UNIVERSITY OF ANBAR

COLLEGE OF ENGINEERING

ELECTRICAL ENGINEERING DEPARTMENT

Power Electronic

Fourth Class

Chapter 01

Introduction to Power Electronic

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2014-2015

CHAPTER 1
Introduction to Power Electronic Devices

1.1 Introduction

Generally the electrical engineering field can be divided into three areas:

i) Electronics

Essentially deal with the study of semiconductor devices and circuits for the processing of information at low power level.

ii) Power

Deals with both rotating and static equipment for the generation, transmission, distribution, and utilization of vast quantities of electrical power.

iii) Control

Deals with the stability and response characteristics of closed-loop system using feedback on either a continuous or sampled data basis.

Power electronics deals with the use of electronics for the control and conversion of large amounts of electrical power. The design of power electronics equipment involves interactions between the source and the load, and utilize small-signal electronic control circuits as well as power semiconductor devices. Therefore, power electronics depend upon all other areas of electrical engineering.

1.2 Power Electronic Systems

The block diagram of generalised power electronics system is shown in Figure 1.1. The power source may be an AC supply system or a DC supply system. Some loads are powered from a battery for example is fork lift and milk vans and the size depends on its application. The typical value are 6 V, 12 V, 24 V, 48 V, and 110 V DC. Solar powered drives which are used in space and water pumping applications are fed from low voltage DC supply.

Power modulator or power converter performs one or more of the following functions:

i) Converts electrical energy of the source as per requirement of the loads.

ii) Select the mode o the operation of the motor, i.e: motoring or braking.

iii) Modulates flow of power from the source to the motor in such manner that the motor is imparted speed-torque characteristic required by the load.

During ransient operations, it restricts source and motor current within permissible values. The excessive current drawn from source may overload it or may cause a voltage dip.

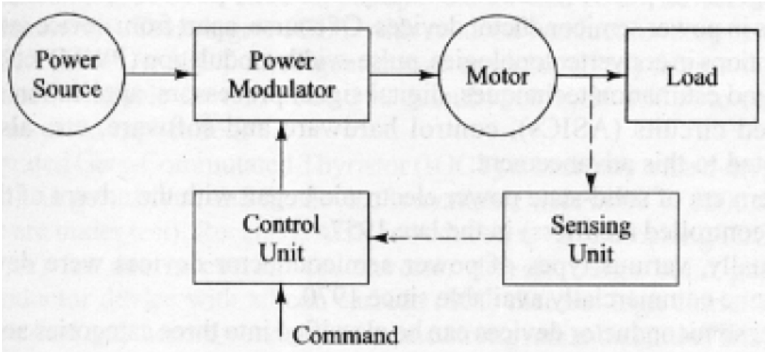


Figure 1.1 Block diagram of power electronic system

Power modulators are controlled by a control unit. Control unit operates at much lower voltage and power levels. Sensing unit measures the load parameters such as speed, current or torque of the motor. The different of the input/reference and measured parameters processed by the control unit are used to determine the turn on and off of power semiconductor devices in power modulators. This is controlled over a wide range with the adjustment of the command.

1.3 Electronic Converters

The objective of a power electronics circuit is to match the voltage and current requirements of the load to the source. Power electronics circuits convert one type or level of a voltage or current waveform to another and also called as power converters. Converters are classified by the relationship between input and output as the following.

1.3.1 Controlled Rectifier (AC to DC Converters)

The AC-DC converter produces a DC output from an ac input. Average power is transferred from an ac source to a dc load. The AC-DC converter is specifically classified as a rectifier. This control circuits use line voltage for their commutation. Hence they are also called as line commutated or naturally commutated AC to DC converters.

Applications:

- High voltage DC transmission system,
- DC motor drives
- Regulated DC power supplies

- Static VAR compensator
- Wind generation converters
- Battery charger circuits.

1.3.2 Chopper (DC to DC Converters)

A chopper converts fixed DC input voltage to a variable DC output voltage at different level. Output voltage can be varied by controlling the duty ratio of the device by low power signals from a control unit.

Applications:

- DC drives
- Battery driven vehicles
- Electric traction
- Switch mode power supplies

1.3.3 Inverter (DC to AC Converters)

An inverter converts a fixed DC voltage to a fixed (or variable) AC voltage with variable frequency. Inverters are widely used from very low power portable electronic systems such as the flashlight discharge system in a photography camera to very high power industrial systems.

Applications:

- Uninterruptible power supply (UPS)
- Aircraft and space power supply
- Induction and synchronous motor drives
- High voltage DC transmission system
- Induction heating supply

1.3.4 Cycloconverter (AC to AC Converters)

This circuits converts input power at one frequency to output power at a different frequency through one stage conversion. These are designed using thyristors and controlled by triggering signals derived from a control unit.

Application: AC drives

1.3.5 AC Voltage Controllers

This converter convert's fixed AC voltage directly to a variable AC voltage at the same frequency using line commutation. It employs a thyristorised voltage controller. The output voltage can be obtained by controlling the firing angle of the thyristors by low power signals from a control unit.

Applications:

- Lighting control
- Speed control of large fans and pumps
- Electronic tap changers

Power conversion can be a multistage process involving more than one type of converter. For example, an AC-DC-AC conversion can be used to modify an AC source by first converting it to DC and then converting the DC signal to an AC signal which has amplitude and frequency different from the original AC source.

1.4 Power Semiconductor Devices

The particular switching device used in a power electronics circuit depends on the existing state of semiconductor device technology. The behavior of power electronics circuits often is not affected significantly by the actual device used for switching, particularly if voltage drops across a conducting switch are small compared to other circuit voltage. Therefore, semiconductor devices are usually modeled as ideal switches so that circuit behavior can be emphasized. Switches are modeled as short circuits when "on" and open circuits when "off". Transitions between states are assumed to be instantaneous. The effects of non-ideal switching are discussed where appropriate.

However, before applied the semiconductor device it is necessary to know two basic limitations of semiconductor devices. First is the maximum voltage, it is according to the breakdown value of the silicon p-n junction. Second is the maximum current, it is according to the current density of the electrode. Product of the maximum voltage and current is defined as a maximum Power Handling Capability (PH_{max}). The product of the maximum voltage and current also related to the Save Operating Area of the semiconductor devices as shown in Figure 1.2.

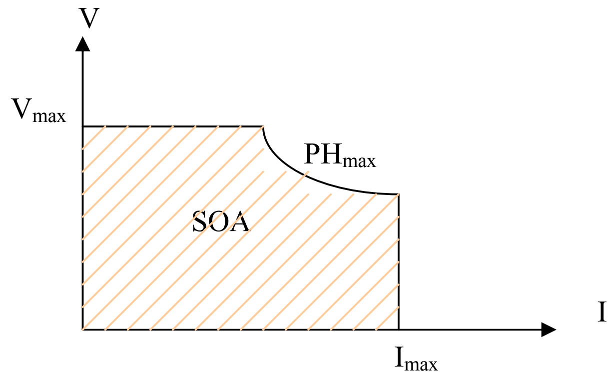


Figure 1.2: General diagram of the Safe Operation Area of power semiconductor devices

Classification of the power semiconductor can be shown in Figure 1.3.

