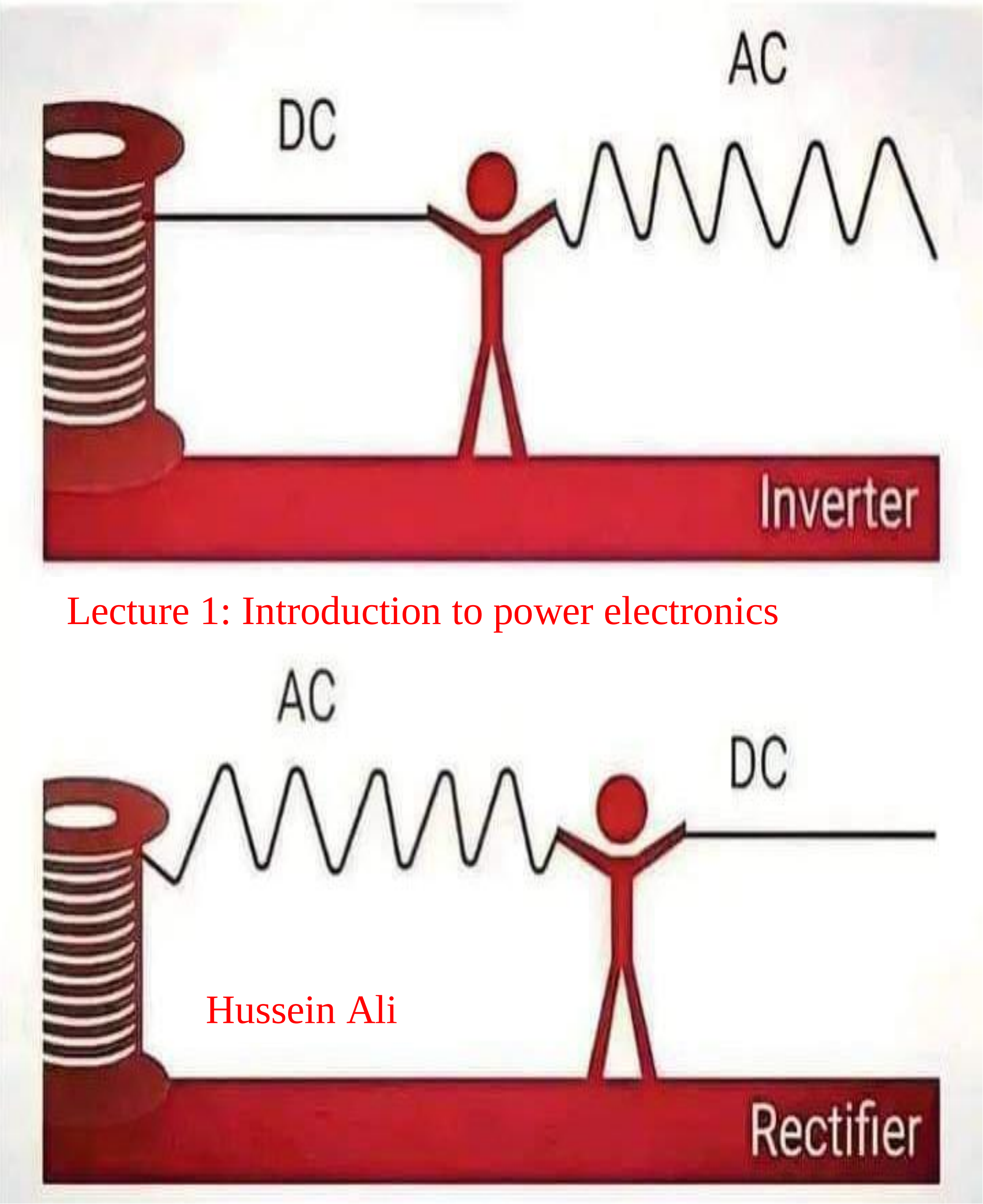
Al-Maarif University College
Computer Engineering Techniques



Lecture 1: Introduction to power electronics

Hussein Ali

Introduction:

Power Electronics is a field which combines Power (electric power), Electronics and Control systems.

- Power engineering deals with the static and rotating power equipment for the generation, transmission and distribution of electric power.
- Electronics deals with the study of solid state semiconductor power devices and circuits for Power conversion to meet the desired control objectives (to control the output voltage and output power).
- Control deals with steady state characteristic and dynamic characteristic.

