GOVERNMENT OF TAMILNADU
DIRECTORATE OF TECHNICAL EDUCATION
CHENNAI – 600 025
STATE PROJECT COORDINATION UNIT

Diploma in Electrical and Electronics Engineering
Course Code: 1030
M – Scheme

e-TEXTBOOK
on
POWER ELECTRONICS
for
VI Semester DEEE

Convener for EEE Discipline:

Er.R.Anbukarasi ME.,
Principal,
Tamilnadu Polytechnic College,
Madurai, 625011.

Team Members for POWER ELECTRONICS

THIRU M.SHANMUGANATHAM, B.E., M.I.S.T.E
LECTURER (SL.Gr)/ELECTRICAL
TAMILNADU POLYTECHNIC COLLEGE, MADURAI

THIRU S.JAWAHAR, M.E.,
HOD /EEE
VSVN POLYTECHNIC COLLEGE, VIRDHUNAGAR

THIRU S.KANNADHASAN, M.E.,
PTLECT/ELECTRICAL
TAMILNADU POLYTECHNIC COLLEGE, MADURAI

Validated by:

Dr.S.AROKIA EDWIN XAVIER, M.E.,PH.D
Associate Professor,
Department of Electrical and Electronics Engineering,
Thiagarajar College of Engineering, Madurai.

DIPLOMA IN ELECTRICAL AND ELECTRONICS ENGINEERING

M - SCHEME

Course Name: Diploma in Electrical and Electronics Engineering

Subject Code: 1030 **Semester: VI**

Subject Title: POWER ELECTRONICS

RATIONALE:

Developments in Electronics have their own impact in other fields of Engineering. Today all the controls and drives for the electrical machines are formed by electronic components and there are many electronic devices available to handle eclectic power in terms Kilo-Amps and Kilo-Volts. This subject gives a comprehensive knowledge base about the devices and circuits used in electrical power control.

OBJECTIVES:

- Explain the scope and application of power electronics
- Explain the operating region and rating of SCR.
- Draw, explain and state the application for commutation circuits and trigger circuits of SCR.
- Familiarize the phase controlled rectifier and know the applications of the phase controlled rectifier.
- Draw and describe the working of half wave controlled rectifier circuit with R and RL load, single phase Semi Converter Bridge, Single phase full Converter Bridge for RL load, single phase and three phase full converter with RL load.
- Familiarizes the dual converter and twelve pulse converters.
- Study the complete protection of converter circuits.
- Understand the working choppers and inverters.
- Know the applications of choppers and inverters.
- Explain the various types of choppers with circuit diagram.
- Describe the various methods of inverters with circuit diagram.
- Failure of AC voltage controller & cyclo converter.
- Understand the application of power electronics devices as CB,UPS and VAR compensator
- Understand the control of DC Drives.
- Know the various methods of speed control of DC drives.
- Familiarize the control of AC drives.
- Know the torque - speed characteristics of three phase induction motor.
- Study the speed control of three phase induction motor using PWM and slip power recovery scheme.
- Understand the closed loop control of AC drive.
- Know the operation of single phase and three phase cyclo converter.
- Understand the micro controller based fault diagnosis in three phase thyristor converter circuits.

DETAILED SYLLABUS

1030 - POWER ELECTRONICS (M - SCHEME)

Unit -1 OVERVIEW OF POWER ELECTRONICS Page No: (5-24)

Power electronics-Definition (A-1.1)-Scope and Applications (B-1.3)-Power Electronic Switch Specifications (A-1.4.3)-Types of Power Electronic Circuits (A-1.5)-Design of Power Electronics Equipment (A-1.6)-Power module (A-1.9)-Intelligent module (A-1.10). Silicon Controlled Rectifier(D-2.4.1)-Forward Blocking Region(D-2.4.2)-Forward Conducting Region(D-2.4.3)-Reverse Blocking Region(D-2.4.4)-Effect of dv/dt and Snubber Circuits (D-2.4.7)-Effect of Rate of Rise in Current(di/dt)(D-2.4.8)-Thyristor Ratings(D-2.4.11) -Thyristor Gate Requirements(D-3.2)-Triggering Circuits for Thyristor(D-3.3)-Resistance Triggering Circuits(D- 3.4.1)-RC Trigger Circuits(D-3.4.1)-UJT based Trigger Circuits- Driver and Buffer Circuits for Thyristor(D-3.4.7) Thyristor Commutation Techniques-Class A, Class B, Class C, Class D, Class E Types(C-5.1 to C-5.6)-Power Devices – MOSFET (A.8.3)-IGBT (A.8.5) – GTO (A.4.8.3)

Unit -2 LINES COMMUTATED POWER CONTROL CIRCUITS Page No: (25-41)