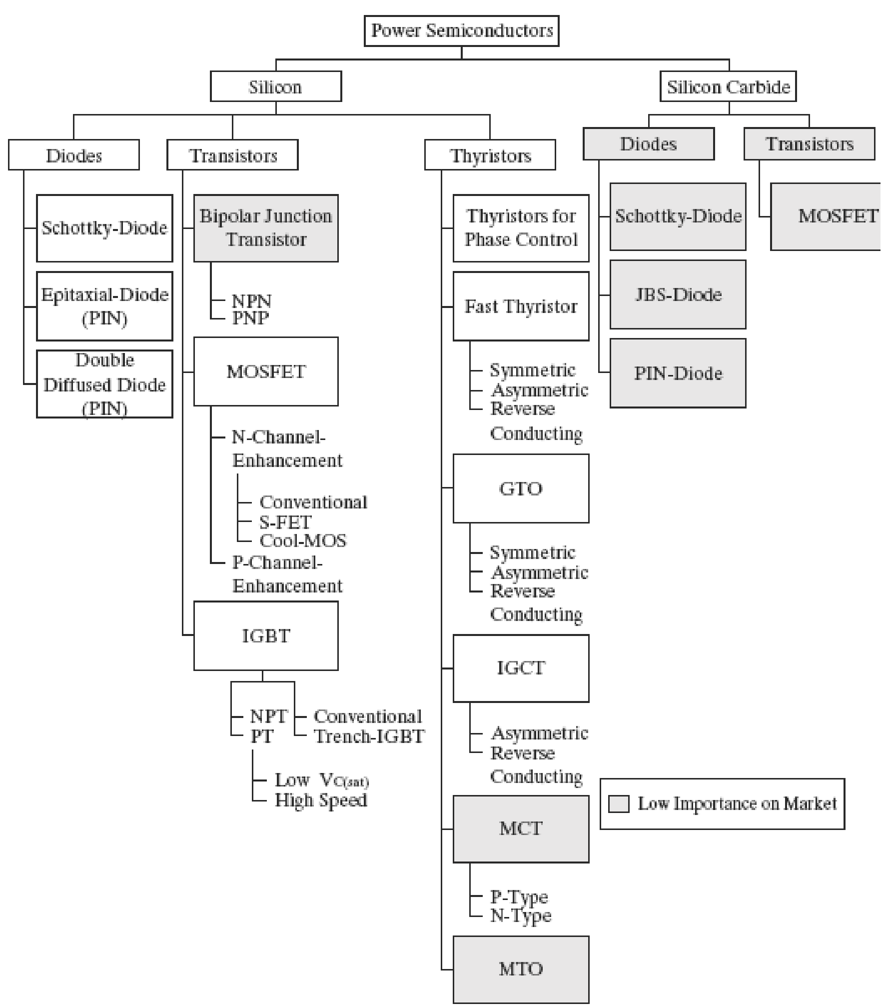


Figure 1.3: Classification of power semiconductor devices

1.4.1 Power Diode

A diodes a two-layer P-N semiconductor device. The structure of a diode and its symbol are shown in Figure. 1.2(a) and (b). High-power diodes are silicon rectifiers that can operate at high junction temperatures.

The voltage-current characteristic of a diode is shown in Figure. 1.2(c). If a reverse voltage is applied across the diode, it behaves essentially as an open circuit. If a forward voltage is applied, it starts conducting and behaves essentially as a closed switch. It can provide uncontrolled ac-to-dc power rectification. The forward voltage drop when it conducts current is in the range of 0.8 to 1 V. Diodes with ratings as high as 4000 V and 2000 A are available.

Following the end of forward conduction in a diode, reverse current flows for a short time. The device does not attain its full blocking capability until the reverse current ceases. The time interval during which reverse current flows is called the rectifier recovery time. During this time, charge carriers stored in the diode at the end of forward conduction are removed. The recovery time is in the range of a few μS (1 – 5 μS) in a conventional diode to several hundred nS in fast-recovery diodes. This recovery time is of great significance in HF applications. The recovery characteristics of conventional and fast-recovery diodes are shown in Figure. 1.2(d).

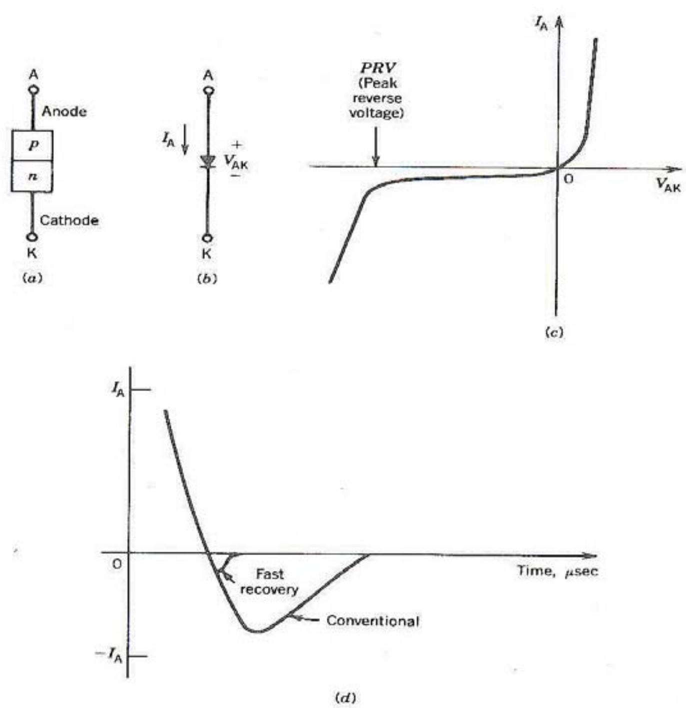


Figure 1.4 Diode rectifier. (a) Structure, (b) Symbol, (c) V – I characteristic, (d) Reverse recovery characteristics.

Classification of diodes are:

a. General purpose diodes/line frequency diodes
b. Fast recovery diodes
c. Schottky diodes

Comparison between different types of diodes are shown in table 1.1

Table 1.1: Specification of diodes

Parameter	Typical of Diodes		
	General purpose	Fast Recovery	Schottky
Voltage	Up to 500V	Up to 300V	50-100 V
Current	Up to 3500A	Up to 1000A	300 A
Reverse recovery time	High Up to 25μS	Low Up to 5μS	Extremely Low
Turn off time	High	Low	Extremely Low
Switching frequency	High	High	Very High

1.4.2 Power Transistor

A transistor is a three-layer p-n-p or n-p-n semiconductor device having two junctions. This type of transistor is known as a bipolar junction transistor (BJT).

The structure and the symbol of an n-p-n transistor are shown in Figure 1.3. The three terminals of the device are called the collector (C), the base (B), and the emitter (E). The collector and emitter terminals are connected to the main power circuit and the base terminal is connected to a control signal.

