Benha University **Benha Faculty of Engineering** **Electrical Engineering Department** Power Electronics–E591 Time: 3 hours Jan. 2014		**جامعة بنها** **كلية الهندسة ببنها** **قسم الهندسة الكهربية**

Answer only four questions and explain by drawing anywhere you can.

Question-1 (15 marks)

Q1a. Explain the operation of the dc chopper circuit shown in Fig.Q1a. Suggest a suitable firing scheme for such circuit. Explain, haw the firing pulses are generated and directed to each Thyristor. Make changes for safety operation with inductive load.

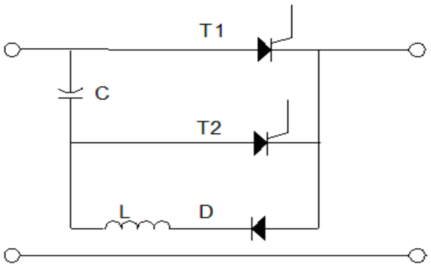


Fig.Q1a

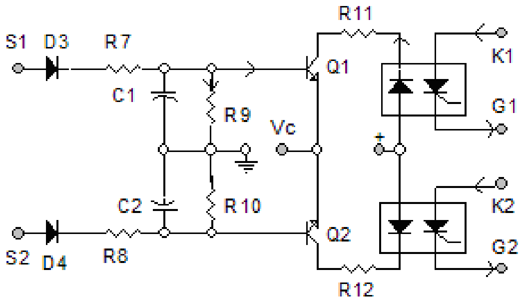


Fig.Q1b

Q1b. Figure Q1b shows a simplified firing circuit which may be used to drive a single phase D.C. converter. It has some disadvantages, which? Explain the operation of this circuit, and what do you suggest to overcome its disadvantages? Remember that, S1 and S2 are Square waves.

Question-2 (15 marks)

Q2a. Figure Q2a shows one of the techniques for power factor correction for three-phase controlled rectifiers. Explain the principle of operation of this scheme and mention its advantages and disadvantages.

Q2b. The converter of Figure Q2b can operate in two modes: as DC Chopper to drive a dc load, or as Single Phase Inverter to drive ac single-phase load. Explain sequence of operation for each mode of operations?

Suggest a suitable firing circuit for the given converter for one mode of operation.

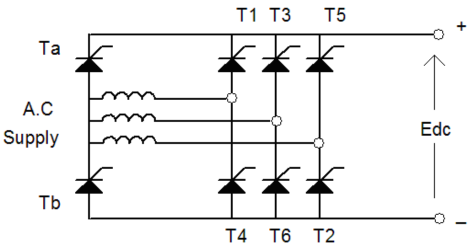


Fig.Q2a

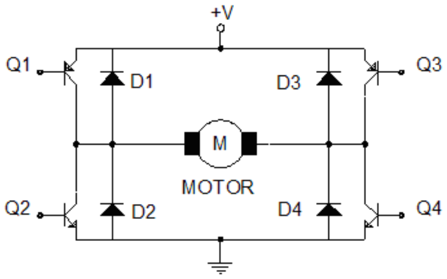


Fig.Q2b

P.T.O.

Question-3 (15 marks)

Q3a. Draw any two Inverter power circuits you know (not given) and explain how do they work? What is a natural and forced commutation? What is the meaning of load commutation, constant current source inverter and constant voltage source inverter?

Q3b. Suggest a suitable firing circuit for one Inverter circuit in Q3a.

Question-4 (15 marks)

a- Write short notes about:
i-power diode ii-transistor iii-thyristor iv- GTO thyristor

b- Write the main parts of a power electronic system?

c- How to protect the transistor against over:
i-current ii- voltage iii-temperature degree iv- di/dt v-dv/dt

Question-5 (15 marks)

a-Define: latch current- hold current?

b-A power electronic circuit consists of DC power supply (200V), thyristor (latching current level 10 mA) and inductive load(40Ω, 1H) neglect the thyristor voltage drop.

i- Draw the power circuit?

ii- Show that the thyristor will fail to remain on when the firing pulse ends after 25µsec.?

iii- Find the minimum pulse length of the correct firing pulse?

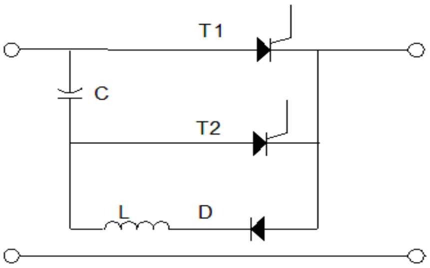
iv- Find the maximum value of shunt resistance (to load) to ensure firing using pulse of length 25µsec.

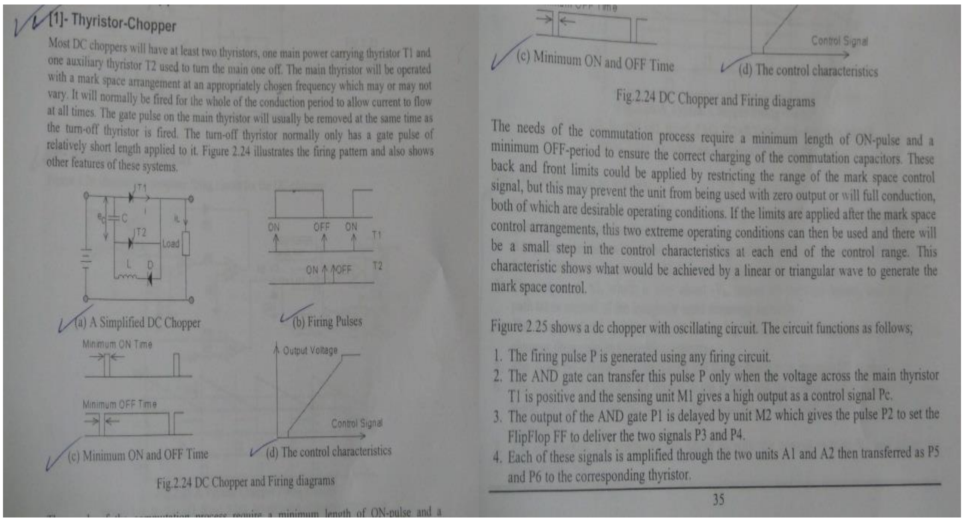
v- Show how to turn off the thyristor?

Model answer

Question-1

Q1a. Explain the operation of the dc chopper circuit shown in Fig.Q1a. Suggest a suitable firing scheme for such circuit. Explain, haw the firing pulses are generated and directed to each Thyristor. Make changes for safety operation with inductive load.





[1]- Thyristor-Chopper

Most DC choppers will have at least two thyristors, one main power carrying thyristor T1 and one auxiliary thyristor T2 used to turn the main one off. The main thyristor will be operated with a mark space arrangement at an appropriately chosen frequency which may or may not vary. It will normally be fired for the whole of the conduction period to allow current to flow at all times. The gate pulse on the main thyristor will usually be removed at the same time as the turn-off thyristor is fired. The turn-off thyristor normally only has a gate pulse of relatively short length applied to it. Figure 2.24 illustrates the firing pattern and also shows other features of these systems.

(a) A Simplified DC Chopper

(b) Firing Pulses

(c) Minimum ON and OFF Time

(d) The control characteristics

Fig.2.24 DC Chopper and Firing diagrams

(c) Minimum ON and OFF Time

(d) The control characteristics

Fig.2.24 DC Chopper and Firing diagrams

The needs of the commutation process require a minimum length of ON-pulse and a minimum OFF-period to ensure the correct charging of the commutation capacitors. These back and front limits could be applied by restricting the range of the mark space control signal, but this may prevent the unit from being used with zero output or will full conduction, both of which are desirable operating conditions. If the limits are applied after the mark space control arrangements, this two extreme operating conditions can then be used and there will be a small step in the control characteristics at each end of the control range. This characteristic shows what would be achieved by a linear or triangular wave to generate the mark space control.

Figure 2.25 shows a dc chopper with oscillating circuit. The circuit functions as follows;

1. The firing pulse P is generated using any firing circuit.
2. The AND gate can transfer this pulse P only when the voltage across the main thyristor T1 is positive and the sensing unit M1 gives a high output as a control signal Pc.
3. The output of the AND gate P1 is delayed by unit M2 which gives the pulse P2 to set the FlipFlop FF to deliver the two signals P3 and P4.
4. Each of these signals is amplified through the two units A1 and A2 then transferred as P5 and P6 to the corresponding thyristor.

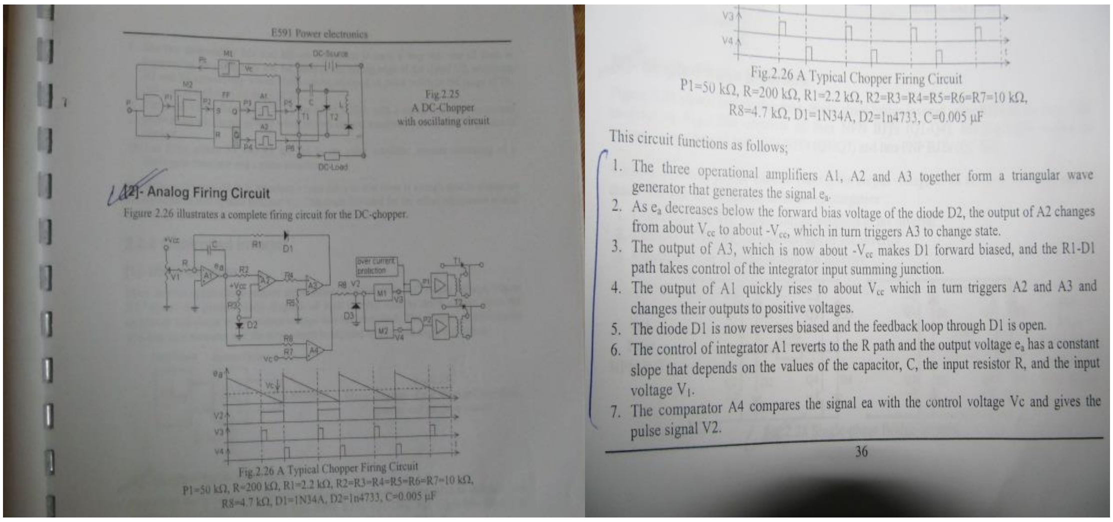


Fig.2.25
A DC-Chopper
with oscillating circuit

[2]- Analog Firing Circuit

Figure 2.26 illustrates a complete firing circuit for the DC-chopper.