Line Commutated Converters(Controlled Rectifiers)- Principle of Phase Controlled Converter Operation(A-10.2)-Single Phase Full Converters(A-10.3)-Single Phase Dual Converters (A-10.3)-Three Phase Full Converters(A-10.6)-Three Phase Dual Converters(A-10.7)-12 Pulse converters(A-10.12) AC Voltage Controllers-Principle of Phase Control(A- 11.3)-Single phase Bidirectional controllers with Resistive Load(A- 11.4)-Single Phase Controller with Inductive Load(A-11.5)-Three Phase Full Wave Controllers(A-11.6)- Cyclo Converters-Single Phase Cyclo Converters(A-11.9.1)-Three Phase Cyclo Converters(A-11.9.2)

Unit -3 FORCED COMMUTATED POWER CONTROL CIRCUITS Page No: (42-54)

DC-DC Switch-Mode Converters(Choppers)-Control of DCDC Converters(B-7.2)-Step-Down(BUCK) Converter(B-7.3)- Continuous-Conduction Mode(B-7.3.1) - Step-Up(BOOST) Converters(B-7.4)-Continuous Conduction Mode (B-7.4.1) –BUCKBOOST Converters (B-7.5) – Continuous Conduction Mode (B- 7.5.1) - Cuk DC-DC Converters(B-7.6) DC-AC Switch-Mode Inverters-Pulse Width Modulated Inverters- Introduction(A-6.1)-Principle of Operation(A-

6.2)-Single Phase Bridge Inverters(A-6.4)-Three Phase Inverters(A-6.5)-1800 Conduction Mode(A-6.5.1)-1200 Conduction Mode(A-6.5.2)- Voltage Control of Single Phase Inverters(A-6.6)-Single Pulse Width Modulation(A-6.6.1)-Multiple Pulse Width Modulation(A- 6.6.2)-Sinusoidal Pulse Width Modulation(A-6.6.3)-Voltage Control of Three Phase Inverters(A-6.8)-Sinusoidal PWM(A.6.8.1).

Unit -4 APPLICATIONS OF POWER ELECTRONICS Page No: (55-64)

Switch Mode Power Supplies-Full Bridge Converter type(C-11.1.4)-Uninterrupted Power Supply-ON line(No Break) and OFF line(Short-Break) types(C-11.2)-Static AC Circuit Breaker(C-11.5.1)-AC Solid State Relays(C-11.6.2). High Frequency Flourescent Lighting (B -16.2.2)- Induction Heating(B16.3.1)-Electric Welding(B -16.3.2)-High Voltage DC Transmission(B -17.2)-Wind and Small Hydro Interconnection(B -17.4.2)-Static VAR Compensators(B -17.3)- Thyristor Controlled Inductors (B -17.3.1)-Thyristor Switched Capacitors(B -17.3.2).

Unit -5 MOTOR DRIVE APPLICATIONS Page No: (65-84)

DC Drives-DC Motor with a Separately Excited Field Winding(B -13.4)-Line Frequency Converters (B-13.7.2)-Effect of Discontinuous Armature Current(B -13.7.3)–Control of Adjustable Speed Drives(B -13.7.4)-Switch-Mode DC-DC Converters(B - 13.7.1) Induction Motor Drives-Introduction(B -14.1)-Basic Principle of Induction Motor Operation (B -14.2)-Induction Motor Characteristics at rated(line) frequency and rated voltage(B -14.3)- Speed Control by Varying Stator frequency and voltage(B -14.4)- Torque-Speed Characteristics(B -14.4.1)-Start-Up Considerations(B -14.4.2)-Voltage Boost required at low frequencies(B -14.4.3)-Induction Motor Capability below and above the rated speed(B -14.4.4)-Variable frequency Converter Classifications(B -14.6)-Variable frequency PWM-VSI Drives (B - 14.7)-Line frequency Variable-Voltage Drives(B -14.11)-Reduced Voltage Starting(“Soft Start”) of Induction Motors(B -14.12)-Speed Control by Static Slip-Power Recovery(B -14.13).

UNIT I

OVERVIEW OF POWER ELECTRONICS

1. Power Electronics – Definition

Power electronics involves the study of electronic circuits intended to control the flow of electrical energy. All power electronic circuits manage the flow of electrical energy between an electrical source and a load.

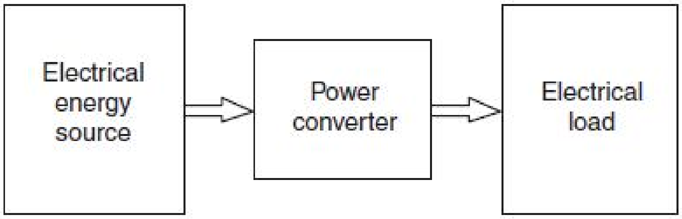


Figure 1.1 Flow of Power Electronics

1.1.1 Scope and Applications

The following are the scope areas in which the power electronics is applicable.