Transistors can also be operated in the switching mode. If the base current I_B is zero, the transistor is in an off state and behaves as an open switch. On the other hand, if the base is driven hard, that is, if the base current I_B is sufficient to drive the transistor into saturation, then the transistor behaves as a closed switch. This type of operation is illustrated in Figure 1.3(c).

The transistor is a current-driven device. The base current determines whether it is in the on state or the off state. To keep the device in the on state there must be sufficient base current.

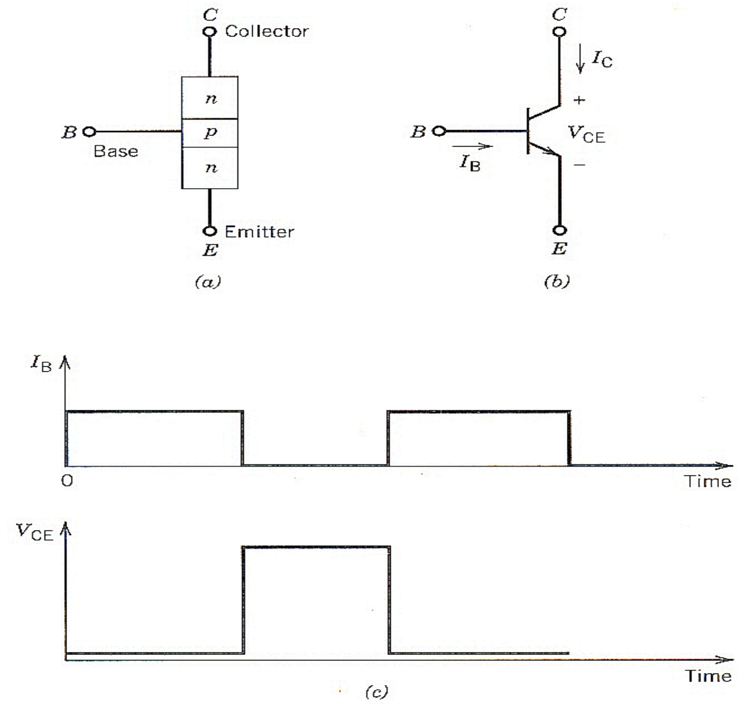


Figure 1.5: Transistor. (a) Structure, (b) Symbol, (c) Switching operation of a transistor.

Transistors with high voltage and current ratings are known as **power transistors.** The current gain (I_C / I_B) of a power transistor can be as low as 10, although it is higher than that of a GTO thyristor. For example, a base current of 10 A may be required for 100 A of collector current. High current gain can be obtained from a Darlington connected transistor pair, as shown in Figure 1.4. The fair can be fabricated on one chip, or two discrete transistors can be physically connected as a Darlington transistor. Current gains in the hundreds can be obtained in a high-power Darlington transistor. Power transistors switch on and switch off much faster than thyristors.

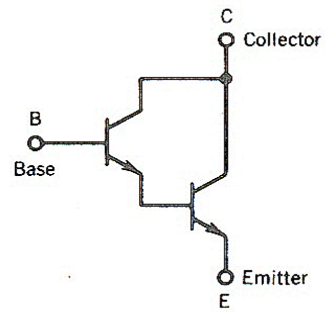


Figure 1.6: Darlington transistor

They may switch on in less than 1 μS and turn off in less than 2 μS. Therefore, power transistors can be used in applications where the frequency is as high as 50 kHz. These devices are, however, very delicate. They fail under certain high-voltage and high current conditions. They should be operated within specified limits, known as the safe operating area (SOA).

The SOA is partitioned into four regions, as shown in Figure 1.5, defined by the following limits:

- Peak current limit (ab)
- Power dissipation limit (bc)
- Secondary breakdown limit (cd)
- Peak voltage limit (de)

If high voltage and high current occur simultaneously during turnoff, a hot spot is formed and the device fails by thermal runaway, a phenomenon known as **secondary breakdown**.

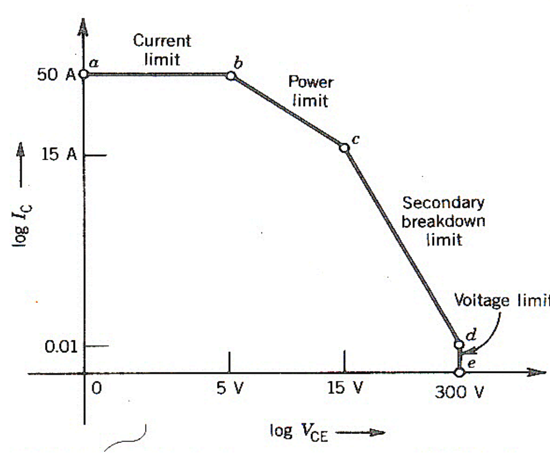


Figure 1.7: Safe operating area (SOA) of a power transistor

Polarized snubbers are used with power transistors to avoid the simultaneous occurrence of peak voltage and peak current. Figure 1.6 shows the effects of the snubber circuit on the turnoff characteristics of a power transistor. A chopper circuit with an inductive load is considered.

If no snubber circuit is used and the base current is removed to turn off the transistor, the voltage across the device, V_{CE}, first rises, and when it reaches the dc supply voltage (V_d) the collector current (I_C) falls. The power dissipation (P) during the turnoff interval is also shown in Figure 1.6 by the dashed line. Note that in these idealized waveforms, the peaks of V_{CE} and I_C occur simultaneously, and this may lead to secondary breakdown failure.

If the snubber circuit is used and base current is removed to turn off the transistor, the collector current is diverted to the capacitor. The collector current, therefore, decreases as the collector-emitter voltage increases, avoiding the simultaneous occurrence of peak voltage and peak current. Figure 1.6 also shows the effect of the size of the snubber capacitor on the turnoff characteristics.

Transistors do not have reverse blocking capability, and they are shunted by antiparallel diodes if they are used in ac circuits.

Because base current is required to keep a power transistor in the "on" condition, the power loss in the base drive circuit may be appreciable. Power transistors of ratings as high as 1000 V, 500 A are available.

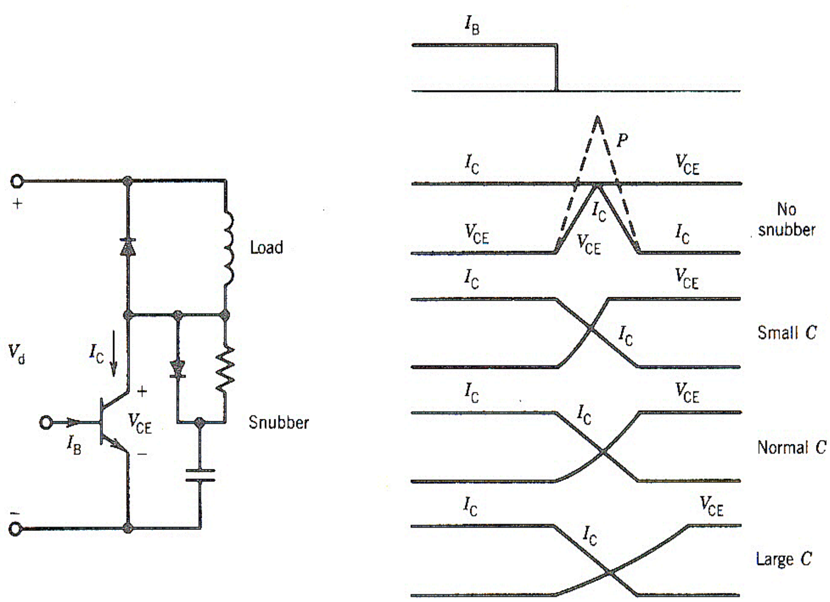


Figure 1.8: Effects of snubber capacitor on turn-off characteristics of a power transistor.