Fig.2.26 A Typical Chopper Firing Circuit
P1=50 kΩ, R=200 kΩ, R1=2.2 kΩ, R2=R3=R4=R5=R6=R7=10 kΩ,
R8=4.7 kΩ, D1=1N34A, D2=1n4733, C=0.005 µF

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P1=50 kΩ, R=200 kΩ, R1=2.2 kΩ, R2=R3=R4=R5=R6=R7=10 kΩ,
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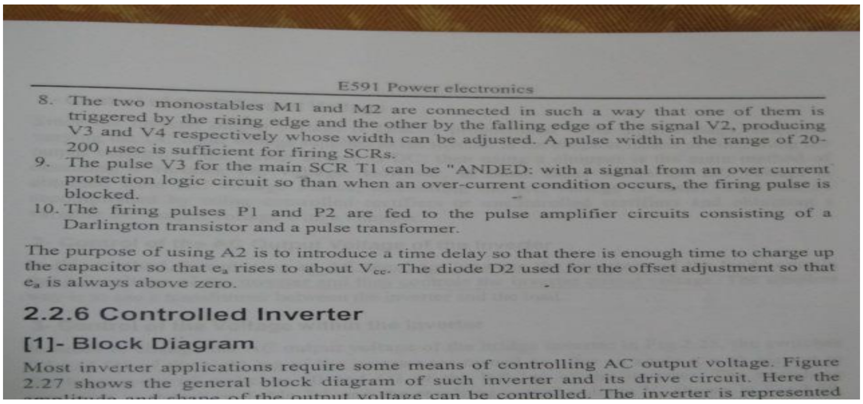
This circuit functions as follows;

1. The three operational amplifiers A1, A2 and A3 together form a triangular wave generator that generates the signal e_a.
2. As e_a decreases below the forward bias voltage of the diode D2, the output of A2 changes from about V_{cc} to about $-V_{cc}$, which in turn triggers A3 to change state.
3. The output of A3, which is now about $-V_{cc}$ makes D1 forward biased, and the R1-D1 path takes control of the integrator input summing junction.
4. The output of A1 quickly rises to about V_{cc} which in turn triggers A2 and A3 and changes their outputs to positive voltages.
5. The diode D1 is now reverses biased and the feedback loop through D1 is open.
6. The control of integrator A1 reverts to the R path and the output voltage e_a has a constant slope that depends on the values of the capacitor, C, the input resistor R, and the input voltage V_1.
7. The comparator A4 compares the signal ea with the control voltage Vc and gives the pulse signal V2.



8. The two monostables M1 and M2 are connected in such a way that one of them is triggered by the rising edge and the other by the falling edge of the signal V2, producing V3 and V4 respectively whose width can be adjusted. A pulse width in the range of 20-200 µsec is sufficient for firing SCRs.
9. The pulse V3 for the main SCR T1 can be "ANDED: with a signal from an over current protection logic circuit so than when an over-current condition occurs, the firing pulse is blocked.
10. The firing pulses P1 and P2 are fed to the pulse amplifier circuits consisting of a Darlington transistor and a pulse transformer.

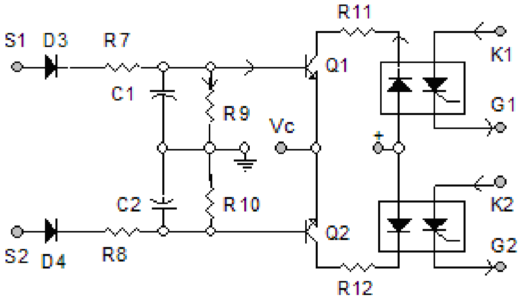
The purpose of using A2 is to introduce a time delay so that there is enough time to charge up the capacitor so that e_a rises to about V_{cc}. The diode D2 used for the offset adjustment so that e_a is always above zero.

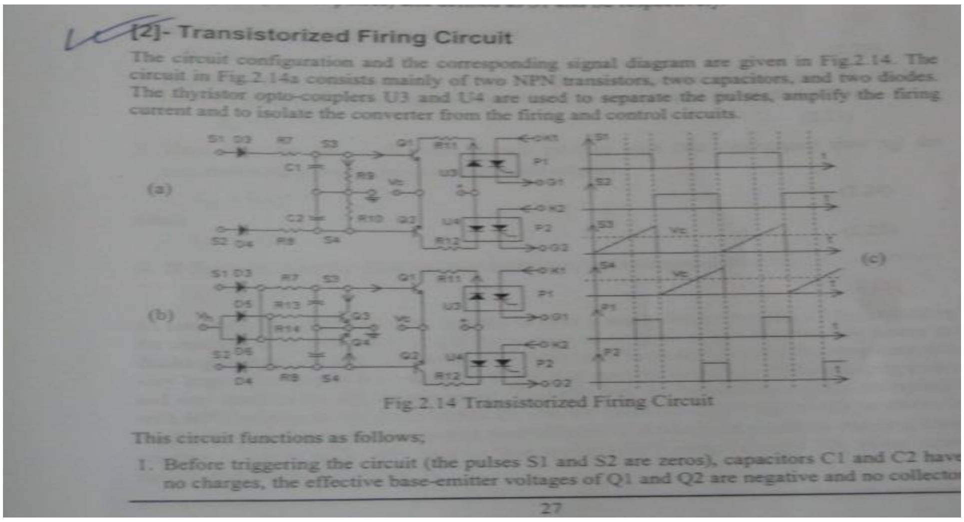
2.2.6 Controlled Inverter

[1]- Block Diagram

Most inverter applications require some means of controlling AC output voltage. Figure 2.27 shows the general block diagram of such inverter and its drive circuit. Here the

Q1b. Figure Q1b shows a simplified firing circuit which may be used to drive a single phase D.C. converter. It has some disadvantages, which? Explain the operation of this circuit, and what do you suggest to overcome its disadvantages? Remember that, S1 and S2 are Square waves.





[2]- Transistorized Firing Circuit

The circuit configuration and the corresponding signal diagram are given in Fig.2.14. The circuit in Fig.2.14a consists mainly of two NPN transistors, two capacitors, and two diodes. The thyristor opto-couplers U3 and U4 are used to separate the pulses, amplify the firing current and to isolate the converter from the firing and control circuits.

(a)

(b)

(c)

Fig.2.14 Transistorized Firing Circuit

This circuit functions as follows;

1. Before triggering the circuit (the pulses S1 and S2 are zeros), capacitors C1 and C2 have no charges, the effective base-emitter voltages of Q1 and Q2 are negative and no collecto

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Question-2 (15 marks)

Q2a. Figure Q2a shows one of the techniques for power factor correction for three-phase controlled rectifiers. Explain the principle of operation of this scheme and mention its advantages and disadvantages.

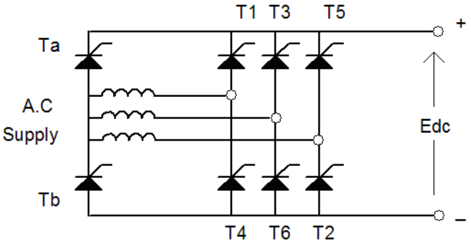
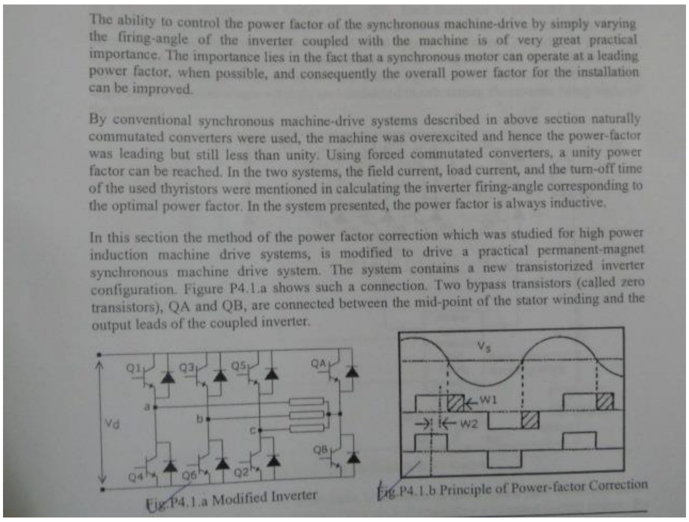


Figure Q2a



The ability to control the power factor of the synchronous machine-drive by simply varying the firing-angle of the inverter coupled with the machine is of very great practical importance. The importance lies in the fact that a synchronous motor can operate at a leading power factor, when possible, and consequently the overall power factor for the installation can be improved.

By conventional synchronous machine-drive systems described in above section naturally commutated converters were used, the machine was overexcited and hence the power-factor was leading but still less than unity. Using forced commutated converters, a unity power factor can be reached. In the two systems, the field current, load current, and the turn-off time of the used thyristors were mentioned in calculating the inverter firing-angle corresponding to the optimal power factor. In the system presented, the power factor is always inductive.

In this section the method of the power factor correction which was studied for high power induction machine drive systems, is modified to drive a practical permanent-magnet synchronous machine drive system. The system contains a new transistorized inverter configuration. Figure P4.1.a shows such a connection. Two bypass transistors (called zero transistors), QA and QB, are connected between the mid-point of the stator winding and the output leads of the coupled inverter.