1. **Switch Mode DC Power Supplies (SMPS)and Uninterrupted Power Supplies (UPS):**

Computers, communication equipment and consumer electronics require SMPS and UPS.

2. **Energy Conservation:**

In conventional pump system, the pump operates at constant speed and the pump flow rate is controlled by adjusting the position of the throttling valve. This procedure results in power loss. The power loss is eliminated by employing adjustable speed drive.

Drive= Power Converter+Motor

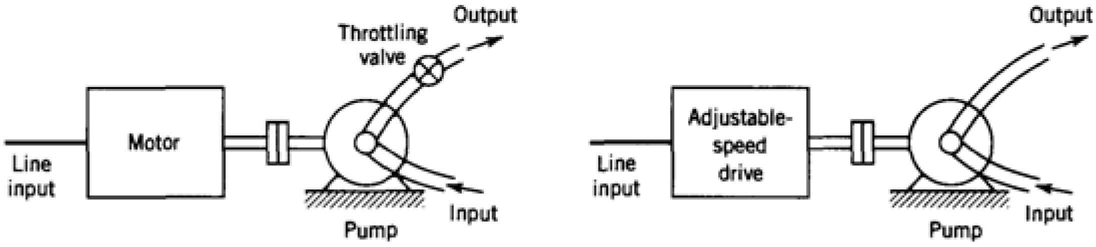


Figure 1.2: Energy Conservation

Another example is the fluorescent lamp. If the fluorescent lamp is operated at higher frequency, its efficiency increases.

3. Process Control and factory automation:

There is a growing demand for the enhanced performance offered by adjustable-speed driven pumps and compressors in process control. Robots in automated factories are powered by electric servo (adjustable speed and position) drives.

4. Transportation:

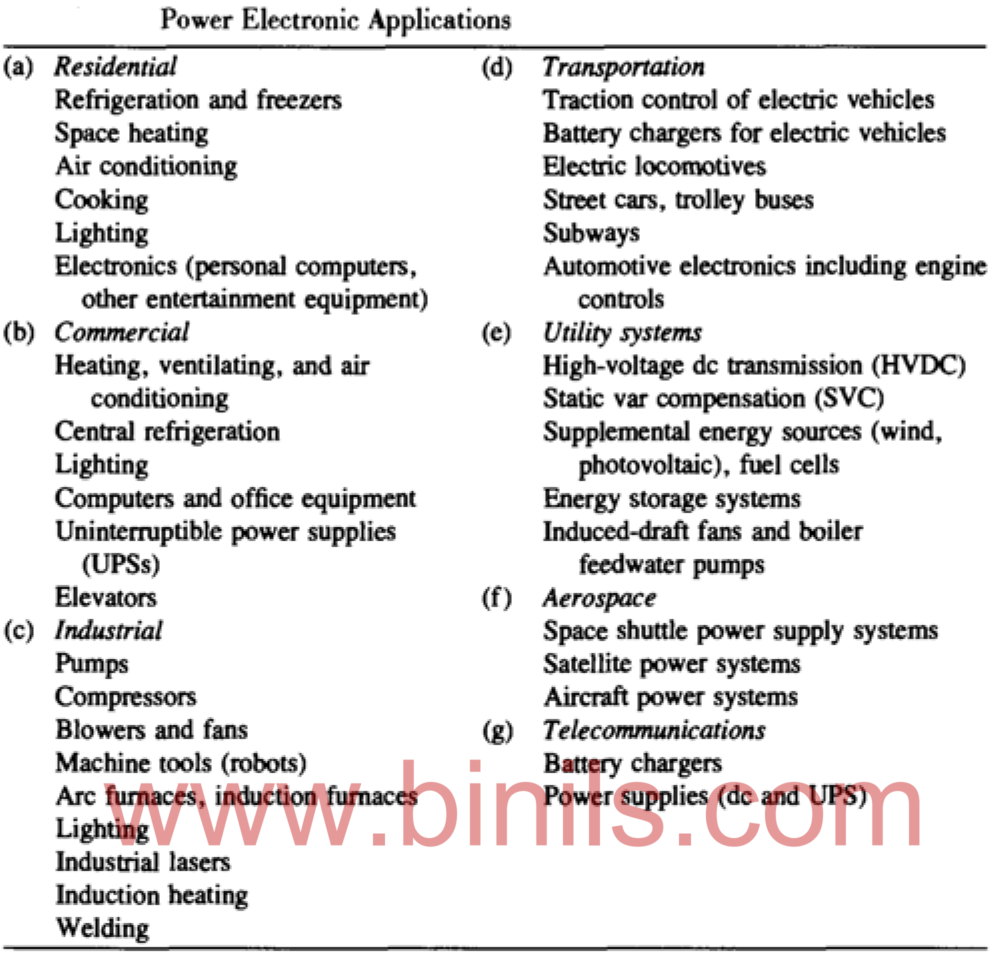
There is a lot of scope in using electric trains in metropolitan cities, which needs power electronics converters.