Power electronic deal with how to control and convert power (electric energy) into one form to another and how utilization of power at high efficiency. Figure 1 below illustrated block diagram of power electronic system

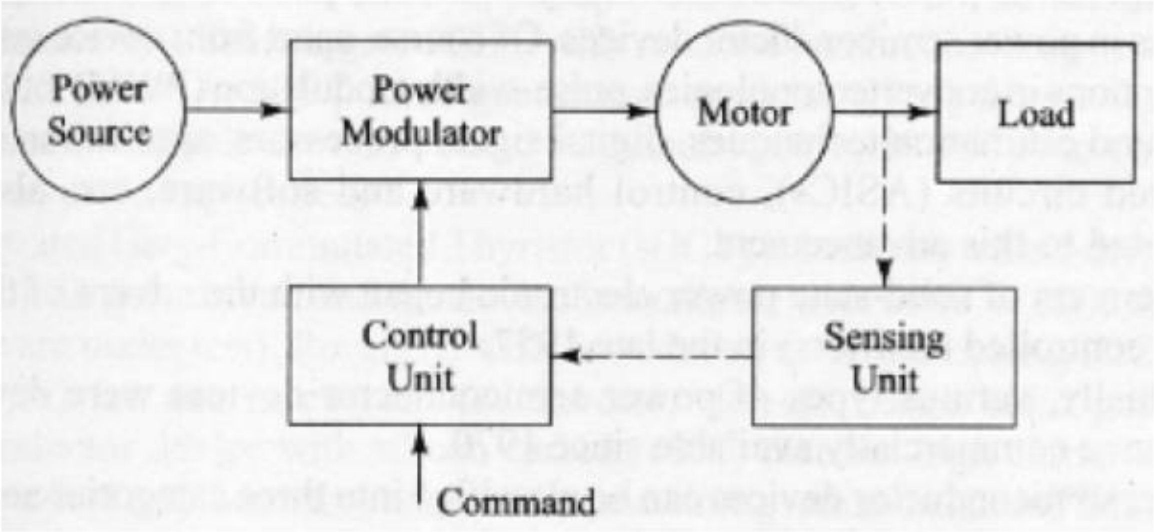


Figure 1 block diagram of power electronic system

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 of 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.

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.

BRIEF HISTORY OF POWER ELECTRONICS:

The first Power Electronic Device developed was the Mercury Arc Rectifier during the year 1900. Then the other Power devices like metal tank rectifier, grid controlled vacuum tube rectifier, ignitron, phanotron, thyratron and magnetic amplifier, were developed & used gradually for power control applications until 1950. The first SCR (silicon controlled rectifier) or Thyristor was invented and developed by Bell Lab’s in 1956 which was the first PNPN triggering transistor. The second electronic revolution began in the year 1958 with the development of the commercial grade Thyristor by the General Electric Company (GE). Thus the new era of power electronics was born. After that many different types of power semiconductor devices & power conversion techniques have been introduced. The power electronics revolution is giving us the ability to convert, shape and control large amounts of power.

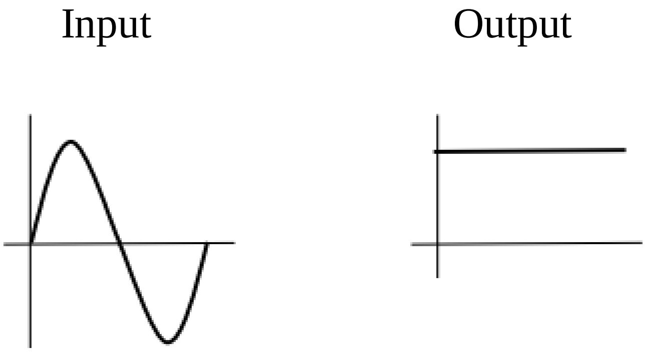
Applications of Power Electronics:

1- AEROSPACE	Space shuttle power supply systems, satellite power systems, aircraft power systems.
2- COMMERCIAL	Heating Systems Ventilating, Air Conditioners, Central Refrigeration, Lighting, Uninterruptible Power Supplies (UPS), Elevators, and Emergency Lamps.
3- TELECOMMUNICATIONS	Battery chargers, power supplies (DC and UPS), mobile cell phone battery chargers.
4- INDUSTRIAL	Pumps, compressors, blowers and fans. Machine tools, arc furnaces, induction furnaces, lighting control circuits, industrial lasers, induction heating.
5- DOMESTIC	Lighting, Heating, Air Conditioners, Refrigerators & Freezers, Personal Computers.
6- TRANSPORTATION	Traction control of electric vehicles, battery chargers for electric vehicles, electric locomotives, street cars, trolley buses, automobile electronics including engine controls.
7- UTILITY SYSTEMS	High voltage DC transmission (HVDC), static VAR compensation (SVC), Alternative energy sources (wind, photovoltaic), fuel cells, energy storage systems, induced draft fans and boiler feed water pumps.