Fig.P4.1.a Modified Inverter

Fig.P4.1.b Principle of Power-factor Correction

Q2b. The converter of Figure Q2b can operate in two modes: as DC Chopper to drive a dc load, or as Single Phase Inverter to drive ac single-phase load. Explain sequence of operation for each mode of operations?

Suggest a suitable firing circuit for the given converter for one mode of operation.

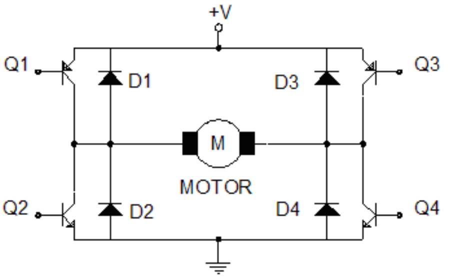
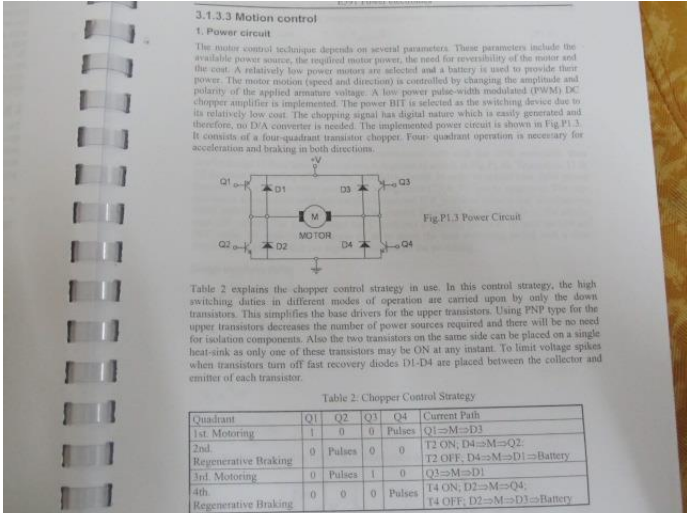


Figure Q2b



3.1.3.3 Motion control

1. Power circuit

The motor control technique depends on several parameters. These parameters include the available power source, the required motor power, the need for reversibility of the motor and the cost. A relatively low power motors are selected and a battery is used to provide their power. The motor motion (speed and direction) is controlled by changing the amplitude and polarity of the applied armature voltage. A low power pulse-width modulated (PWM) DC chopper amplifier is implemented. The power BJT is selected as the switching device due to its relatively low cost. The chopping signal has digital nature which is easily generated and therefore, no D/A converter is needed. The implemented power circuit is shown in Fig.P1.3. It consists of a four-quadrant transistor chopper. Four- quadrant operation is necessary for acceleration and braking in both directions.

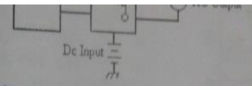
Fig.P1.3 Power Circuit

Table 2 explains the chopper control strategy in use. In this control strategy, the high switching duties in different modes of operation are carried upon by only the down transistors. This simplifies the base drivers for the upper transistors. Using PNP type for the upper transistors decreases the number of power sources required and there will be no need for isolation components. Also the two transistors on the same side can be placed on a single heat-sink as only one of these transistors may be ON at any instant. To limit voltage spikes when transistors turn off fast recovery diodes D1-D4 are placed between the collector and emitter of each transistor.

Table 2: Chopper Control Strategy

Quadrant	Q1	Q2	Q3	Q4	Current Path
1st. Motoring	1	0	0	Pulses	Q1⇒M⇒D3
2nd. Regenerative Braking	0	Pulses	0	0	T2 ON; D4⇒M⇒Q2; T2 OFF; D4⇒M⇒D1⇒Battery
3rd. Motoring	0	Pulses	1	0	Q3⇒M⇒D1
4th. Regenerative Braking	0	0	0	Pulses	T4 ON; D2⇒M⇒Q4; T4 OFF; D2⇒M⇒D3⇒Battery

Q3a. Draw any two Inverter power circuits you know (not given) and explain how do they work? What is a natural and forced commutation? What is the meaning of load commutation, constant current source inverter and constant voltage source inverter?



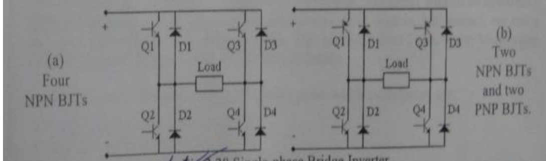
Block diagram of the Voltage Controlled Inverter and its drive circuit

[2]- Single-Phase Inverters

Figure 2.28 shows two modes for a single-phase bridge inverter using BJTs as switches. The inverter in Fig.2.28a consists of four NPN BJTs (Q1-Q4), but Fig.2.28b shows an inverter consisting of two NPN BJTs (Q1-Q3) and two PNP BJTs (Q2-Q4).

Various methods can be used to control the output voltage of an inverter, and they can be classified into the following three broad categories:

1. Control of the DC input voltage supplied to the inverter
2. Control of the AC output voltage of the inverter
3. Control of the voltage within the inverter



(a) Four NPN BJTs

(b) Two NPN BJTs and two PNP BJTs.

Fig.2.28 Single-phase Bridge Inverter

1- Control of the DC Input Voltage

Since the inverter output voltage is directly proportional to its input voltage, therefore varying the DC input voltage supplied to the inverter is the simplest means of controlling the output voltage. If the power source is DC, then using a chopper is the main method of obtaining a variable DC voltage. However, in those cases where the DC voltage is obtained from AC voltage source, controlling the AC voltage is easier. This can be accomplished by using controlled rectifiers or uncontrolled rectifiers and obtaining a variable DC output voltage with a chopper.

2- Control of the AC Output Voltage of the Inverter

In this method, introducing an AC regulator between the inverter and the load controls the AC voltage of the inverter and thus controls the inverter output voltage. The simplest way is to use a transformer between the inverter and the load.

3- Control of the Voltage within the Inverter

In order to change the AC output voltage of the bridge inverter in Fig.2.28, the switches Q3 and Q4 of the right leg of the inverter are turned on after an angle α with respect to the turning-on of switches Q1 and Q2 of the left leg of the inverter. The switching sequence is shown in Table 2.1 and the resulting output voltage V_o shown in Fig.2.29, has a pulse width t_w.

01	Q2	03	04	V_o
ON	OFF	OFF	ON	+E
ON	OFF	ON	OFF	0
OFF	ON	ON	OFF	-E
OFF	ON	OFF	ON	0
ON	OFF	OFF	ON	+E
ON	OFF	ON	OFF	0

Table 2.1 Switching sequence

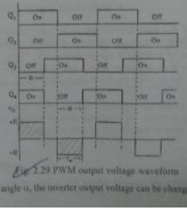
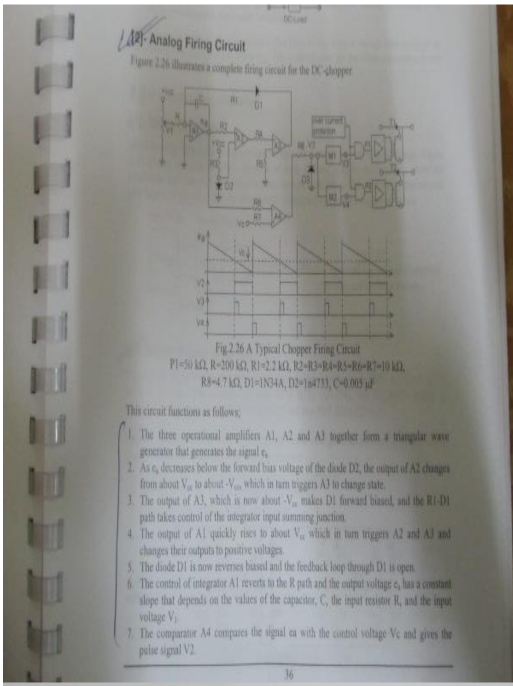


Fig. 2.29 PWM output voltage waveform

angle pulse width

Also, as seen, by changing the shift angle α, the inverter output voltage can be changed.



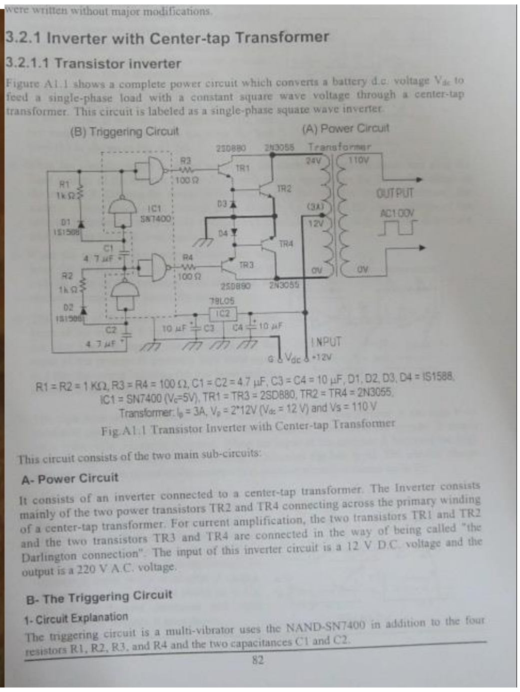
[2]- Analog Firing Circuit

Figure 2.26 illustrates a complete firing circuit for the DC-chopper

Fig.2.26 A Typical Chopper Firing Circuit
P1=50 kΩ, R=200 kΩ, R1=2.2 kΩ, R2=R3=R4=R5=R6=R7=10 kΩ,
R8=4.7 kΩ, D1=1N34A, D2=1n4733, C=0.005 μF

This circuit functions as follows;

1. The three operational amplifiers A1, A2 and A3 together form a triangular wave generator that generates the signal e_s
2. As e_s decreases below the forward bias voltage of the diode D2, the output of A2 changes from about V_{cc} to about $-V_{cc}$, which in turn triggers A3 to change state.
3. The output of A3, which is now about $-V_{cc}$ makes D1 forward biased, and the R1-D1 path takes control of the integrator input summing junction.
4. The output of A1 quickly rises to about V_{cc} which in turn triggers A2 and A3 and changes their outputs to positive voltages.
5. The diode D1 is now reverses biased and the feedback loop through D1 is open.
6. The control of integrator A1 reverts to the R path and the output voltage e_s has a constant slope that depends on the values of the capacitor, C, the input resistor R, and the input voltage V_1.
7. The comparator A4 compares the signal ea with the control voltage Vc and gives the pulse signal V2.



were written without major modifications.