5. Electro – technical applications:

Electro-plating, welding and induction heating are done by the help of power converters efficiently.

6. Utility related applications:

Power electronics plays an important role in interconnection of photo-voltaic and wind energy systems with the utility grid. It is also used in HVDC transmission system.



Power Electronic Applications

- (a) *Residential*
  - Refrigeration and freezers
  - Space heating
  - Air conditioning
  - Cooking
  - Lighting
  - Electronics (personal computers, other entertainment equipment)
- (b) *Commercial*
  - Heating, ventilating, and air conditioning
  - Central refrigeration
  - Lighting
  - Computers and office equipment
  - Uninterruptible power supplies (UPSs)
  - Elevators
- (c) *Industrial*
  - Pumps
  - Compressors
  - Blowers and fans
  - Machine tools (robots)
  - Arc furnaces, induction furnaces
  - Lighting
  - Industrial lasers
  - Induction heating
  - Welding
- (d) *Transportation*
  - Traction control of electric vehicles
  - Battery chargers for electric vehicles
  - Electric locomotives
  - Street cars, trolley buses
  - Subways
  - Automotive electronics including engine controls
- (e) *Utility systems*
  - High-voltage dc transmission (HVDC)
  - Static var compensation (SVC)
  - Supplemental energy sources (wind, photovoltaic), fuel cells
  - Energy storage systems
  - Induced-draft fans and boiler feedwater pumps
- (f) *Aerospace*
  - Space shuttle power supply systems
  - Satellite power systems
  - Aircraft power systems
- (g) *Telecommunications*
  - Battery chargers
  - Power supplies (dc and UPS)

1.2 Power Electronic Switch Specifications

The important parameters of power electronic devices are given below.

1. Voltage ratings: Forward and reverse repetitive peak voltages and ON state forward voltage drop.
2. Current ratings: average, rms, repetitive and non repetitive peak current and OFF state leakage currents.
3. Switching frequency: Transition from fully conduction state to fully non conduction state and vice versa are important parameter that decides the switching frequency.

4. di/dt rating: If the rate of rise of current through the device is rapid, the device may get damaged.
5. dv/dt rating: If the voltage across the device changes rapidly, the device will not have any control over gate.
6. Switching losses: During the device turn on process the forward current rises before voltage falls and during the turn off process the voltage raises before the current falls. This creates switching power loss in the device.
7. Gate drive requirement: The gate-drive voltage and current are the important parameters to turn on and turn off the device.

1.3 Types of Power Electronic Circuits

For the control of electric power, the conversion of electric power from one form (AC or DC) to another form (Variable AC or DC) is necessary. The switching characteristics of the power electronic devices permit these power conversions. The power electronic circuits are classified into six types.

a. Diode rectifiers – converts ac voltage into fixed dc voltage.

b. AC-DC Converters (Controlled rectifiers) – converts ac voltage into variable dc voltage.
c. AC-AC Converters (ac voltage regulators) – converts fixed ac voltage into variable ac voltage.
d. DC-DC Converters (dc choppers) – converts fixed dc voltage into variable dc voltage.
e. DC-AC converters (inverters) – converts dc voltage into variable ac voltage.
f. Static Switches – connect or disconnect ac or dc input voltage to load.

1.4 Design of Power Electronics Equipments

The design of power electronics equipments can be divided into four parts:

1. Design of power circuits
2. Protection of power devices
3. Determination of control strategy
4. Design of logic and gating circuits

The practical power devices and circuits differ from ideal conditions. However, in the early stage of design, the simplified analysis of a circuit is very useful to understand the operation of the circuit. When prototype is developed, the device and environment should be considered.

1.4.1 Power Modules

Power devices are available as a single unit or in a module. A power converter often requires two, four or six devices depending on its topology. Power modules with dual (in half-bridge configuration) or quad (in full bridge) or six (in three phase) are available. The module offer the advantages of lower on state losses, high voltage and current characteristics and higher speed than that of individual units. Some modules include transient protection and gate drive circuits.