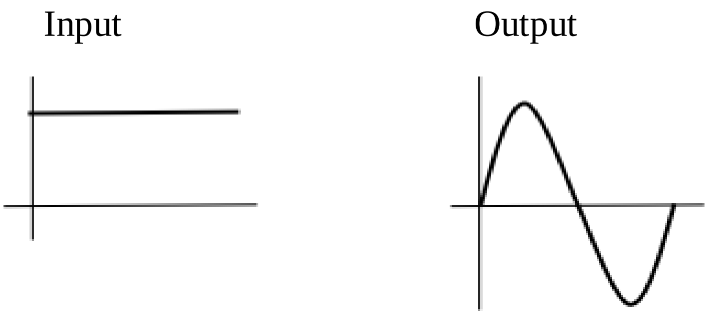
Electronic Converters

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.

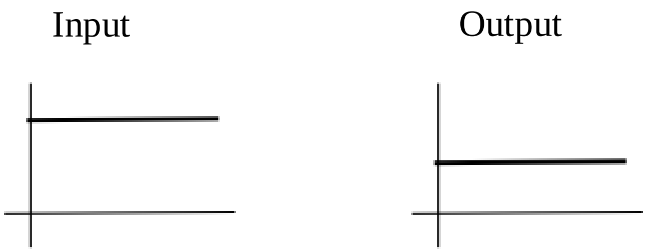
1. Rectifier convert AC to DC as illustrated in figure below



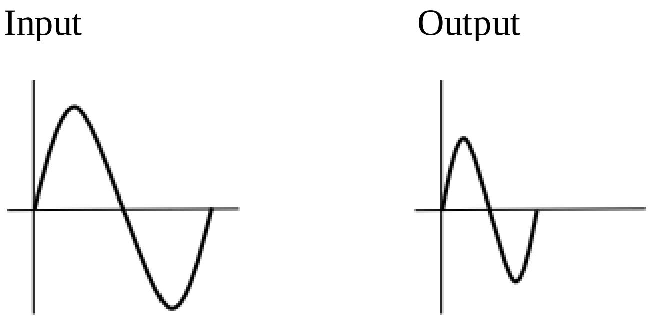
2. Inverter converts a fixed DC voltage to a fixed (or variable) AC voltage with variable frequency. As illustrated in figure below



3. 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.



4. Cycloconverter This circuits converts input power at one frequency to output power at a different frequency through one stage conversion.



5. AC Voltage Controller: 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.

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 utilization of the Bipolar junction transistor, Figure.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, Figure 3. Saturation and cutoff zones in the VCE - IC plane are avoided. In a Power electronic switching amplifier, only those areas in the VCE - IC plane which have been skirted above, are suitable. Onstate dissipation is minimum if the device is in saturation (or quasi-saturation for optimizing 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 minimize switching losses.

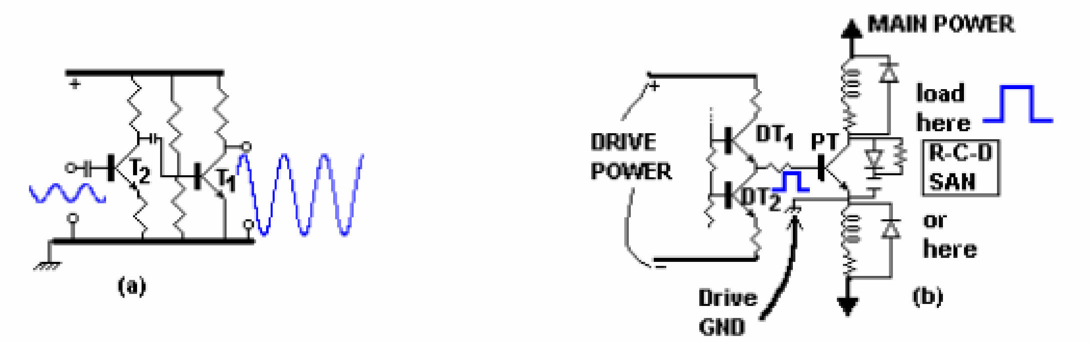


Figure 2 Typical Bipolar transistor based (a) linear (common emitter) (voltage) amplifier stage and (b) switching (power) amplifier