3.2.1 Inverter with Center-tap Transformer

3.2.1.1 Transistor inverter

Figure A1.1 shows a complete power circuit which converts a battery d.c. voltage V_{dc} to feed a single-phase load with a constant square wave voltage through a center-tap transformer. This circuit is labeled as a single-phase square wave inverter.

(B) Triggering Circuit (A) Power Circuit

R1 = R2 = 1 KΩ, R3 = R4 = 100 Ω, C1 = C2 = 4.7 μF, C3 = C4 = 10 μF, D1, D2, D3, D4 = IS1588,
IC1 = SN7400 (V_c=5V), TR1 = TR3 = 2SD880, TR2 = TR4 = 2N3055,
Transformer: I_p = 3A, V_p = 2*12V (V_{dc} = 12 V) and Vs = 110 V
Fig.A1.1 Transistor Inverter with Center-tap Transformer

This circuit consists of the two main sub-circuits:

A- Power Circuit

It consists of an inverter connected to a center-tap transformer. The Inverter consists mainly of the two power transistors TR2 and TR4 connecting across the primary winding of a center-tap transformer. For current amplification, the two transistors TR1 and TR2 and the two transistors TR3 and TR4 are connected in the way of being called "the Darlington connection". The input of this inverter circuit is a 12 V D.C. voltage and the output is a 220 V A.C. voltage.

B- The Triggering Circuit

1- Circuit Explanation

The triggering circuit is a multi-vibrator uses the NAND-SN7400 in addition to the four resistors R1, R2, R3, and R4 and the two capacitances C1 and C2.

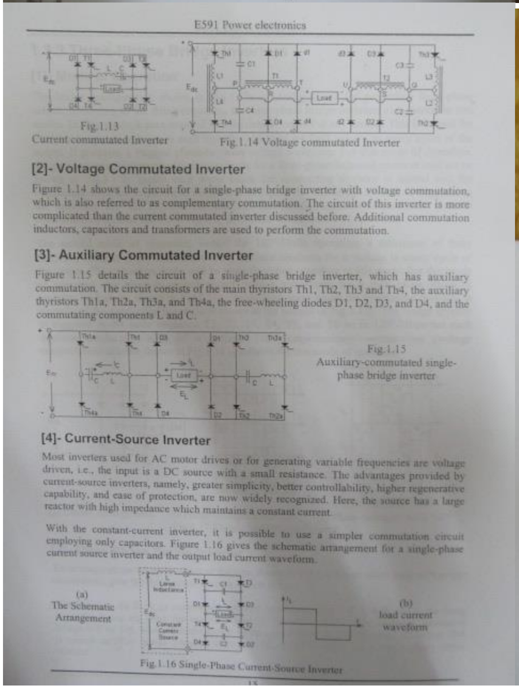


Fig.1.13
Current commutated Inverter

Fig.1.14 Voltage commutated Inverter

[2]- Voltage Commutated Inverter

Figure 1.14 shows the circuit for a single-phase bridge inverter with voltage commutation, which is also referred to as complementary commutation. The circuit of this inverter is more complicated than the current commutated inverter discussed before. Additional commutation inductors, capacitors and transformers are used to perform the commutation.

[3]- Auxiliary Commutated Inverter

Figure 1.15 details the circuit of a single-phase bridge inverter, which has auxiliary commutation. The circuit consists of the main thyristors Th1, Th2, Th3 and Th4, the auxiliary thyristors Th1a, Th2a, Th3a, and Th4a, the free-wheeling diodes D1, D2, D3, and D4, and the commutating components L and C.

Fig.1.15
Auxiliary-commutated single-phase bridge inverter

[4]- Current-Source Inverter

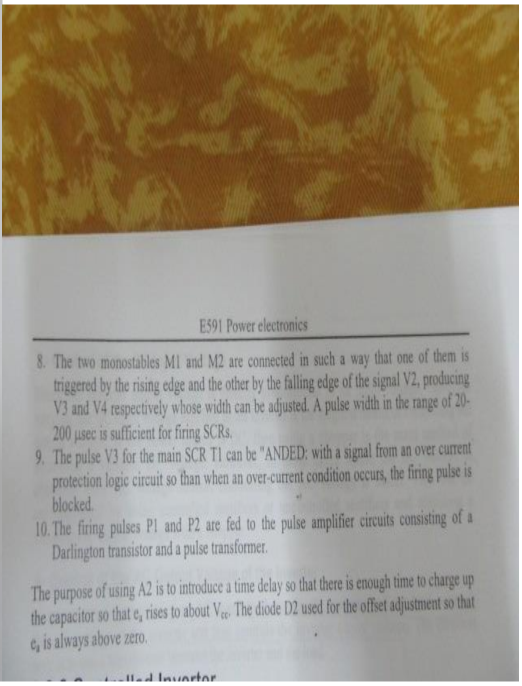
Most inverters used for AC motor drives or for generating variable frequencies are voltage driven, i.e., the input is a DC source with a small resistance. The advantages provided by current-source inverters, namely, greater simplicity, better controllability, higher regenerative capability, and ease of protection, are now widely recognized. Here, the source has a large reactor with high impedance which maintains a constant current.

With the constant-current inverter, it is possible to use a simpler commutation circuit employing only capacitors. Figure 1.16 gives the schematic arrangement for a single-phase current source inverter and the output load current waveform.

(a)
The Schematic Arrangement

(b)
load current waveform

Fig.1.16 Single-Phase Current-Source Inverter



8. The two monostables M1 and M2 are connected in such a way that one of them is triggered by the rising edge and the other by the falling edge of the signal V2, producing V3 and V4 respectively whose width can be adjusted. A pulse width in the range of 20-200 μsec is sufficient for firing SCRs.
9. The pulse V3 for the main SCR T1 can be "ANDED: with a signal from an over current protection logic circuit so than when an over-current condition occurs, the firing pulse is blocked.
10. The firing pulses P1 and P2 are fed to the pulse amplifier circuits consisting of a Darlington transistor and a pulse transformer.

The purpose of using A2 is to introduce a time delay so that there is enough time to charge up the capacitor so that e_s rises to about V_{cc}. The diode D2 used for the offset adjustment so that e_s is always above zero.

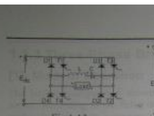
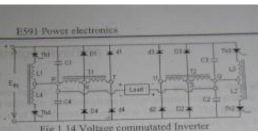


Fig.1.13
Current commutated Inverter



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[3]- Auxiliary Commutated Inverter

Figure 1.15 details the circuit of a single-phase bridge inverter, which has auxiliary commutation. The circuit consists of the main thyristors Th1, Th2, Th3 and Th4, the auxiliary thyristors Th1a, Th2a, Th3a, and Th4a, the free-wheeling diodes D1, D2, D3, and D4, and the commutating components L and C.

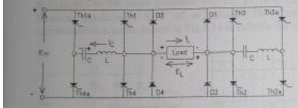
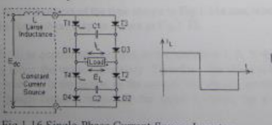


Fig.1.15
Auxiliary-commutated single-phase bridge inverter

[4]- Current-Source Inverter

Most inverters used for AC motor drives or for generating variable frequencies are voltage driven, i.e., the input is a DC source with a small resistance. The advantages provided by current-source inverters, namely, greater simplicity, better controllability, higher regenerative capability, and ease of protection, are now widely recognized. Here, the source has a large reactor with high impedance which maintains a constant current.

With the constant-current inverter, it is possible to use a simpler commutation circuit employing only capacitors. Figure 1.16 gives the schematic arrangement for a single-phase current source inverter and the output load current waveform.



(a)
The Schematic Arrangement

(b)
load current waveform

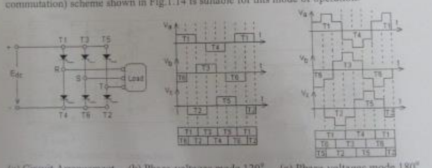
Fig.1.16 Single-Phase Current-Source Inverter

1.3.3 Three-Phase Bridge Inverters

[1]- Mode of Operation

The bridge configuration shown in Fig.1.17a is ideally suited for generating three-phase output. According to the firing sequence, the three-phase bridge inverters can operate in two modes. In first mode, a maximum of two thyristors conduct at any instant. This is named the 120°-Mode operation because each thyristor conducts for $2\pi/3$ radians in every cycle of the output. It produces a stepped phase-to-phase voltage waveform. For this mode of operation, the phase-to-neutral output voltage waveforms for a three-phase balanced resistive load are as shown in Fig.1.17b. Inside each wave block the conducting thyristor is named and the conducting sequence is shown at the bottom of Fig.1.17b. The bridge inverter is triggered in the sequence T1, T2, T3, T4, T5, and T6. The parallel-capacitor-commutation (current commutation) scheme shown in Fig.1.13 is suitable for this mode of operation.

The second mode of operation, named the 180°-Mode operation, a maximum of three thyristors conduct at any instant and each thyristor conducts for π radians in every cycle of the output. The utilization factor will be more thyristors operating in this mode. For this mode of operation, the phase-to-neutral output voltage waveforms for a three-phase balanced resistive load are as shown in Fig.1.17c. Inside each wave-block the conducting thyristor is named and the conducting sequence is shown at the bottom of Fig.1.17c. The bridge inverter is triggered in the same sequence T1, T2, T3, T4, T5, and T6 as in 120°-Mode but each thyristor conducts a time of π radiant. The Complementary commutation (voltage commutation) scheme shown in Fig.1.14 is suitable for this mode of operation.