1.4.2 Intelligent modules

Intelligent modules integrate the power module and the peripheral circuit. The peripheral circuit consists of input or output isolators, drive circuit, protection and diagnostic circuits (against excess current, short circuit, an open load, overheating and an excess voltage), microcomputer control and a controlled power supply. An intelligent module is also known as smart power module.

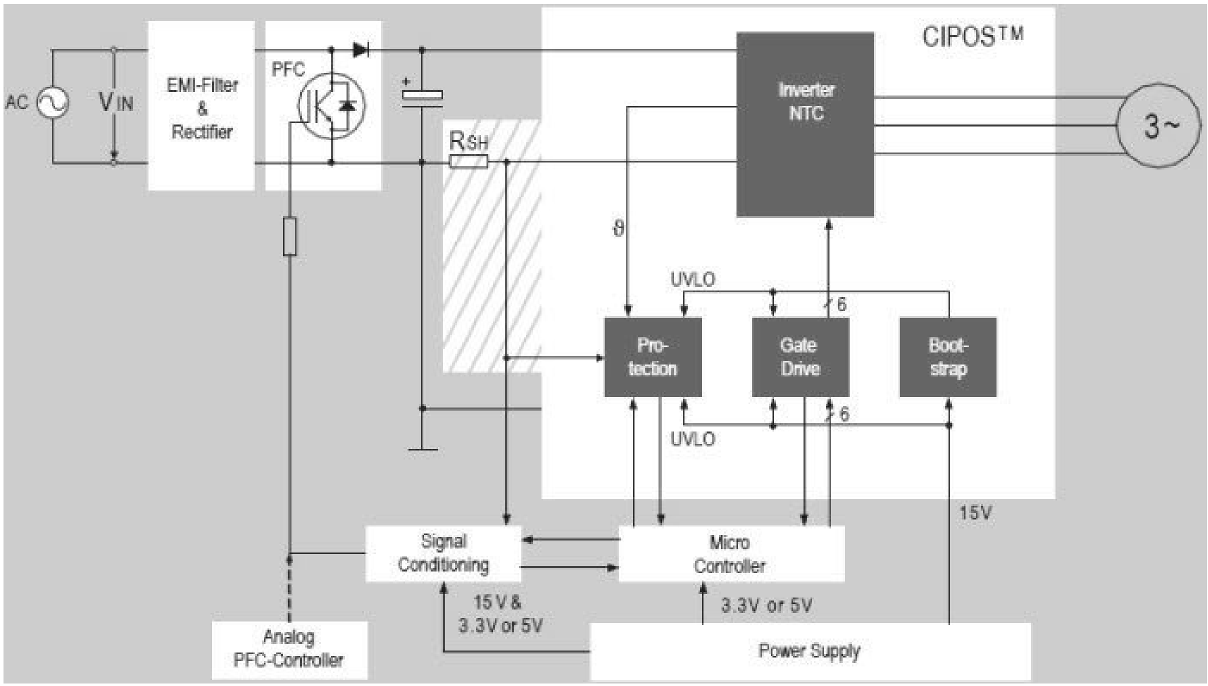


Figure 1.3: Intelligent Modules

1.5 Silicon Controlled Rectifier (SCR)

1.5.1 Basic Structure and Operation:

SCR is a three-terminal device. It has four layers of *p*-type and *n*-type material (i.e. three *p*–*n* junctions). The control terminal of the SCR is called the gate (*G*) electrode. The other two terminals, called the anode (*A*) and cathode (*K*), handle the large applied potentials and conduct the major current through the SCR. The anode and cathode terminals are connected in series with the load to which the power is to be controlled. SCRs are used as closed switch (no voltage drop between anode and cathode) or open (no anode current flow) switch for the control of power flow in a circuit.

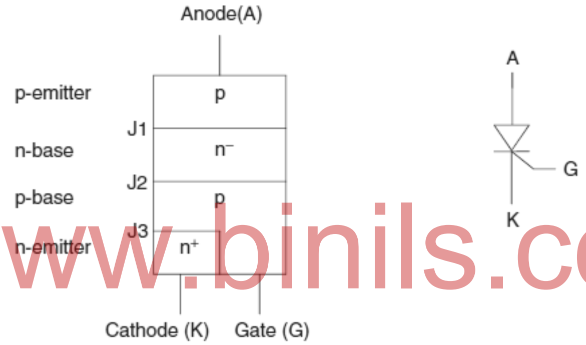


Figure 1.4: SCR Symbol

1.5.2 SCR construction and Symbol

When a positive voltage is applied to the anode with respect to cathode, the thyristor is in its forward-blocking state. Junction J1 and J3 are forward biased and junction J2 is reverse biased. In this operating mode the gate current is zero. As long as the forward applied voltage does not exceed the value necessary to cause avalanche breakdown around J2, the SCR remains in off-state (forward-blocking). If the applied voltage exceeds the maximum forward-blocking voltage of the SCR, it will switch to its on-state. This method of turn on damages the device.