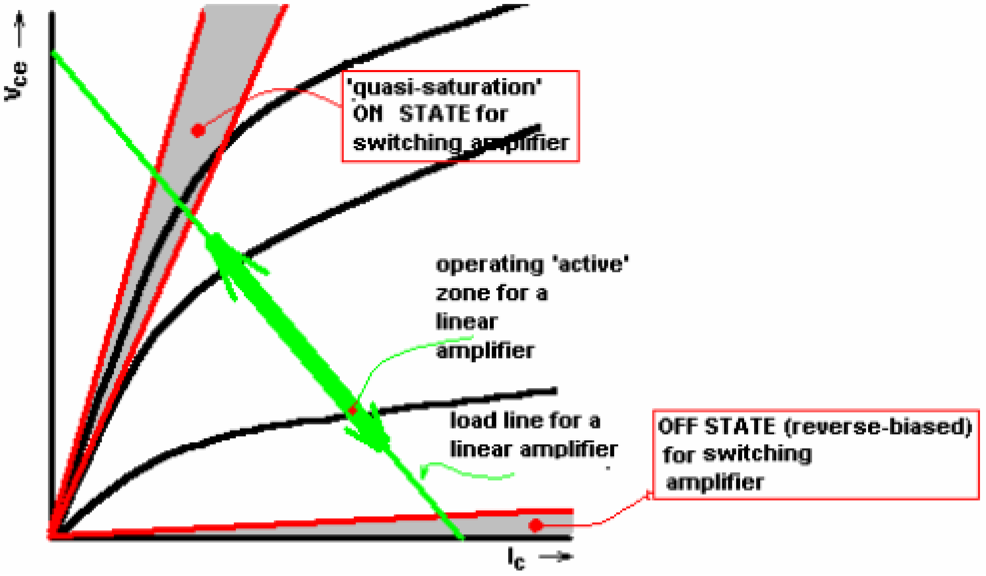


Figure 3 Operating zones for operating a Bipolar Junction Transistor as a linear and a switching amplifier

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
Utilization of transistor rating of secondary importance	Utilization of transistor rating optimized