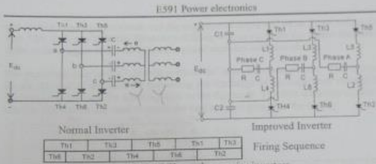


(a) Circuit Arrangement (b) Phase-voltages mode 120° (c) Phase-voltages mode 180°
Fig.1.17 Three-phase Bridge-Inverter

[2]- Three-Phase Series Inverter

Three single-phase series inverters of the type shown in Fig.1.11a can, when used with proper connections, give the three-phase outputs shown in Fig.1.18.

The thyristors are fired, as controlled rectifiers, in the sequence 1, 2, 3, 4, 5, and 6, the firing frequency being six times the output frequency. Therefore, the interval between successive firings will be T/6, where T is the period of the output. Th1 should be turned off before Th4 is turned on. The design considerations are the same as those for a single-phase series inverter.

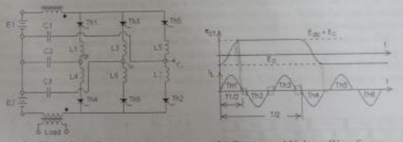


Normal Inverter
Improved Inverter
Firing Sequence

Fig.1.18 Three-phase series inverters

[3]- High-Frequency Series Inverter

The output frequency of the series inverter is limited to its resonant frequency. Any attempt to increase this frequency by decreasing the value of commutating components will be faced with the problem of satisfying the minimum turn-off time requirement of the thyristors. One method of obtaining high-frequency output, with normal thyristors which have a large turn-off time, is to use a number of series inverters in parallel as shown in Fig.1.19a, and to operate them one at a time in a specified sequence. Thus, the thyristors are fired in the order 1, 2, 3, 4, 5, and 6, producing alternate positive and negative half-cycles of current in the load as shown in Fig.1.19b.



(a)-The Schematic Arrangement (b)-Current and Voltage Waveforms

Fig.1.19 High-frequency series inverter

The output of the inverter is coupled to the load through a transformer. When Th1 is fired, the current will flow from the DC source E1 to the load through Th1, L1, and C1, charging the capacitor to voltage E_C, which will be more than E1. After Th1 is turned off, Th2 is fired. The load current will now flow in the opposite direction.

[4]- Current Commutated Inverter

The inverter circuit in Fig.1.20 is for the 120º-mode. There are six conducting intervals in each cycle of the output. When the load is resistive, in each interval two thyristors will conduct, but for reactive loads the free-wheeling diodes will conduct in each interval for some time before the incoming thyristor conducts. Here, only one thyristor will be fired at the end of each conducting interval, and the sequence of firing will be as given before Th1, Th2, Th3, Th4, Th5, and Th6. The frequency of firing will be six times the output frequency. If the order of the firing is reversed, the output phase sequence will also change.

The capacitors Cxx in Fig.1.20 will produce the required commutation. The diodes d1, d2, d3, d4, d5, and d6 are used for preventing the discharge of the capacitors through the load. The inductors are used for reducing di/dt in the thyristors. The free-wheeling diodes D1, D2, D3, D4, D5, and D6 are used to return the load reactive energy to the supply.

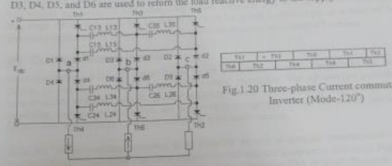


Fig.1.20 Three-phase Current commutated Inverter (Mode-120°)

[5]- Voltage Commutated Inverter

The inverter circuit shown in Fig.1.21 is a voltage commutated inverter for the 180º-mode. There are also six conducting intervals in each cycle of the output. When the load is resistive, three thyristors will conduct for at any time. For reactive loads the free-wheeling diodes will conduct in each interval for some time before the incoming thyristor conducts. Only one thyristor will be fired at the end of each conducting interval, and the sequence of firing will be the same as for current commutated inverter Th1, Th2, Th3, Th4, Th5, and Th6. Also the frequency of firing will be six times the output frequency. If the order of the firing is reversed, the output phase sequence will also change.

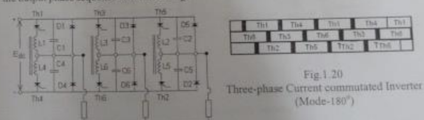
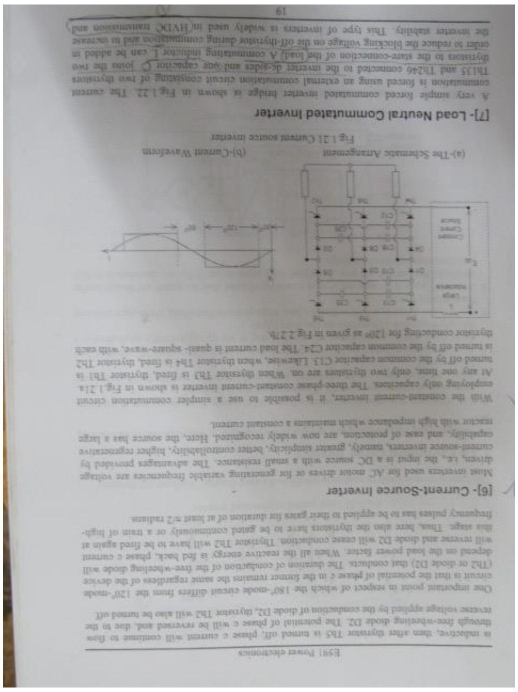


Fig.1.20
Three-phase Current commutated Inverter
(Mode-180°)

During the first conducting interval, the thyristors Th1, Th5, and Th6 will conduct. For this duration, phase-a and phase c currents will be positive and phase b current will be negative and have the maximum amplitude. At the end of this interval thyristor Th2 is triggered. This will turn off Th5 by discharging capacitor C2 through the loop C2, L2, Th2, back to C2. The voltage on C2 (E_{dc}) will appear across inductor L2, which is closely coupled to inductor L5. A voltage equal E_{dc} across inductor L5 will be induced. So, the cathode of the conducting thyristor Th5 will be raised to a potential of $2E_{dc}$, and will therefore be turned off. If the load



E591 Power electronics

is inductive, then after thyristor Th5 is turned off, phase c current will continue to flow through free-wheeling diode D2. The potential of phase c will be reversed and, due to the reverse voltage applied by the conduction of diode D2, thyristor Th2 will also be turned off.

One important point in respect of which the 180°-mode circuit differs from the 120°-mode circuit is that the potential of phase c in the former remains the same regardless of the device (Th2 or diode D2) that conducts. The duration of conduction of the free-wheeling diode will depend on the load power factor. When all the reactive energy is fed back, phase c current will reverse and diode D2 will cease conduction. Thyristor Th2 will have to be fired again at this stage. Thus, here also the thyristors have to be gated continuously or a train of high-frequency pulses has to be applied to their gates for duration of at least π/2 radians.

[6]- Current-Source Inverter

Most inverters used for AC motor drives or for generating variable frequencies are voltage driven, i.e., the input is a DC source with a small resistance. The advantages provided by current-source inverters, namely, greater simplicity, better controllability, higher regenerative capability, and ease of protection, are now widely recognized. Here, the source has a large reactor with high impedance which maintains a constant current.

With the constant-current inverter, it is possible to use a simpler commutation circuit employing only capacitors. The three-phase constant-current inverter is shown in Fig.1.21a. At any one time, only two thyristors are on. When thyrsitor Th3 is fired, thyristor Th1 is turned off by the common capacitor C13. Likewise, when thyristor Th4 is fired, thyristor Th2 is turned off by the common capacitor C24. The load current is quasi- square-wave, with each thyristor conducting for 120° as given in Fig.2.27b.

(a)-The Schematic Arrangement (b)-Current Waveform

Fig.1.21 Current source inverter

[7]- Load Neutral Commutated Inverter

A very simple forced commutated inverter bridge is shown in Fig.1.22. The current commutation is forced using an external commutation circuit consisting of two thyristors Th135 and Th246 connected to the inverter dc-sides and one capacitor C joins the two thyristors to the stare-connection of the load. A commutating inductor L can be added in order to reduce the blocking voltage on the off-thyristor during commutation and to increase the inverter stability. This type of inverters is widely used in HVDC transmission and

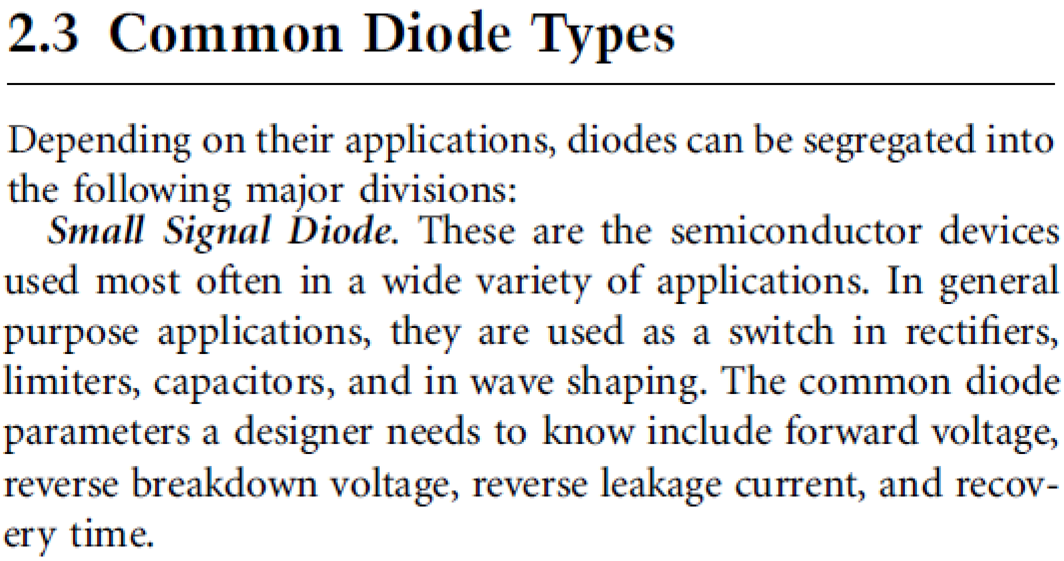
19

Q3b. Suggest a suitable firing circuit for one Inverter circuit in Q3a.