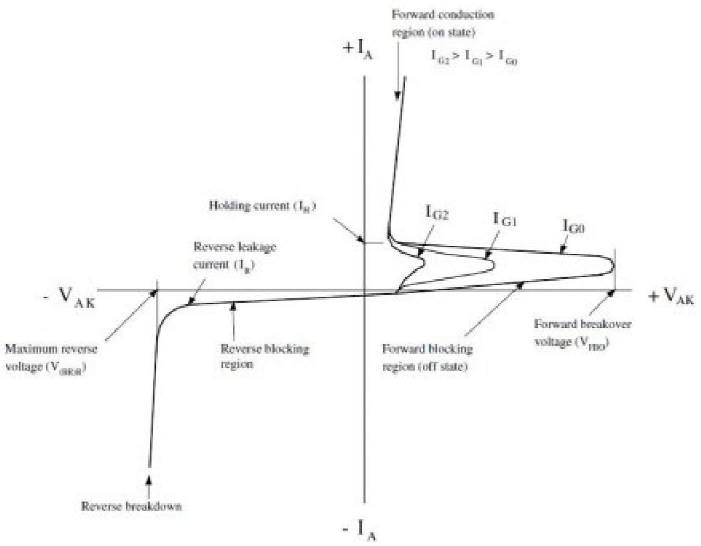


Figure 1.5: SCR V-I Characteristics

When the gate current is given the turn on takes place at lesser anode to cathode voltages. The effect of gate current is to lower the blocking voltage at which switching takes place. The SCR moves rapidly along the negatively sloped portion of the curve until it reaches a stable operating point determined by the external circuit. As the SCR moves from forward-blocking to forward conduction, the external circuit must allow sufficient anode current to flow to keep the device latched.

When the SCR is reverse-biased, a small reverse leakage current flows. This is called reverse blocking state. If the reverse bias is increased beyond the reverse breakdown voltage, the reverse current will increase sharply. If the current is not limited to a safe value, the SCR will be destroyed.

1.5.3 Latching and Holding Current

The minimum anode current that will cause the device to remain in forward conduction stage as it switches from forward-blocking is called the latching current I_L. If the thyristor is already in forward conduction stage and the anode current is reduced, then the device can move its operating mode from forward-conduction stage back to forward-blocking stage. The minimum value of anode current necessary to keep the device in forward-conduction after it has been operating at a high anode current value is called the holding current I_H. The holding current value is lower than the latching current value.

1.5.4 SCR Ratings

A data sheet for a typical thyristor follows this section and includes the following information:

Surge Current Rating (I_{FM})—The surge current rating (*I*FM) of an SCR is the peak anode current an SCR can handle for a short duration.

Latching Current (I_L)—A minimum anode current must flow through the SCR in order for it to stay ON initially after the gate signal is removed. This current is called the latching current (*IL*).

Holding Current (I_H)—After the SCR is latched on, a certain minimum value of anode current is needed to maintain conduction. If the anode current is reduced below this minimum value, the SCR will turn OFF.

Peak Repetitive Reverse Voltage (*V*RRM)—The maximum instantaneous reverse voltage that an SCR can withstand, without breakdown.

Peak Repetitive Forward Blocking Voltage (*V*DRM)—The maximum instantaneous voltage that the SCR can block in the forward direction. If the *V*DRM rating is exceeded, the SCR will conduct without a gate voltage.

Nonrepetitive Peak Reverse Voltage (*V*RSM)—The maximum transient reverse voltage that the SCR can withstand.

Maximum Gate Trigger Current (*I*GTM)—The maximum DC gate current allowed to turn the SCR.

Minimum Gate Trigger Voltage (V_{GT})—The minimum DC gate-to-cathode voltage required to trigger the SCR.

Minimum Gate Trigger Current (I_{GT})—The minimum DC gate current necessary to turn the SCR ON.

1.5.5 Effect of dv/dt and snubber circuits

When the SCR is forward biased, junctions J1 and J3 are forward biased and junction J2 is reverse biased. This reverse biased junction J2 exhibits the characteristics of a capacitor. Therefore, if the rate of forward voltage applied is very high across the SCR, charging current flows through the junction J2 is high enough to turn ON the SCR even without any gate signal. The snubber circuit consists of a series combination of capacitor and resistor which is connected across the SCR. This also consists an inductance in series with the SCR to prevent the high di/dt. When the switch closed, a sudden voltage appears across the SCR which is bypassed to the RC network. This is because the capacitor acts as a short circuit which reduces the voltage across the SCR to zero. If the SCR is turned ON, the capacitor starts discharging which causes a high current to flow through the SCR. To limit the discharge current, a small resistance is placed in series with the capacitor.