1.5 Power MOSFET

The MOSFET (metal oxide semiconductor field effect transistor) is a very fast switching transistor that has shown great promise for applications involving HF (up to 1 MHz) and low power (up to a few kW). There are other trade names for this device, such as HEXFET (International Rectifier), SIMMOS (Siemens) and TIMOS (Motorola).

The circuit symbol of the MOSFET is shown in Figure 1.7(a). The three terminals are called drain (D), source (S) and gate (G). The current flow is from drain to source. The device has no reverse-voltage blocking capability and it always comes with an integrated reverse diode, as shown in Figure 1.7(a).

Unlike a bipolar transistor (which is a current-driven device), a MOSFET is a voltage-controlled majority carrier device. With positive voltage applied to the gate (i.e., V_{GS} positive), the transistor switches on. The gate is isolated by a silicon oxide (SO_2) layer, and therefore the gate circuit input impedance is extremely high. This feature allows a MOSFET to be driven directly from CMOS or TTL logic. The gate drive current is therefore very low – it can be less than 1 mA.

The MOSFET has a positive temperature coefficient of resistance and the possibility of secondary breakdown is almost nonexistent. If local heating occurs, the effect of the positive temperature coefficient of resistance forces the local concentrations of current to be distributed over the area, thereby avoiding the creation of local hot spots. The SOA of a MOSFET is shown in Figure 1.7(b). It is bounded by three limits: the current limit (ab), the power dissipation limit (bc), and the voltage limit (cd). The SOA can be increased for pulse operation of the device, shown dashed in Figure 1.7(b).

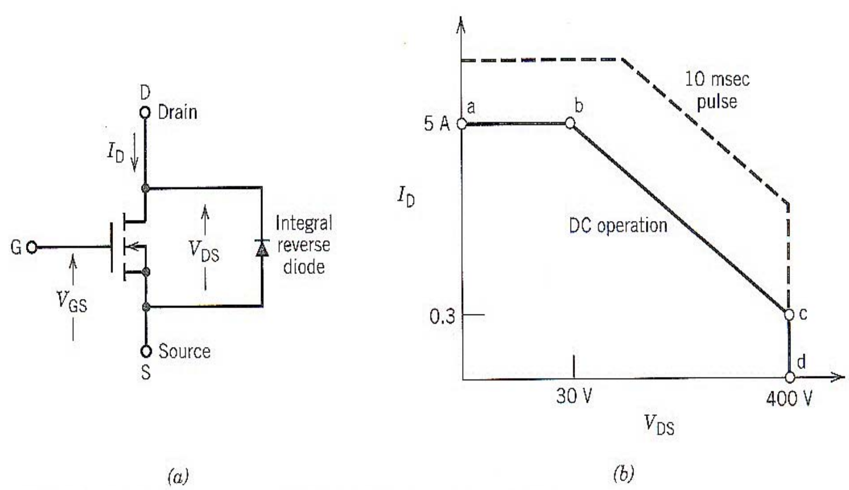


Figure 1.9: Power MOSFET. (a) Symbol. (b) SOA.

The switching characteristics of the MOSFET are similar to those of the BJT. However, MOSFETs switch on and off very fast, in less than 50 nS. Because MOSFETs can switch under high voltage and current conditions (i.e. practically no secondary breakdown), no current snubbing is required during turnoff. However, these devices are very sensitive to voltage spikes appearing across them and snubber circuits may be required to suppress voltage spikes.

MOSFETs switch very fast and their switching losses are almost negligible. However, conduction (i.e., on-state) voltage drop is high and therefore conduction loss is high. For example, the conduction voltage drop of a 400 V device is 2.5 V at 10 A, and this drop increases with temperature and current.

MOSFETs are still not available in high power ratings. MOSFETs with ratings of 600 V, 50 A, 50 nS are available. These devices can be used in parallel for higher current ratings.

The MOSFET parameter consist of:

a. Mutual Transonductance

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}} \tag{1.1}$$

b. Output/Drain Resistance

$$R_{ds} = \frac{\Delta V_{DS}}{\Delta I_D} \tag{1.2}$$

Amplification factor of the MOSFET:

$$\mu = R_{ds} \times g_m \tag{1.3}$$

1.6 Insulated Gate Bipolar Transistor (IGBT)

The IGBT is a hybrid power semiconductor device which combine the attributes of the BJT and the MOSFET. It has a MOSFET-type gate and therefore has a high input impedance. The gate is voltage driven, as in the MOSFET. The symbol used is shown in Figure 1.8(a). Like the power MOSFET, the IGBT does not exhibit the secondary breakdown phenomenon, common to the BJT. As well, the IGBT has low on-state voltage drop, similar to the BJT. The switching speed of the IGBT is significantly lower than the MOSFET and is similar to the BJT. IGBTs are available with ratings of 1500 V, 1000 A, and they are presently preferred to BJTS.

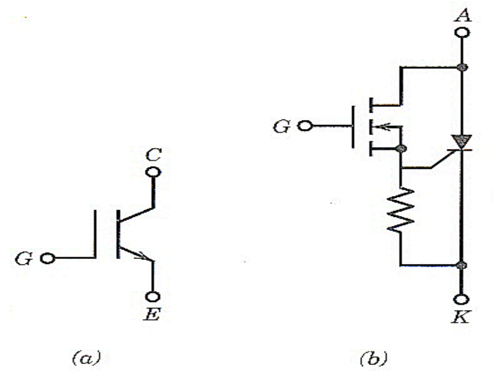


Figure 1.10: Hybrid devices. (a) IGBT. (b) MCT

1.7 Thyristor (SCR)

The thyristor or silicon-controlled rectifier (SCR), has been widely used in industry for more than two decades for power conversion and control. The thyristor has a four-layer p-n-p-n structure with three terminals, anode (A), cathode (K) and gate (G) as shown in Figure 1.9. The anode and cathode are connected to the main power circuit. The gate terminal carries a low-level gate current in the direction from gate to cathode. The thyristor operates in two stable states: on or off.

Thyristor can only be turned on with two conditions: (1) the device is in forward blocking state (i.e. V_{ak} is positive), (2) a positive gate current (I_g) is applied at the gate. Once conducting, the anode current is latched (continuously flowing).

