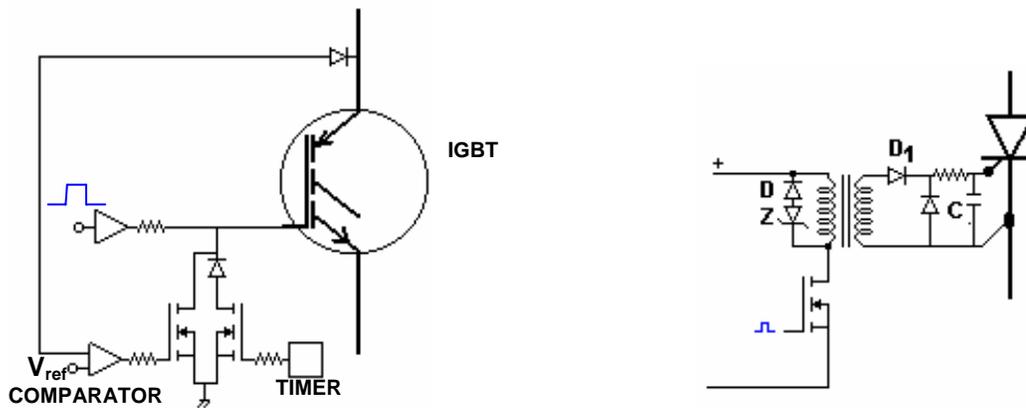
Fig. 1.7 Simple gate-drive and protection circuit for a stand-alone IGBT and a SCR

Protection of Power devices and converters

Power electronic converters often operate from the utility mains and are exposed to the disturbances associated with it. Even otherwise, the transients associated with switching circuits and faults that occur at the load point stress converters and devices. Consequently, several protection schemes must be incorporated in a converter. It is necessary to protect both the Main Terminals and the control terminals. Some of these techniques are common for all devices and converters. However, differences in essential features of devices call for special protection schemes particular for those devices. The IGBT must be protected against latching, and similarly the GTO's turn-off drive is to be disabled if the Anode current exceeds the maximum permissible turn-off-able current specification. Power semiconductor devices are commonly protected against:

1. Over-current;
2. di/dt;
3. Voltage spike or over-voltage;
4. dv/dt ;
5. Gate-under voltage;
6. Over voltage at gate;
7. Excessive temperature rise;
8. Electro-static discharge;

Semiconductor devices of all types exhibit similar responses to most of the stresses, however there are marked differences. The SCR is the most robust device on practically all counts. That it has an I^2t rating is proof that its internal thermal capacities are excellent. A HRC fuse, suitably selected, and in co-ordination with fast circuit breakers would mostly protect it. This sometimes becomes a curse when the cost of the fuse becomes exorbitant. All transistors, specially the BJT and the IGBT is actively protected (without any operating cost!) by sensing the Main Terminal voltage, as shown in Fig. 1.7. This voltage is related to the current carried by the device. Further, the transistors permit designed gate current waveforms to minimise voltage spikes as a consequence of sharply rising Main terminal currents. Gate resistances have significant effect on turn-on and turn-off times of these devices - permitting optimisation of switching times for the reduction of switching losses and voltage spikes.

Protection schemes for over-voltages - the prolonged ones and those of short duration - are guided by the energy content of the surges. Metal Oxide Varistors (MOV's), capacitive dynamic voltage-clamps and crow-bar circuits are some of the strategies commonly used. For high dv/dt stresses, which again have similar effect on all devices, R-C or R-C-D clamps are used depending on the speed of the device. These 'snubbers' or 'switching-aid-networks', additionally minimise switching losses of the device - thus reducing its temperature rise.

Gates of all devices are required to be protected against over-voltages (typically $\pm$ 20 V) specially for the voltage driven ones. This is achieved with the help of Zener clamps - the zener being also a very fast-acting device.

Protection against issues like excessive case temperatures and ESD follow well-set practices. Forced-cooling techniques are very important for the higher rated converters and whole environments are air-cooled to lower the ambient.

Objective type questions

Qs#1   Which is the Power semiconductor device having

a) Highest switching speed;
b) Highest voltage / current ratings;
c) Easy drive features;
d) Can be most effectively paralleled;
e) Can be protected against over-currents with a fuse;
f) Gate-turn off capability with regenerative features;
g) Easy drive and High power handling capability

Ans: a) MOSFET; b) SCR; c) MOSFET; d) MOSFET; e) SCR ; (f) GTO; (g) IGBT

Qs#2   An SCR requires 50 mA gate current to switch it on. It has a resistive load and is supplied from a 100 V DC supply. Specify the Pulse transformer details and the circuit following it, if the driver circuit supply voltage is 10 V and the gate-cathode drop is about 1 V.

Ans: The most important ratings of the Pulse transformer are its volt-secs rating, the isolation voltage and the turns ratio.
The volt-secs is decided by the product of the primary pulse-voltage multiplied by the period for which the pulse is applied to the winding

If the primary pulse voltage = (Supply voltage – drive transistor drop)
The turn-on time of he SCR may be in the range 50 μsecs for an SCR of this rating.
Consequently the volt secs may be in the range of 9 x 50 = 450 μvolt-secs

The Pulse transformer may be chosen as: 1:1, 450 μVs, V_{isol} = 2.5 KV, I_M = 150 mA
The circuit shown in Fig. 1.7 may be used. Diodes 1N4002
Series resistance
 = (Supply voltage – drive transistor drop – gate-cathode drop)/100mA
 = (10 –1 –1) / 100 E-3
 = 80 Ohm
 = 49 or 57 Ohm (nearest available lower value)