Question-4 (15 marks)

a- Write short notes about:

i-power diode ii-transistor iii-thyristor iv- GTO thyristor



2.3 Common Diode Types

Depending on their applications, diodes can be segregated into the following major divisions:

Small Signal Diode. These are the semiconductor devices used most often in a wide variety of applications. In general purpose applications, they are used as a switch in rectifiers, limiters, capacitors, and in wave shaping. The common diode parameters a designer needs to know include forward voltage, reverse breakdown voltage, reverse leakage current, and recovery time.

Silicon Rectifier Diode. These are the diodes that have high forward-current carrying capability, typically up to several hundred amperes. They usually have a forward resistance of only a fraction of an ohm while their reverse resistance is in the megaohm range. Their primary application is in power conversion, such as for power supplies, UPS, rectifiers/inverinverters etc. In case of current exceeding the rated value, their case temperature will rise. For stud mounted diodes, their thermal resistance is between 0.1 to 1° C/W.

Zener Diode. Its primary applications are in the voltage reference or regulation. However, its ability to maintain a certain voltage depends on its temperature coefficient and impedance. The voltage reference or regulation application of Zener diodes are based on their avalanche properties. In the reverse-biased mode, at a certain voltage the resistance of these devices may suddenly drop. This occurs at the Zener voltage V_X, a parameter the designer knows beforehand.

Photodiode. When a semiconductor junction is exposed to light, photons generate hole-electron pairs. When these charges diffuse across the junction, they produce photo current. Hence this device acts as a source of current that increases with the intensity of light.

Light-Emitting Diode (LED). Power diodes used in PE circuits are high-power versions of the commonly used devices employed in analog and digital circuits. They are manufactured in many varieties and ranges. The current rating can be from a few amperes to several hundreds while the voltage rating varies from tens of volts to several thousand volts.

1.2 Diodes

Sohail Anwar

Power diodes play an important role in power electronics circuits. They are mainly used as uncontrolled rectifiers to convert single-phase or three-phase AC voltage to DC. They are also used to provide a path for the current flow in inductive loads. Typical types of semiconductor materials used to construct diodes are silicon and germanium. Power diodes are usually constructed using silicon because silicon diodes can operate at higher current and at higher junction temperatures than germanium diodes. The symbol for a semiconductor diode is given in Fig. 1.9. The terminal voltage and current are represented as V_d and I_d, respectively. Figure 1.10 shows the structure of a diode. It has an anode (A) terminal and a cathode (K) terminal. The diode is constructed by joining together two pieces of semiconductor material—a *p*-type and an *n*-type—to form a *pn*-junction. When the anode terminal is positive with respect to the cathode

Characteristics

The voltage-current characteristics of a diode are shown in Fig. 1.11. In the forward region, the diode starts conducting as the anode voltage is increased with respect to the cathode. The voltage where the current starts to increase rapidly is called the knee voltage of the diode. For a silicon diode, the knee voltage is approximately 0.7 V. Above the knee voltage, small increases in the diode voltage produce large increases in the diode current. If the diode current is too large, excessive heat will be generated, which can destroy the diode. When the diode is reverse-biased, diode current is very small for all values of reverse voltage less than the diode breakdown voltage. At breakdown, the diode current increases rapidly for small increases in diode voltage.

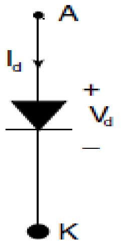


FIGURE 1.9 Diode symbol.

Principal Ratings for Diodes

Figures 1.12 and 1.13 show typical data sheets for power diodes.

Maximum Average Forward Current

The maximum average forward current ($I_{f(avg)max}$) is the current a diode can safely handle when forward biased. Power diodes are available in ratings from a few amperes to several hundred amperes. For example, the power diode D_6 described in the data specification sheet (Fig 1.12) can handle up to 6 A in the forward direction when used as a rectifier.

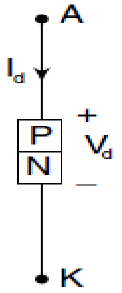


FIGURE 1.10 Diode structure.

Peak Inverse Voltage

The peak inverse voltage (PIV) of a diode is the maximum reverse voltage that can be connected across a diode without breakdown. The peak inverse voltage is also called peak reverse voltage or reverse breakdown voltage. The PIV ratings of power diodes extend from a few volts to several thousand volts. For example, the power diode D_6 has a PIV rating of up to 1600 V, as shown in Fig. 1.12.

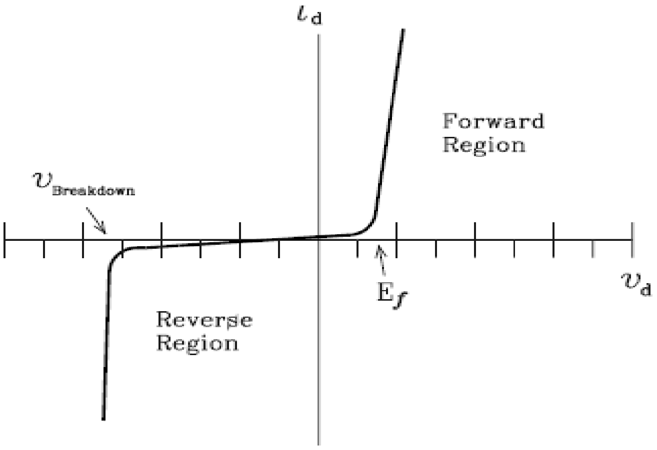


FIGURE 1.11 Diode voltage-current characteristic.

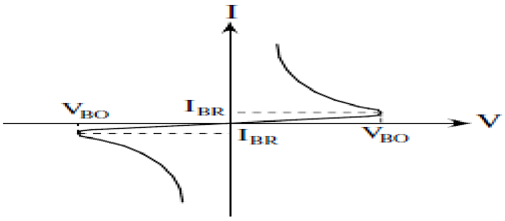
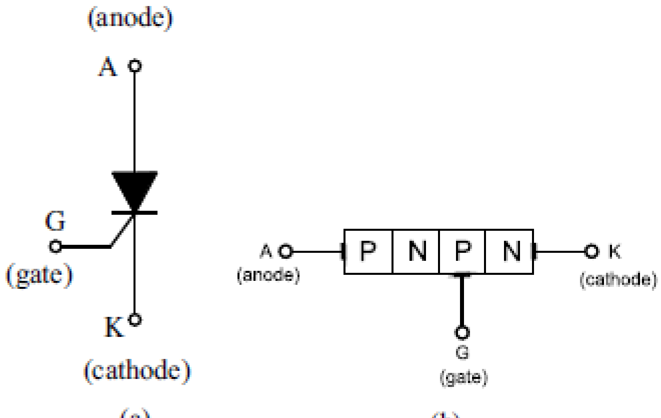


FIGURE 1.25 The DIAC characteristics.

Thyristor and Triac

The thyristor, also called a silicon-controlled rectifier (SCR), is basically a four-layer three-junction *pnpn* device. It has three terminals: anode, cathode, and gate. The device is turned on by applying a short pulse across the gate and cathode. Once the device turns on, the gate loses its control to turn off the device. The turn-off is achieved by applying a reverse voltage across the anode and cathode. The thyristor symbol and its volt–ampere characteristics are shown in Fig. 1.1. There are basically two classifications of thyristors: converter grade and inverter grade. The difference between a converter-grade and an inverter-



(a)

(b)

FIGURE 1.21 (a) The SCR symbol; (b) the SCR structure.

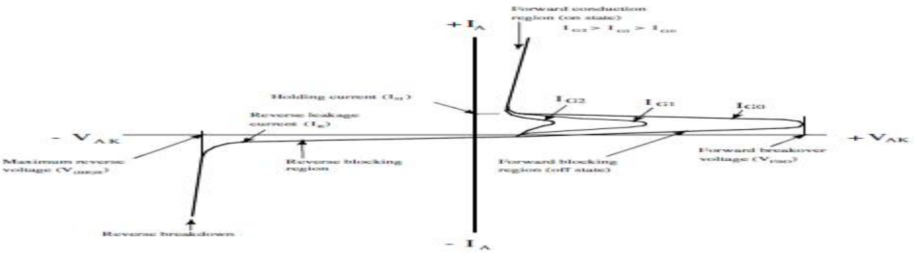


FIGURE 1.22 SCR characteristics.

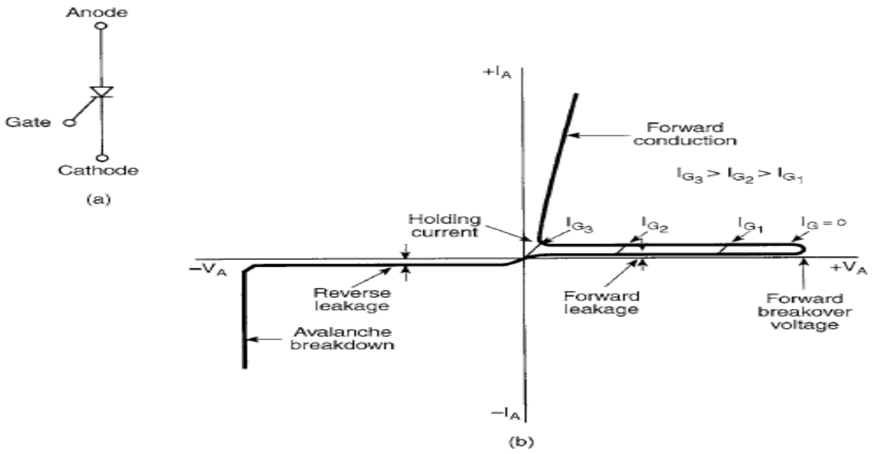


FIGURE 1.1 (a) Thyristor symbol and (b) volt–ampere characteristics. (From Bose, B.K., *Modern Power Electronics: Evaluation, Technology, and Applications*, p. 5. © 1992 IEEE. With permission.)