Power Diodes

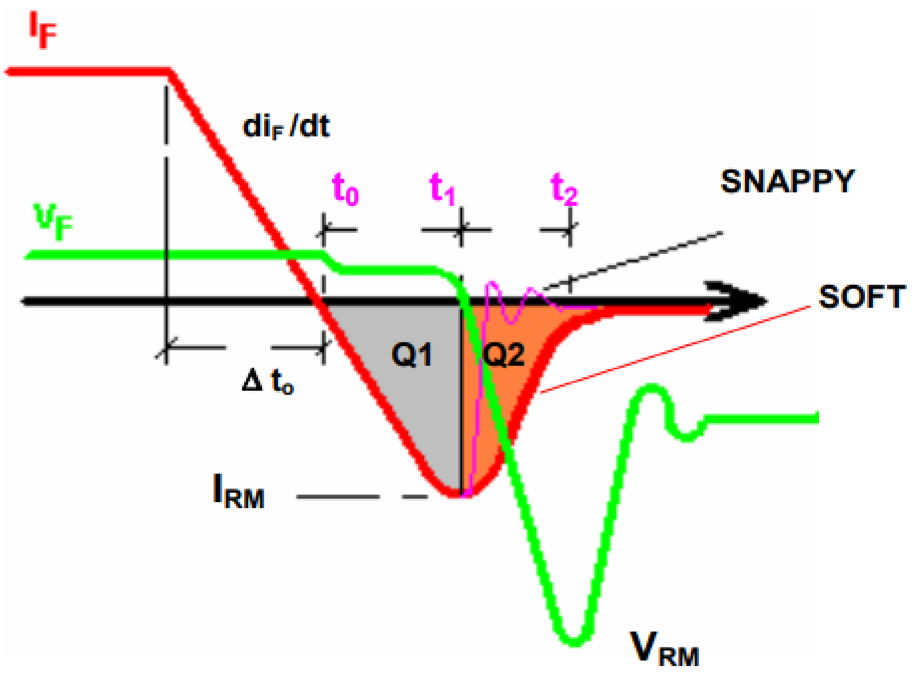


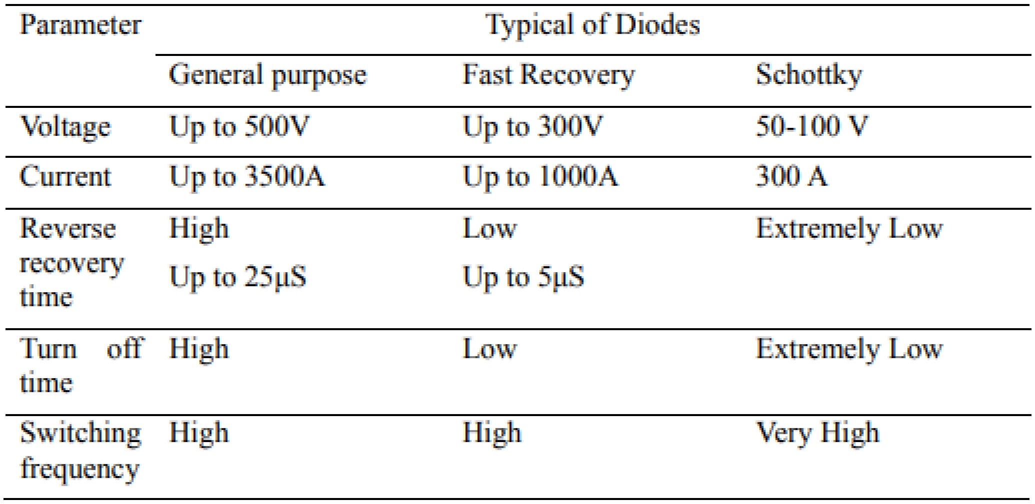
Figure 4 Typical turn-off dynamics of a soft and a 'snappy' diode'

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 Figure 4. The minority carriers in the diodes require finite time – trr (reverse recovery time) to recombine with opposite charges and neutralize. Large values of Qrr (= Q1 + Q2) - the charge to be dissipated as a negative current when the and diode turns off and trr (= t2 - t0) - 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.

Power diode are classified into three types:

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

Comparison between different types of diodes are shown in table



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

Protection of Power devices and converters

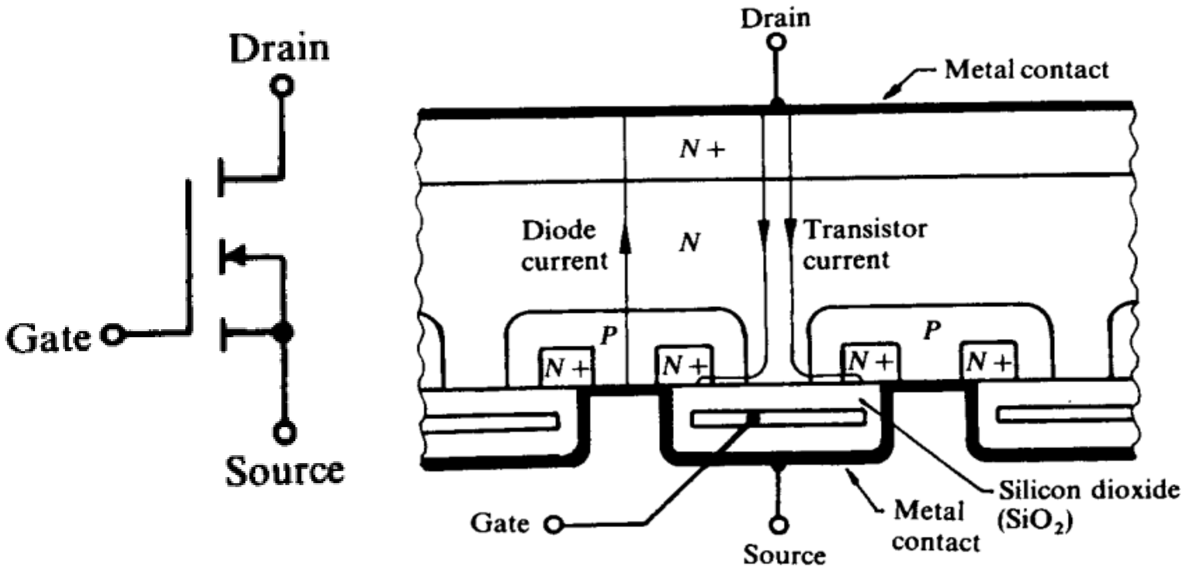
Power semiconductor devices are commonly protected against:

1. Over-current

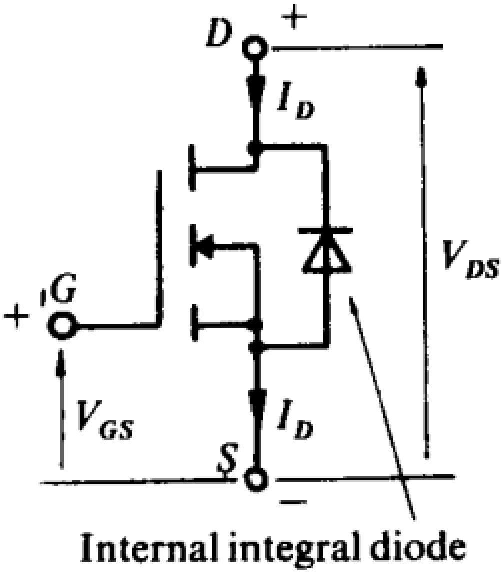
2. di/dt
3. Voltage spike or over-voltage
4. dv/dt
5. Gate-under voltage
6. Over voltage at gate
7. Excessive temperature rise
8. Electro-static discharge

Power MOSFET

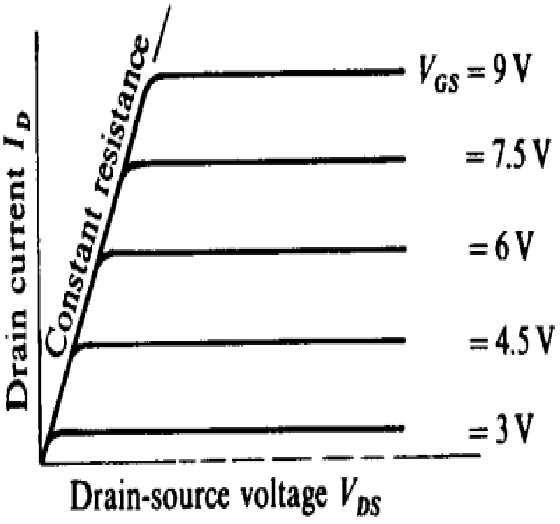
The power metal oxide semiconductor field-effect transistor (MOSFET) is a device derived from the field-effect transistor (FET) for use as a fast-acting switch at power levels. Unlike the bipolar transistor which is current controlled, the MOSFET is a voltage-controlled device. Referring to Figure 5 (a), the main terminals are the drain and source, the current flow from drain to source being controlled by the gate to source voltage. Figure 5 (b) shows the cross-section of a part of a MOSFET. With zero gate to source voltage, a positive voltage at the drain relative to the source will result in current of up to possibly a few hundred volts being blocked. If a sufficiently positive voltage, approximately 3 V, is applied to the gate, a negative charge is induced on the silicon surface under the gate which causes the Player to become an induced N layer, allowing electrons to flow. Hence, a positive gate voltage sets up a surface channel for current flow from drain to source. The gate voltage determines the depth of the induced channel and in this manner determines the current flow. The characteristic of the MOSFET is shown in Figure 5 (d) to the circuit reference of Figure 5 (c). At very low values of drain-source voltage the device has a constant resistance characteristic, but at the higher values of drain-source voltage the current is determined by the gate voltage. However, in power applications the drain-source voltage must be small in order to minimize the on-state conduction losses. The gate voltage is thus set at a high enough level to ensure that the drain current limit is above the load current value, that is, the device is operating in the constant resistance condition. The gate voltage must be limited to a maximum value of approximately 20 V. The silicon dioxide which insulates the gate from the body of the transistor is an insulator with negligible leakage current. Once the gate charge is established there is no further gate current giving a very high gain between the output power and control power. Reference to Figure 5 (b) shows that in the opposite direction, that is, from the source to drain, there is a P-N path, which means that there is a diode integral with the transistor from the source to drain as shown in Figure 5 (c). The absence of any stored charge makes very fast switching possible, with on and off times being much less than one microsecond. The on-resistance of the MOSFET is a function of the voltage breakdown rating, with typical values being 0.1 Q for a 100 V device and 0.5 Q for a 500 V device. The resistance is always higher for the higher-rated voltages but the actual resistance will vary according to the device structure. Figure 5 (b) shows only a very small section of the interdigitated structure. The power MOSFET can be directly controlled from microelectronic circuits and is limited to much lower voltages than the thyristor, but is easily the fastest acting device. Above approximately 100 V conduction losses are higher than for the bipolar transistor and the thyristor, but the switching loss is much less. The MOSFET has a positive temperature coefficient for resistance; hence paralleling of devices is relatively simple. In terms of current and voltage capability the MOSFET is inferior to the current-controlled devices of the bipolar transistor and thyristor family of devices.