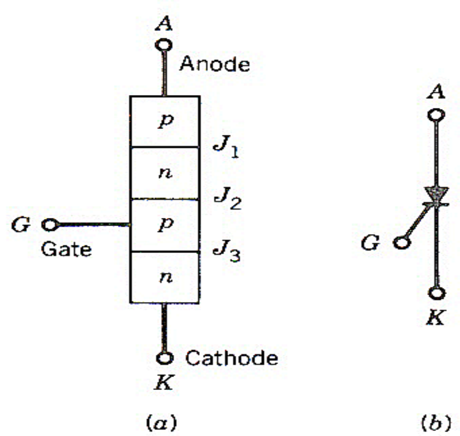


Figure 1.11: Thyristor (SCR). (a) Structure. (b) Symbol.

1.7.1 Volt-Ampere (V-I) Characteristics

The terminal V-I characteristics of a thyristor are shown in Figure 1.10. With zero gate current ($i_g = 0$), if a forward voltage is applied across the device (i.e., anode positive with respect to cathode) junction J_1 and J_3 are forward biased while junction J_2 remains reverse biased and therefore the anode current is a small leakage current. If the anode-to-cathode forward voltage reaches a critical limit, called the **forward breakover voltage**, the device switches into high conduction. If gate current are applied, the forward breakover voltage is reduced. For a sufficiently high gate current, such as i_{g3}, the entire forward blocking region is remove and the device behaves as a diode. When the device is conducting, the gate current can be removed and the device remains in the on state. If the anode current falls below a critical limit, called the **holding current** (I_h), the device returns its forward blocking state.

If a reverse voltage is applied across the device (i.e., anode negative with respect to cathode), the outer junctions J_1 and J_3 are reverse biased and the central junction J_2 is forward biased. Therefore only a small leakage current flows. If the reverse voltage is increased, then at a critical breakdown level (**reverse breakdown voltage**), an avalanche will occur at J_1 and J_3 and the current will increase sharply. If this current is not limited to a safe value, power dissipation will increase to a dangerous level that will destroy the device.

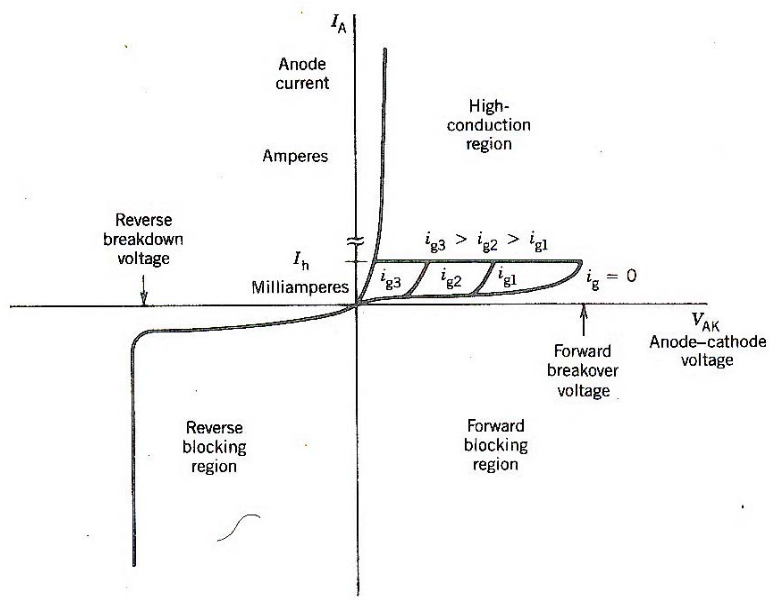


Figure 1.12: Terminal V-I characteristics of a thyristor (SCR)

1.7.2 Thyristor Conduction

If a thyristor is forward biased and a gate pulse is applied, the thyristor switches on. However, once the thyristor starts conducting an appreciable forward current, the gate has no control on the device. The thyristor will turn off if the anode current becomes zero, called natural commutation, or is forced to become zero, called forced commutation.

However, if a forward voltage is applied immediately after the anode current is reduced to zero, the thyristor will not block the forward voltage and will start conducting again although it is not triggered by a gate pulse. It is therefore necessary to keep the device reverse biased for a finite period before a forward anode voltage can be applied. This period is known as the turnoff time, t_{off}, of the thyristor. The turnoff time of the thyristor is defined as the minimum time interval between the instant the anode current becomes zero and the instant the device is capable of blocking the forward voltage.

Thyristor cannot be turned off by applying negative gate current. It can only be turned off if I_g goes negative (reverse) as shown in Figure 1.11. This happens when negative portion of the sine-wave occurs (natural commutation). Another method of turning off is known as "force commutation" when the anode current is "diverted" to another circuitry.

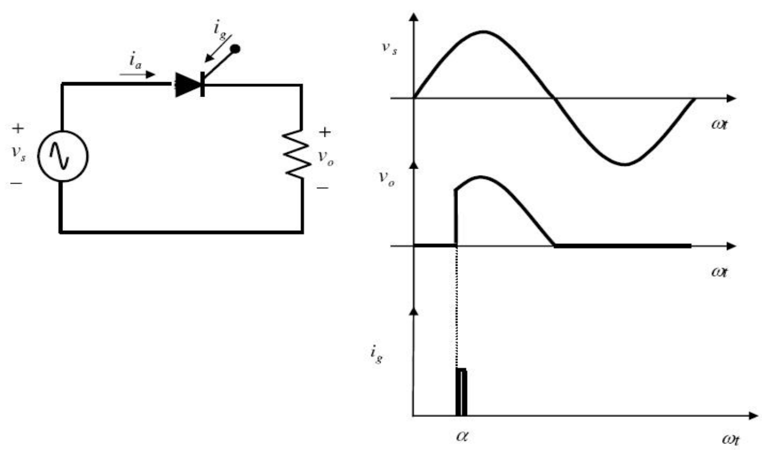


Figure 1.13: Thyristor conduction

1.8 GTO (Gate-Turn-Off) Thyristor

A GTO thyristor can be turned on by a single pulse of positive gate current (like a thyristor), but in addition it can be turned off by a pulse of negative gate current. Both on-state and off-state operation of the device are therefore controlled by the gate current.

The symbol and switching characteristics of the GTO thyristor are shown in Figure 1.12(a) and (b). The turn-on process is the same as that of a thyristor. The turnoff characteristics are somewhat different. When a negative voltage is applied across the gate and cathode terminals, the gate current i_g rises. When the gate current reaches its maximum value, I_{GR}, the anode current begins to fall, and the voltage across the device, V_{AK}, begins to rise. The fall time of I_A is abrupt, typically less than 1µS. Thereafter the anode current changes slowly and this portion of the anode current is known as the **tail current**.

The ratio (I_A / I_{GR}) of the anode current I_A (prior to turnoff) to the maximum negative gate current I_{GR} required for turnoff is low, typically between 3 and 5. For example, a 2500 V, 1000 A GTO typically requires a peak negative gate current of 250 A for turnoff.

Not that during turnoff both voltage and current are high. Therefore switching losses are somewhat higher in GTO thyristors. Consequently GTOs are restricted to operate at or below a 1 kHz switching frequency. If the spike voltage V_p is large, the device may be destroyed. The power losses in the gate drive circuit are also somewhat higher than those of thyristors. However, since no commutation circuits are required, the overall efficiency of the converter is improved. Elimination of commutation circuits also results in a smaller and less expensive converter.