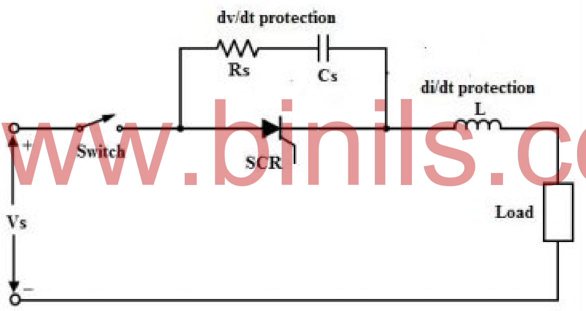


Figure 1.6: Snubber Circuits

1.5.6 Effect of rate of rise of current (di/dt)

The anode current starts flowing through the SCR when it is turned ON by the application of gate signal. This anode current takes some finite time to spread across the junctions of an SCR. For a good working of SCR, this current must spread uniformly over the surface of the junction. If the rate of rise of anode current (di/dt) is high results a non-uniform spreading of current over the junction. Due to the high current density, this further leads to form local hot spots near the gate-cathode junction. This effect may damage the SCR due to overheating. Hence, during turn ON process of SCR, the di/dt must be kept below the specified limits.

To prevent the high rate of change of current, an inductor is connected in series with thyristor.

1.6RESISTANCETRIGGERING(R-Triggering):

The following circuit shows the resistance triggering.

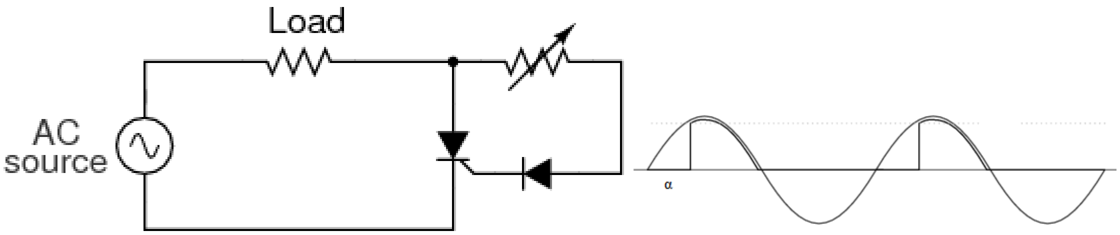


Figure1.7: R-Triggering

- In this method, the variable resistance R is used to control the gate current.
- Depending upon the value of R, when the magnitude of the gate current reaches the sufficient value (latching current of the device) the SCR starts to conduct.
- The diode D is called as blocking diode. It prevents the gate cathode junction from getting damaged in the negative half cycle.
- Using this method we can achieve maximum firing angle of 90°.

1.7RCTriggering

The following circuit shows the resistance-capacitance triggering.

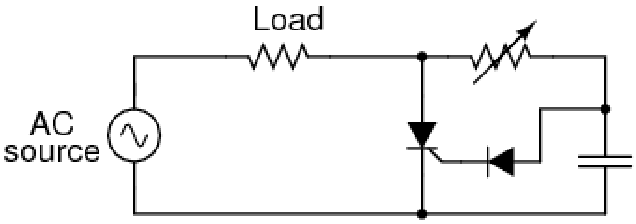


Figure1.8: RC-Triggering

- By using this method we can achieve firing angle up to 180°.

- In the positive half cycle, the capacitor is charged through the variable resistance R up to the peak value of the applied voltage.
- The variable resistor R controls the charging time of the capacitor.
- The Voltage across the capacitor is applied across the gate. When this voltage reaches the gate threshold voltage the thyristor starts conduction.

The diode D is called as blocking diode. It prevents the gate cathode junction from getting damaged in the negative half cycle.

1.8 UJT Triggering

AC input voltage is stepped down and rectified. The portion of the positive half cycle is clipped by zener diode.

The capacitor charges through R. When the capacitor voltage reaches ηVz, UJT conducts and sharp pulses produced across primary of the pulse transformer where ‘η’ is intrinsic stand off ratio. The sharp pulses are used to trigger the SCR.