(a) (b)



(c)

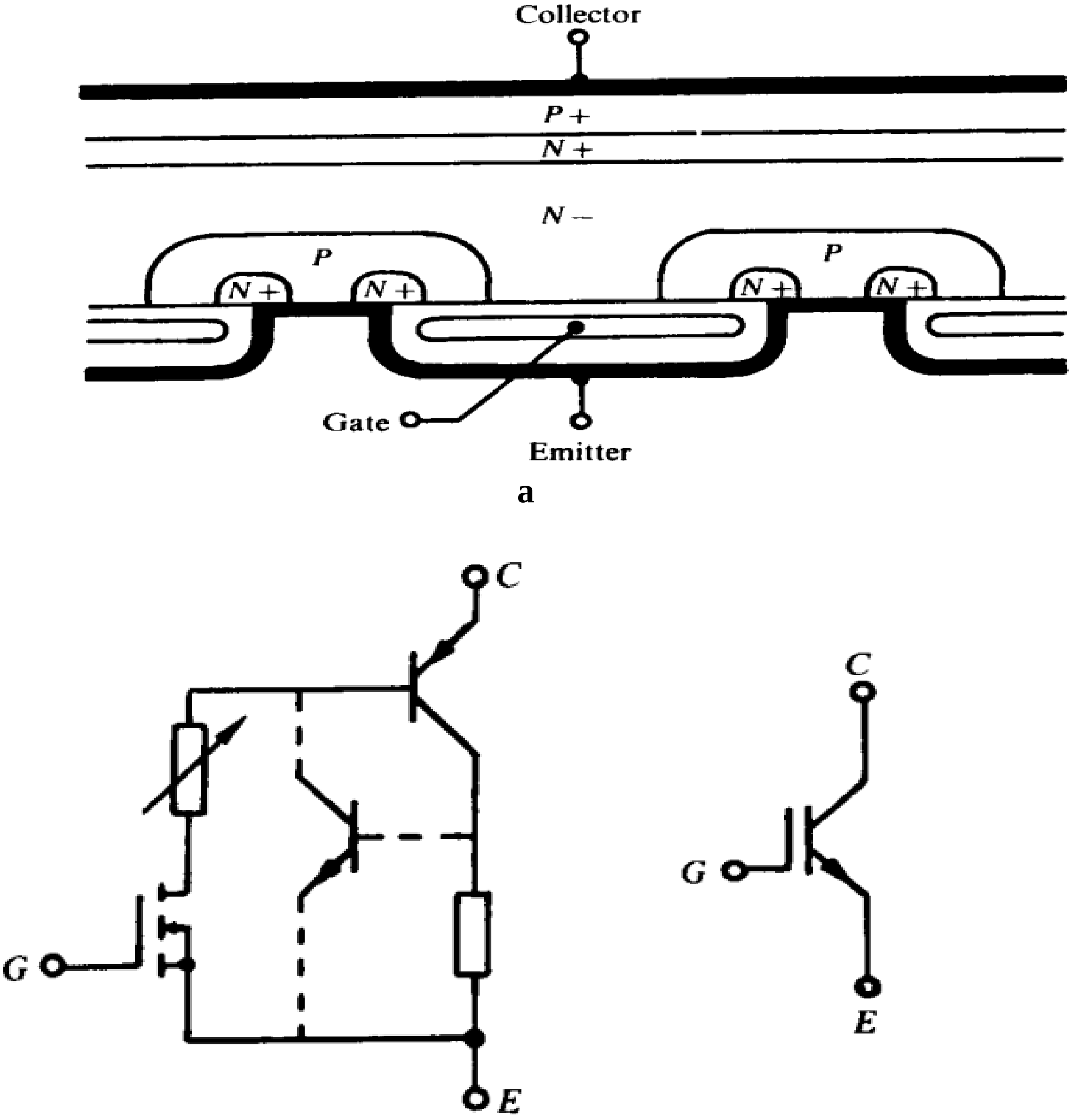


(d)

IGBT

The insulated gate bipolar transistor (IGBT) is a device which combines the fast-acting features and high power capability of the bipolar transistor, with the voltage control features of the MOSFET gate. In simple terms the collector- emitter characteristics are similar to those of the bipolar transistor but the control features are those of the MOSFET. The cross-section of an IGBT as shown in Figure 6 a is similar to that of the MOSFET, the difference being the substrate of the IGBT is P-N rather than the N-N of the MOSFET. The application of the gate voltage forms a channel for current flow, as described for the MOSFET, which is then the base current for the P-N-P transistor whose path is from the collector to the emitter. Note that although the N-P-N structure is invariably used for the bipolar power transistor the P-N-P structure is preferred in the IGBT. The equivalent circuit and the circuit symbol are illustrated in Figure 6 b and c. The switching times are less than that of the bipolar transistor, in particular the turn-on time, typically 0.15 jlS, being associated with the MOSFET characteristic, although the turn-off time, typically 1jls, is more related to that of the P-N-P characteristic. The on-state collector-emitter voltage is slightly higher than that of the bipolar transistor.