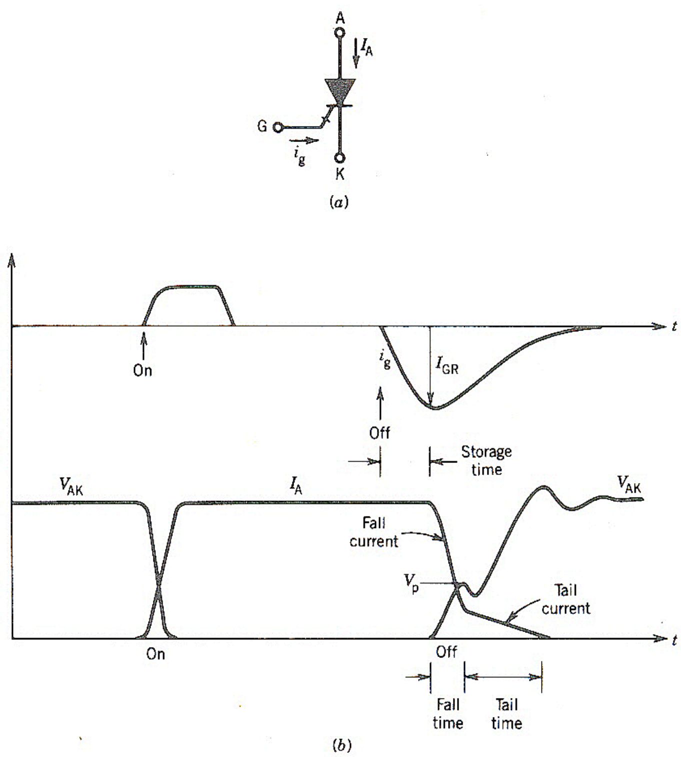


Figure 1.14: GTO thyristor. (a) Symbol. (b) Switching characteristics

GTOs may have no reverse-voltage blocking capability, or else little – 20 percent of the forward breakover voltage. New devices are being developed having higher reverse-voltage blocking capability. Therefore an inverse diode must be used, as shown in Figure 1.13, if there is a possibility that appreciable reverse voltage may appear across the device. A Polarized snubber consisting of a diode, capacitor and resistor as shown in Figure 1.13 is used for the following purposes:

- During the fall time of the turnoff process the device current is diverted (known as current Snubbing) to the snubber capacitor (charging it up).
- The snubber limits the dv / dt across the device during turnoff.

Although GTOs and thyristors became available at almost the same time, the development of GTOs did not receive as much attention as that of thyristors. The Japanese persisted in the development of high-power GTOs. Recently (1997), these devices have been developed with large voltage and current ratings and improved performance (4000 V, 3000 A, 5 – 10 μS GTOs are being used). They are becoming increasingly popular in power control equipment, and it is predicted that GTOs will replace thyristors where forced commutation is necessary, as in choppers and inverters.

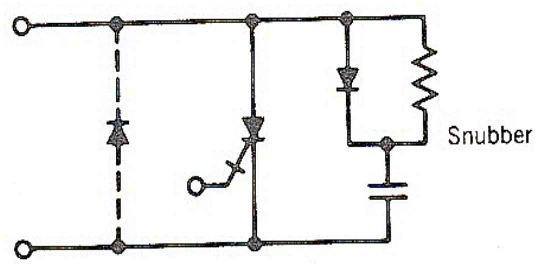


Figure 1.15: GTO with antiparallel diode and snubber circuit

1.9 IGCTs (Integrated Gate Commutated Thyristors)

The IGCT integrates a gate-commutated thyristor (GCT) with a multilayered printed circuit board gate drive. The GCT is a hard-switched GTO with a very fast and large gate current fast, as large as the full-rated current, that draws out all the current, from the cathode into the gate in about 1 μS to ensure a fast turn-off.

The internal structure and equivalent circuit of a GCT are similar to that of a GTO shown in Figure 1.14. A IGCT may also have an integrated reverse diode, as shown by the $n^+ n^- p$ junction on the right side of Figure 1.14. Similar to a GTO, an MTO and an ETO, the n-buffer layer evens out the voltage stress across the n^- -layer, reduces the thickness of the n^- -layer, decreases the on-state conduction losses, and make the device asymmetric. The anode p-layer is made thin and lightly doped to allow faster removal of charges from the anode-side during turn-off.

Turn-on. Similar to a GTO, the IGCT is turned on by applying the turn-on current to its gate.

Turn-off. The IGCT is turn-off by a multilayered by gate-driver circuit board that can supply a fast rising turn-off pulse, for example, a gate current of 4 kA/µS with a gate-cathode voltage of 20 V only. With this rate of gate current, the cathode side npn-transistor is totally turned off within about 1µS and the anode-side pnp-transistor is effectively left with an open base and it is turned-off almost immediately. Due to a very short duration short pulse, the gate-drive energy is greatly reduced and the gate-drive energy consumption is minimize. The gate-drive power requirement is decreased by a factor of five compared with that of the GTO. To apply a fast-rising and high-gate current, the IGCT incorporates a special effort to reduce the inductance of the gate circuitry as low as possible. This feature is also necessary for a gate-drive circuits of the MTO and ETO.

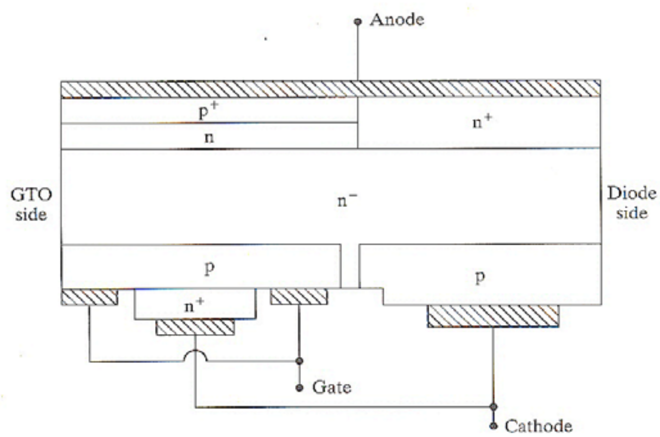


Figure 1.16: Cross section of IGCT with a reverse diode.

1.10 Switching Power Loss in Controllable Switches

As discussed previously, several types of semiconductor power devices including BJT, MOSFET, GTO, and IGBT can be turn on and off by control signals applied to the control terminal of the devices.

The ideal controllable switch has the characteristics:

i) Block large forward and reverse voltages with zero current flow when off.

ii) Conduct large currents with zero voltage drop when on.

iii) Switch from on to off or vise versa instantaneously when triggered.

However in real devices, it has power dissipation during turn on and off. If the power dissipation is too much, it will destroy the devices and may damage the other system components. In order to consider power dissipation in a semiconductor device, a controllable switch is connected in the simple circuit as shown in Figure 1.15(a). The diode is assumed to be ideal because the focus is on the switch characteristic.