Gate Turn-Off Thyristor

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 high-frequency operation than thyristors. The GTO symbol and turn-off characteristics are shown in Fig. 1.3.

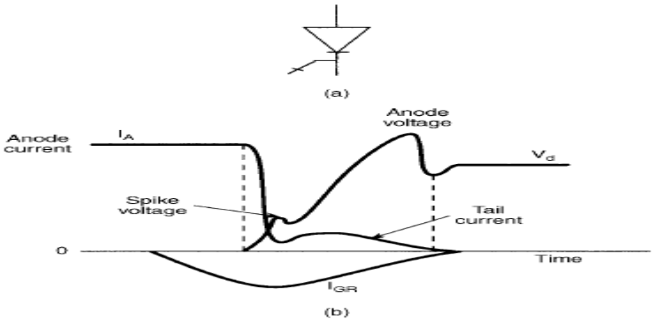


FIGURE 1.3 (a) GTO symbol and (b) turn-off characteristics. (From Bose, B.K., *Modern Power Electronics: Evaluation, Technology, and Applications*, p. 5. © 1992 IEEE. With permission.)

The Gate Turn-Off Thyristor

The GTO is a power semiconductor switch that turns ON by a positive gate signal. It can be turned OFF by a negative gate signal. The GTO symbol is shown in Fig. 1.29a and the GTO structure is shown in Fig. 1.29b. The GTO voltage and current ratings are lower than those of SCRs. The GTO turn-off time is lower than that of SCR. The turn-on time is the same as that of an SCR.

A GTO can operate safely in the “reverse avalanche” region for a short time provided the gate
.cathode junction is reverse biased
The switching delay times and energy loss of a GTO can be reduced by increasing the gate •
.current magnitude and its rate of rise
The maximum turn off anode current of a GTO can be increased by increasing the turn off •
snubber capacitance

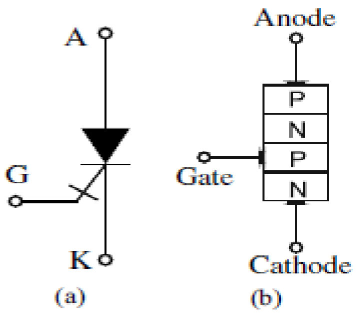


FIGURE 1.29 (a) The GTO symbol; (b) the GTO structure.

1.5 Power Bipolar Junction Transistors

Sohail Anwar

Power bipolar junction transistors (BJTs) play a vital role in power circuits. Like most other power devices, power transistors are generally constructed using silicon. The use of silicon allows operation of a BJT at higher currents and junction temperatures, which leads to the use of power transistors in AC applications where ranges of up to several hundred kilowatts are essential.

The power transistor is part of a family of three-layer devices. The three layers or terminals of a transistor are the base, the collector, and the emitter. Effectively, the transistor is equivalent to having two *pn*-diode junctions stacked in opposite directions to each other. The two types of a transistor are termed *npn* and *pnp*. The *npn*-type transistor has a higher current-to-voltage rating than the *pnp* and is preferred for most power conversion applications. The easiest way to distinguish an *npn*-type transistor from a *pnp*-type is by virtue of the schematic or circuit symbol. The *pnp* type has an arrowhead on the emitter that points toward the base. Figure 1.36 shows the structure and the symbol of a *pnp*-type transistor. The *npn*-type transistor has an arrowhead pointing away from the base. Figure 1.37 shows the structure and the symbol of an *npn*-type transistor.

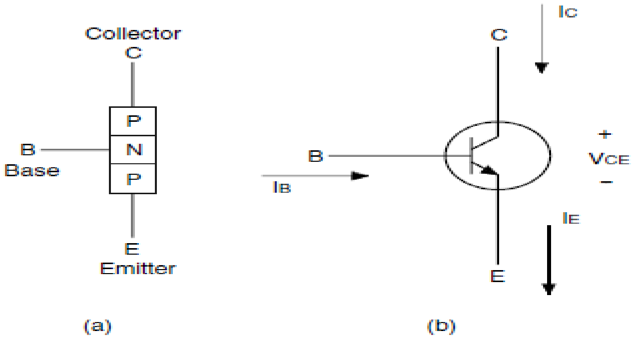


FIGURE 1.36 *pnp* transistor structure (a) and circuit symbol (b).

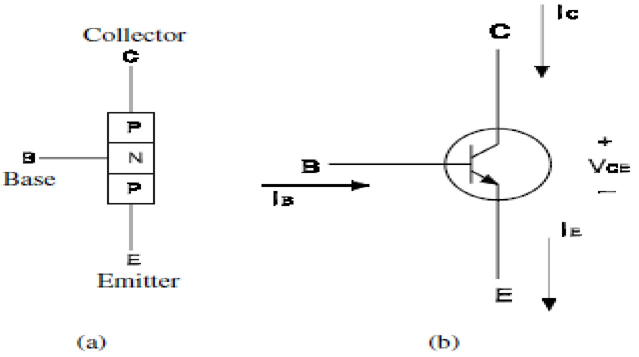


FIGURE 1.37 *npn* transistor structure (a) and circuit symbol (b).

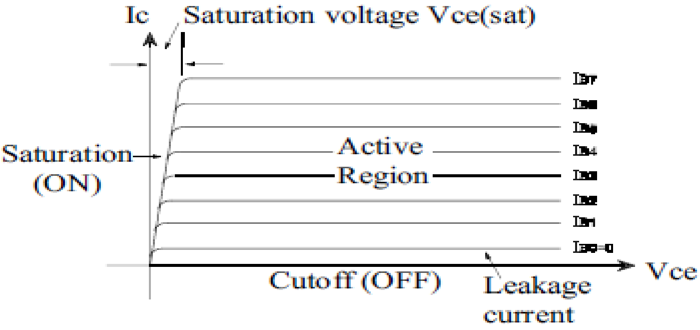


FIGURE 1.38 BJT V-I characteristic.

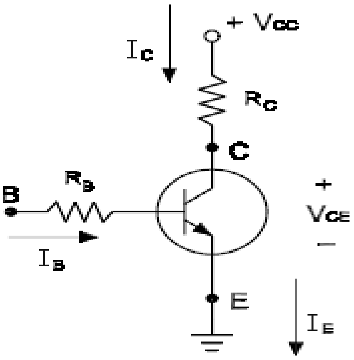


FIGURE 1.39 Biasing of a transistor.

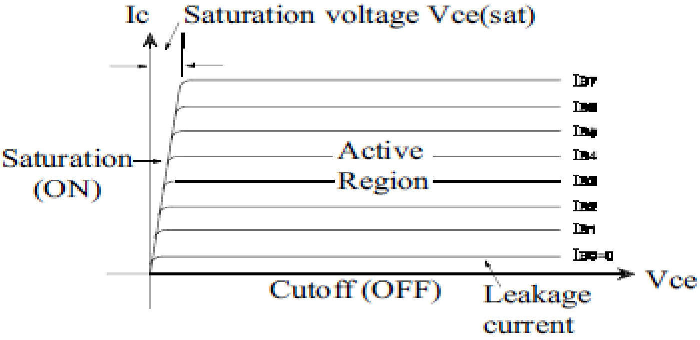


FIGURE 1.38 BJT V-I characteristic.

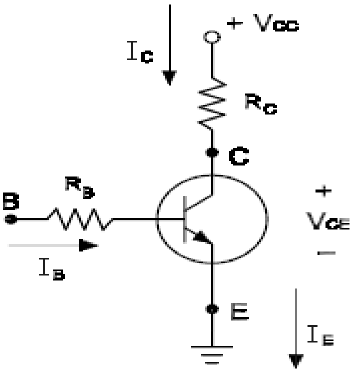


FIGURE 1.39 Biasing of a transistor.

Power Transistor

Power transistors are used in applications ranging from a few to several hundred kilowatts and switching frequencies up to about 10 kHz. Power transistors used in power conversion applications are generally *npn* type. The power transistor is turned on by supplying sufficient base current, and this base drive has to be maintained throughout its conduction period. It is turned off by removing the base drive and making the base voltage slightly negative (within $-V_{BE(\max)}$). The saturation voltage of the device is normally 0.5 to 2.5 V and increases as the current increases. Hence, the on-state losses increase more than proportionately with current. The transistor off-state losses are much lower than the on-state losses because the leakage current of the device is of the order of a few milliamperes. Because of relatively larger switching times, the switching loss significantly increases with switching frequency. Power transistors can block only forward voltages. The reverse peak voltage rating of these devices is as low as 5 to 10 V.

Power transistors do not have I^2t withstand capability. In other words, they can absorb only very little energy before breakdown. Therefore, they cannot be protected by semiconductor fuses, and thus an electronic protection method has to be used.

Power MOSFET

Power MOSFETs are marketed by different manufacturers with differences in internal geometry and with different names such as MegaMOS, HEXFET, SIPMOS, and TMOS. They have unique features that make them potentially attractive for switching applications. They are essentially voltage-driven rather than current-driven devices, unlike bipolar transistors.