Maximum possible voltage and current ratings are approximately equal to those of the bipolar transistor.



a

b

c

Figure 6 Insulated gate bipolar transistor. (a) Simplified cross-section. (b) Equivalent electric circuit. (c) IGBT symbol.

Gate-Turn-Off Thyristor (GTO)

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. Figure 7 illustrated the GTO symbol

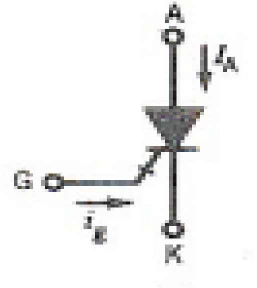
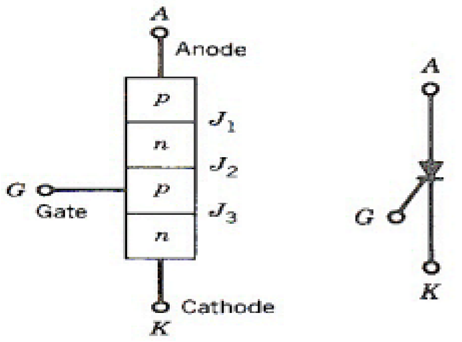


Figure 7 GTO symbol

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 8. 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. Vak is positive), (2) a positive gate current (Ig) is applied at the gate. Once conducting, the anode current is latched (continuously flowing).



(a) (b)

Figure 8 Thyristor (SCR). (a) Structure. (b) Symbol

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

1. Why IGBT is very popular nowadays?

Answer:
a. Lower heat requirements
b. Lower switching losses
c. Smaller snubber circuit requirements

2. IGBT is a voltage controlled device. Why?

Answer:
Because the controlling parameter is gate-emitter voltage.

3. Power MOSFET is a voltage controlled device. Why?

Answer:
Because the output (drain) current can be controlled by gate-source voltage.

4. Power BJT is a current controlled device. Why?

Because the output (collector) current can be controlled by base current.

5. What are the different types of power MOSFET?

Answer:

a. N-channel MOSFET
b. P-channel MOSFET

6. How can a thyristor turned off?

Answer:

A thyristor can be turned off by making the current flowing through it to zero.

7. Define latching current.

Answer:

The latching current is defined as the minimum value of anode current which it must attain during turn on process to maintain conduction when gate signal is removed.

8. Define holding current.

Answer:

The holding current is defined as the minimum value of anode current below which it must fall to for turning off the thyristor.

9. What is a snubber circuit?

Answer:

It consists of a series combination of a resistor and a capacitor in parallel with the thyristors. It is mainly used for dv / dt protection.

10. What losses occur in a thyristor during working conditions?

Answer:

a. Forward conduction losses
b. Loss due to leakage current during forward and reverse blocking.
c. Switching losses at turn-on and turn-off.
d. Gate triggering loss.

11. Define hard-driving or over-driving.

Answer:

When gate current is several times higher than the minimum gate current required, a thyristor is said to be hard-fired or over-driven. Hard-firing of a thyristor reduces its turn-on time and enhances its di/dt capability.

12. Define circuit turn off time.

Answer:

It is defined as the time during which a reverse voltage is applied across the thyristor during its commutation process.

13. Why circuit turn off time should be greater than the thyristor turn-off time?

Answer:

Circuit turn off time should be greater than the thyristor turn-off time for reliable turn-off, otherwise the device may turn-on at an undesired instant, a process called commutation failure.

14. What is the turn-off time for converter grade SCRs and inverter grade SCRs?

Answer:

Turn-off time for converter grade SCRs is 50 – 100 ms turn-off time for converter grade SCRs and inverter grade SCRs and for inverter grade SCRs is 3 – 50 ms.

15. What are the advantages of GTO over SCR?

Answer:

a. Elimination of commutation of commutating components in forced commutation, resulting in reduction in cost, weight and volume.
b. Reduction in acoustic noise and electromagnetic noise due to elimination of commutation chokes.
c. Faster turn-off, permitting high switching frequencies.
d. Improved efficiency of the converters.