When the switch is on, the entire current I_o is flows through the switch and diode is reverse biased. When the switch is turn off, I_o is flows through the diode and a voltage equal to the input voltage V_d appears across the switch (assuming zero voltage drop across the ideal diode). Figure 1.15(a) shows the waveforms for the current flows through the switch and voltage across the switch with the switching frequency, *fs*.

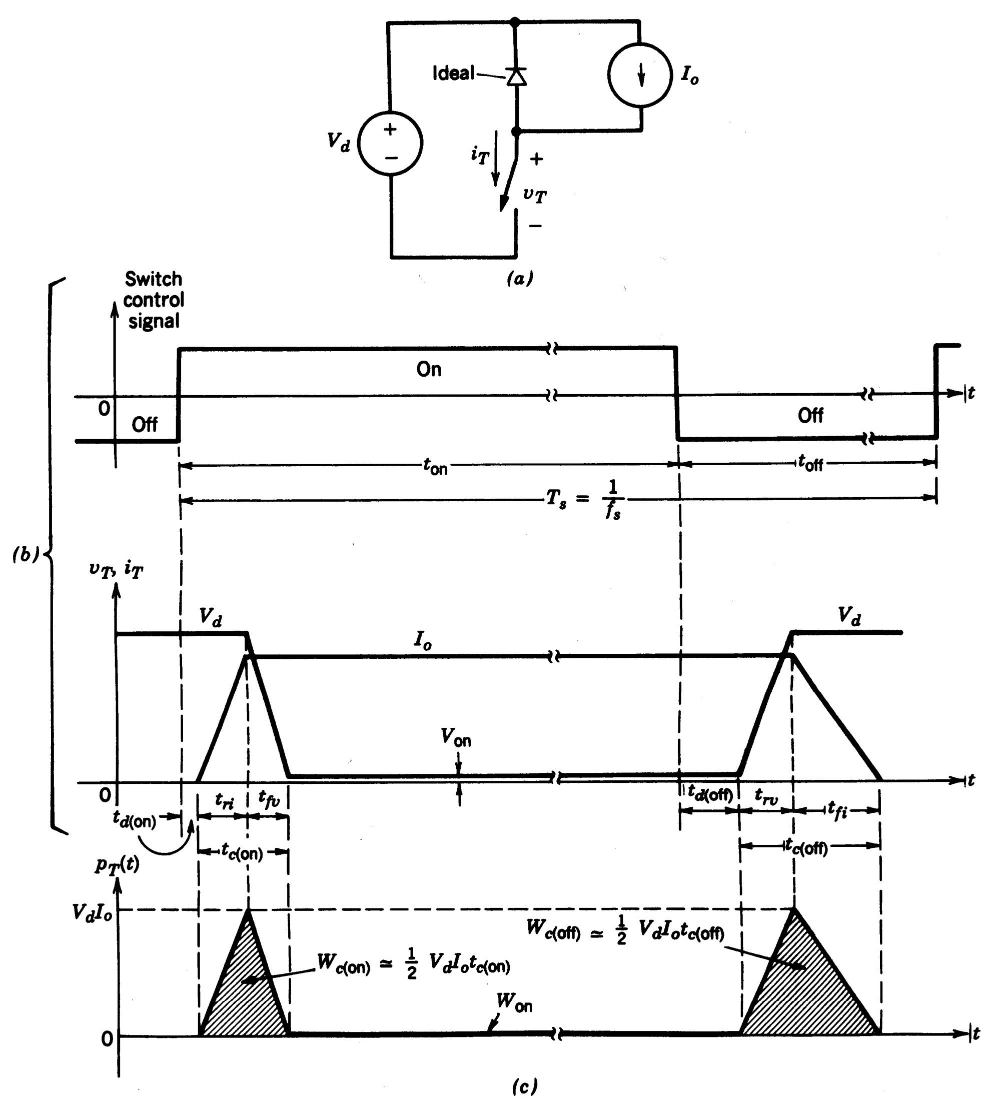


Figure 1.17: Switch switching characteristics: (a) simplified clamped-inductive-switching circuit, (b) switch waveforms, (c) instantaneous switch power loss.

Where

V_d - input voltage = voltage across switch during off-state.
I_o - current flows through the switch.
v_{on} - small on-state voltage
$t_{d(on)}$ - delay time before the rising current through the switch.
t_{ri} - current rise time.
t_{fv} - fall time voltage
$t_{c(on)}$ - turn-on-crossover interval.
$t_{c(off)}$ - turn-off transition time
t_{rv} - voltage rise time

From the Figure 1.15(b), the turn-on-crossover interval is given by

$$t_{c(on)} = t_{ri} + t_{fv} \tag{1.4}$$

The energy dissipated during turn-on transition is

$$W_{c(on)} = \tfrac{1}{2} V_d I_o t_{c(on)} \tag{1.5}$$

The energy dissipation during on-state interval can be express as

$$W_{on} = V_{on} I_o t_{on} \tag{1.6}$$

Where $t_{on} > t_{c(on)}$ and $t_{c(off)}$

During turn off transition period, the voltage build up consist of a turn-off delay time $t_{d(off)}$ and voltage rise time t_{rv}. Once the voltage reaches its maximum value V_d, diode become forward biased and conduct the current. The current in the switch falls to zero with fall time t_{fi}. Large voltage and current occurs during crossover interval $t_{c(off)}$, where

$$t_{c(off)} = t_{rv} + t_{fi} \tag{1.7}$$

The energy dissipated during turn-off transition can written as

$$W_{c(off)} = \tfrac{1}{2} V_d I_o t_{c(off)} \tag{1.8}$$

It it recognized that no energy dissipated during the turn-on and turn-off delay interval.

Figure 1.15(c) shows the instantaneous power dissipation occurs in the switch during the turn-on and turn-off intervals. Hence, the average switching power loss P_s is approximated as

$$P_s = \tfrac{1}{2} V_d I_o f_s (t_{c(on)} + t_{c(off)}) \tag{1.9}$$

It is shows that the switching power loss in semiconductor switches varies linearly with the switching frequency and the switching times.

The average power dissipated during on-state also can be written as

$$P_{on} = V_{on} I_o \frac{t_{on}}{T_s} \qquad (1.10)$$

Therefore, the total average power dissipation is

$$P_T = P_s + P_{on} \qquad (1.11)$$

1.11 Gate and Base Drive Circuits

The driver circuit is the interface between the control circuit which is low power electronic components and high power switch. The primary function of a drive circuit is to switch a power semiconductor device from the off state and vice versa. Figure 1.16 shows the basic block diagram of drive circuit between the control signal and power semiconductor switch.