The gate of a MOSFET is isolated electrically from the source by a layer of silicon oxide. The gate draws only a minute leakage current on the order of nanoamperes. Hence, the gate drive circuit is simple and power loss in the gate control circuit is practically negligible. Although in steady state the gate draws virtually no current, this is not so under transient conditions. The gate-to-source and gate-to-drain

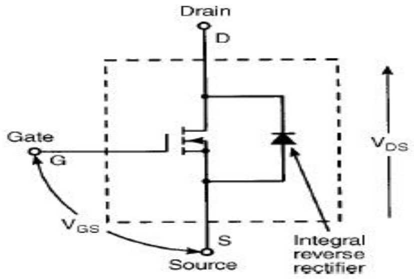


FIGURE 1.5 Power MOSFET circuit symbol. (From Bose, B.K., *Modern Power Electronics: Evaluation, Technology, and Applications*, p. 7. © 1992 IEEE. With permission.)

1.6 MOSFETs

Vrej Barkhordarian

The metal-oxide-semiconductor field-effect transistor (MOSFET) is the most commonly used active device in very large scale integrated (VLSI) circuits. Figure 1.54 shows the device schematic, current-voltage characteristics, transfer characteristics and device symbol for a MOSFET. It is a lateral device and though very suitable for integration into integrated circuits, it has severe limitations at high power levels. The power MOSFET design is based on the original field-effect transistor and, since its invention in the early 1970s, has gone through several evolutionary steps. The processing of power MOSFETs is very similar to that of today's VLSI circuits although the device geometry is significantly different from the

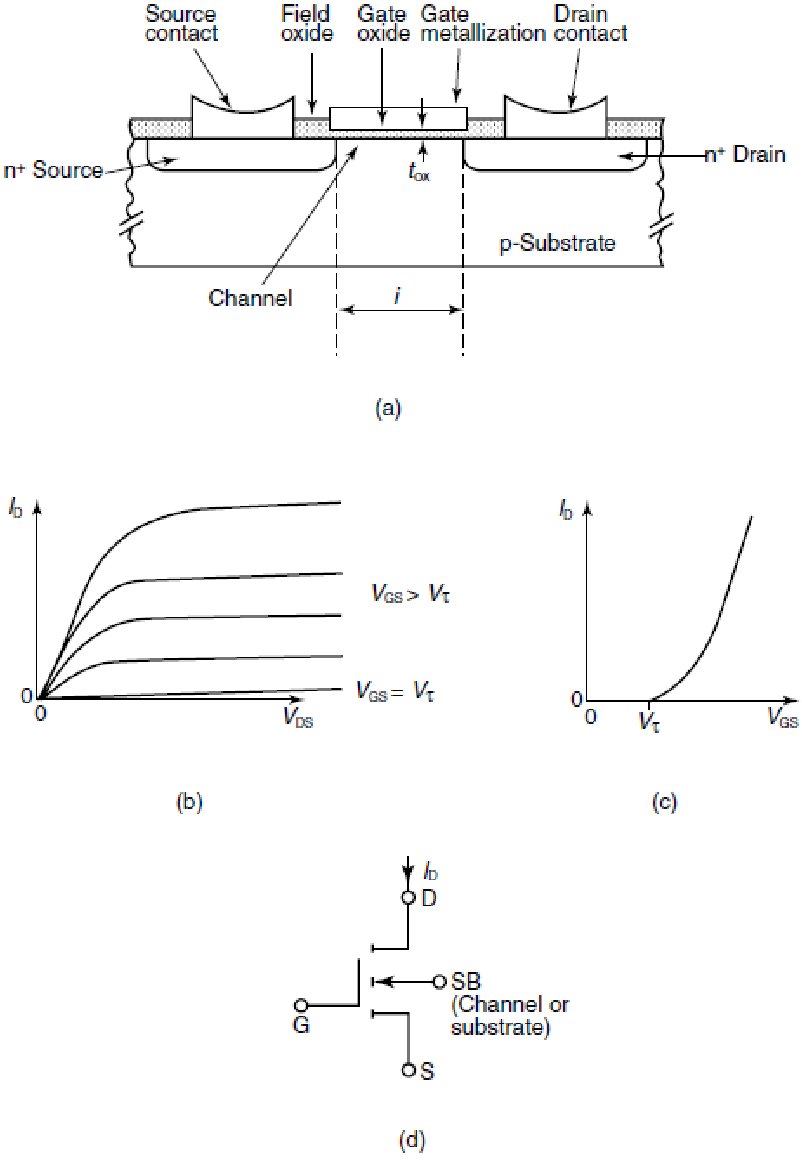


FIGURE 1.54 (a) Schematic diagram, (b) current-voltage characteristics, (c) transfer characteristics, and (d) device symbol for an *n*-channel enhancement mode MOSFET.

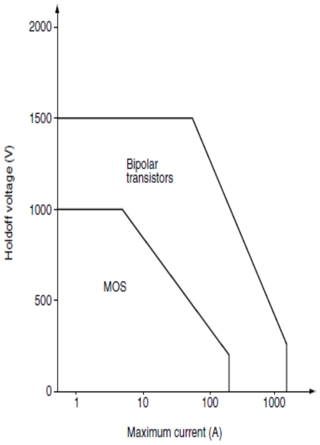


FIGURE 1.55 Current-voltage limitations of MOSFETs and BJTs.

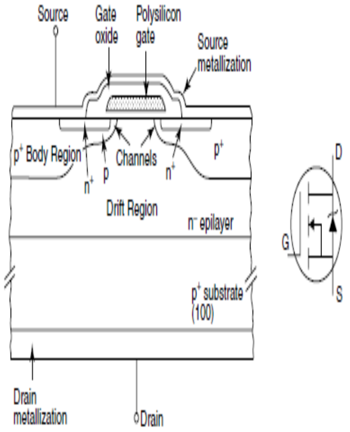


FIGURE 1.56 Schematic diagram for an *n*-channel power MOSFET and the device symbol.

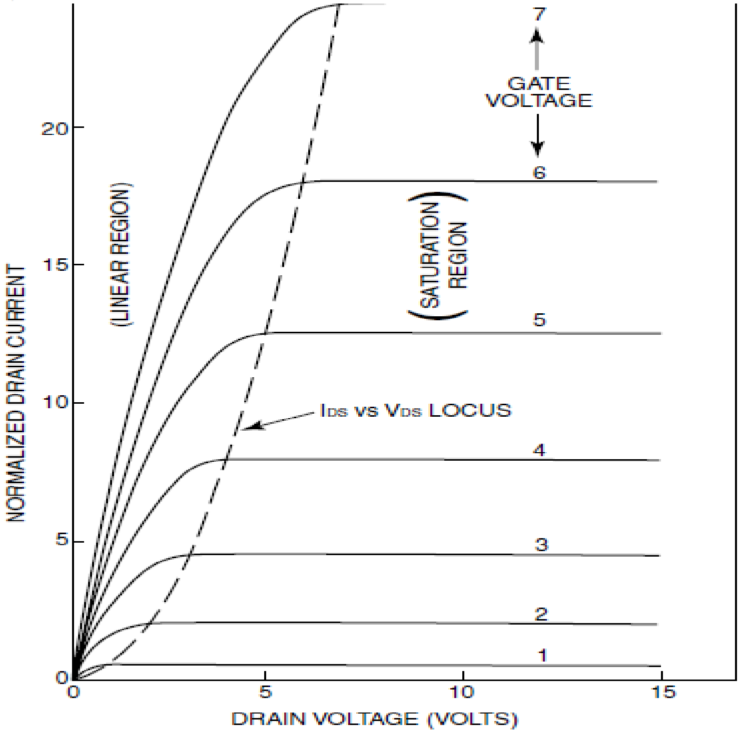


FIGURE 1.59 Current-voltage characteristics of a power MOSFET.

Insulated-Gate Bipolar Transistor (IGBT)

The IGBT has the high input impedance and high-speed characteristics of a MOSFET with the conductivity characteristic (low saturation voltage) of a bipolar transistor. The IGBT is turned on by applying a positive voltage between the gate and emitter and, as in the MOSFET, it is turned off by making the gate signal zero or slightly negative. The IGBT has a much lower voltage drop than a MOSFET of similar ratings.

b- Write the main parts of a power electronic system?•

1-Isolated power supplies	2-main power circ uit	3-protection circuit
4-control circuit	5-drive circuit	6-commutation circuit

c- How to protect the transistor against:

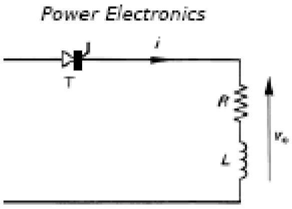
i- over current	Using series fast fuse or circuit breaker
ii- over voltage	Using varestor or selenium diode
iii- over temperature degree	Using heat sinks with fins
iv- over di/dt	Using series inductances
v- over dv/dt	Using snubber circuit RCD

Question-5 (15 marks)

a-Define: latch current is the minimum anode current after which the thyristor changes to on state from off state unless removing the gate pulse

hold current is the minimum anode current after which the thyristor changes to off state from on state.

b-A power electronic circuit consists of DC power supply (200V), thyristor (latching current level 10 mA) and inductive load(40Ω, 1H) neglect the thyristor voltage drop.



(a)

i- Draw the power circuit

ii- Show that the thyristor will fail to remain on when the firing pulse ends after 25µsec.? $i_l = \frac{V}{R}\left(1 - e^{-\frac{Rt}{L}}\right) = \frac{200}{40}\left(1 - e^{-\frac{40*25*10^{-6}}{1}}\right) = 5mA$

iii- Find the minimum pulse length of the correct firing pulse?

$$i_l = \frac{V}{R}\left(1 - e^{-\frac{Rt}{L}}\right) = \frac{200}{40}\left(1 - e^{-\frac{40*t}{1}}\right) = 10mA, then\ t = 50\mu sec$$

iv- Find the maximum value of shunt resistance (to load) to ensure firing using pulse of length 25µsec.

$R = \frac{V}{I} = \frac{200}{10mA-5mA} = \frac{200}{5mA}$, R=40KΩ

v- Show how to turn off the thyristor?

Connect a positive of DC power supply of 200V to a cathode of the thyristor