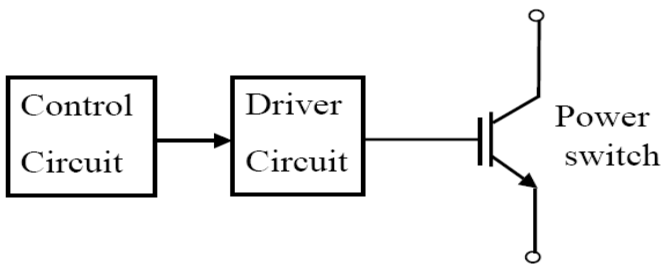


Figure 1.18: Block diagram of drive circuit

In the on state, he drive circuit must provide adequate drive power to the devices to keep the power switch in the on state where the conduction losses are low. The drive circuit amplifies the control signals to level required to drive the power switch sand provides electrical isolation when required between the power switch and the logic label of control circuit. It is may included in the drive circuit for protection of the power switch from overcurrent. The component values to be used and the complexity of a drive circuit will vary depending on the characteristics of the power switch being driven. For example, the MOSFET or IGBT drivers are simple but for GTO it is vary complicated and expensive.

A simple MOSFET gate drive circuit with only one switch to control the gate current is shown in Figure 1.17 where the output transistor of a comparator (LM311) controls the MOSFET. The MOSFET requires V_{GS} = +15 V for turn on and 0 V to turn off. When the output of the comparator is low, V_{GS} is pulled to V_{GG}. If V_{GG} is set to +15 V, the MOSFET turn on. When output of the comparator is high, V_{GS} is pulled to the ground, and then the MOSFET is off.

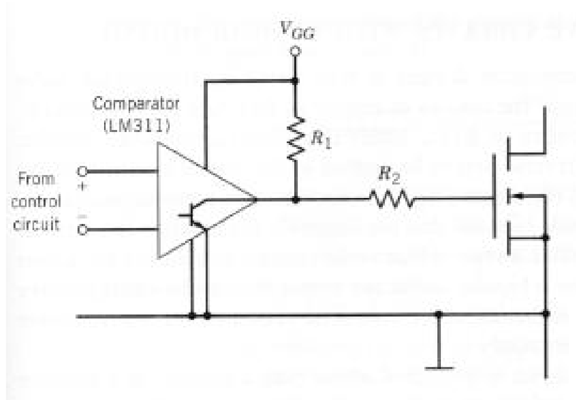


Figure 1.19: Simple MOSFET gate drive circuit

While Figure 1.18 shows a simple gate drive for a thyristor. In this circuit, a pulse transformer is used to conduct the thyristor with the R_1 is to limit the gate current. Normally, a pulse with length of 10 us and amplitude of 50 mA is sufficient to turn-on the thyristor. However, this simple circuit is not possible to turn-off the thyristor.

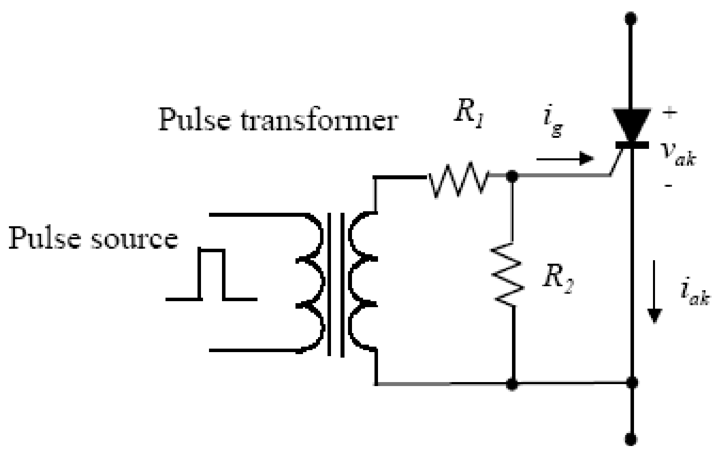


Figure 1.20: A simple gate drive circuit for a thyristor

1.12 Electrical Isolation for Drivers

Very often, there is need for electrical isolation between the logic-level control signals and the drive circuit to prevent damages on the high power switch to propagate back to low power electronics. This is illustrated in Figure 1.19 for the case of a power BJT half-bridge converter.

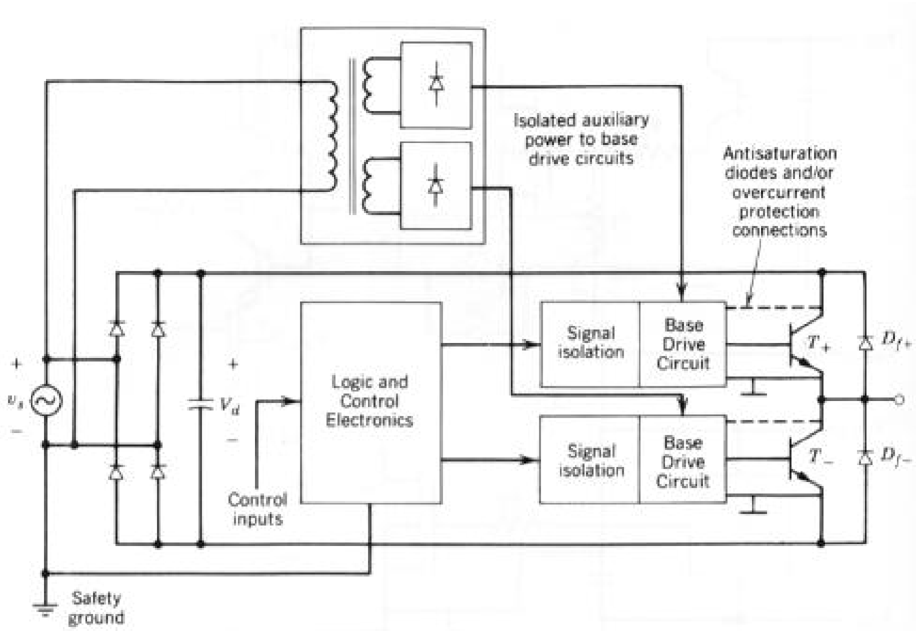
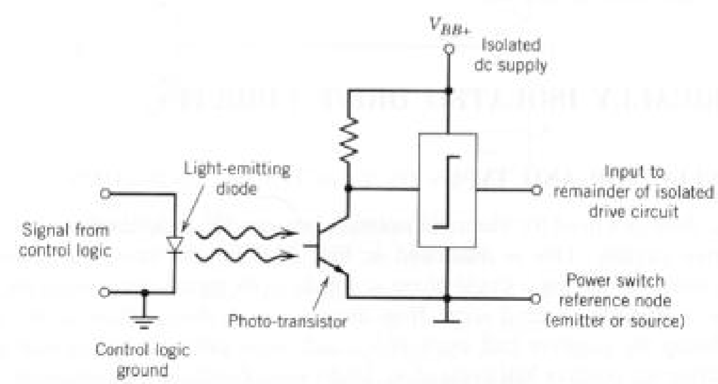


Figure 1.21: Electrical isolation in power BJT

The basic ways to provide electrical isolation are either by optocoupler, fiber optics or by transformer. The optocoupler shown in Figure 1.20 consist of a light-emitting diode, the output transistor, and built in Schmitt trigger. Many standard driver chips have built-in isolation for example TLP-20 from Toshiba and HP 3150 from Hewlett-Packard uses optocoupling isolation.



Fiugre 1.22: Schematic of an optocoupler use for electrical isolation in drive circuit