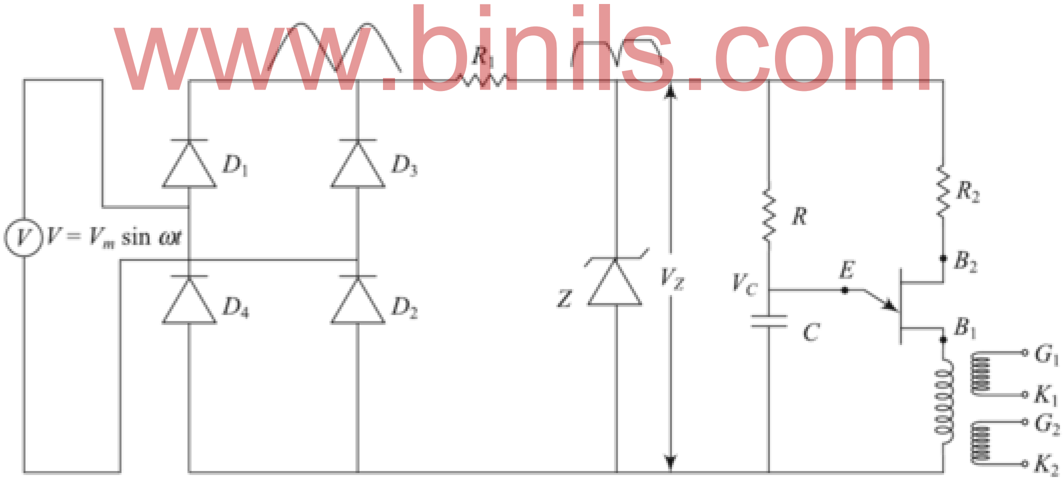


Figure 1.9: UJT Trigger Circuit

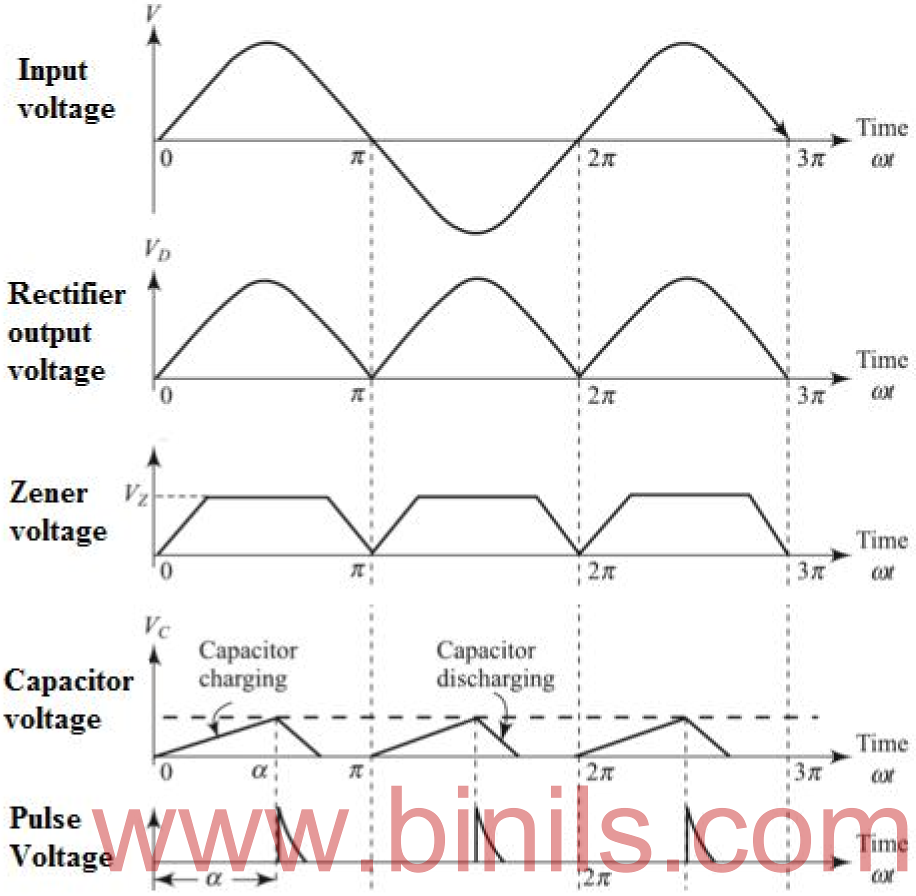


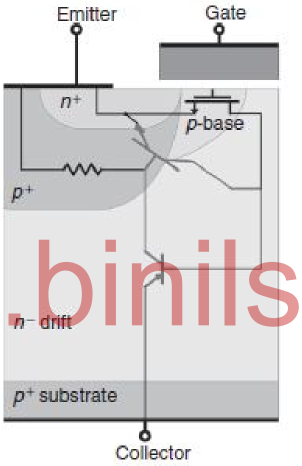
Figure 1.9: UJT Trigger circuit Waveforms

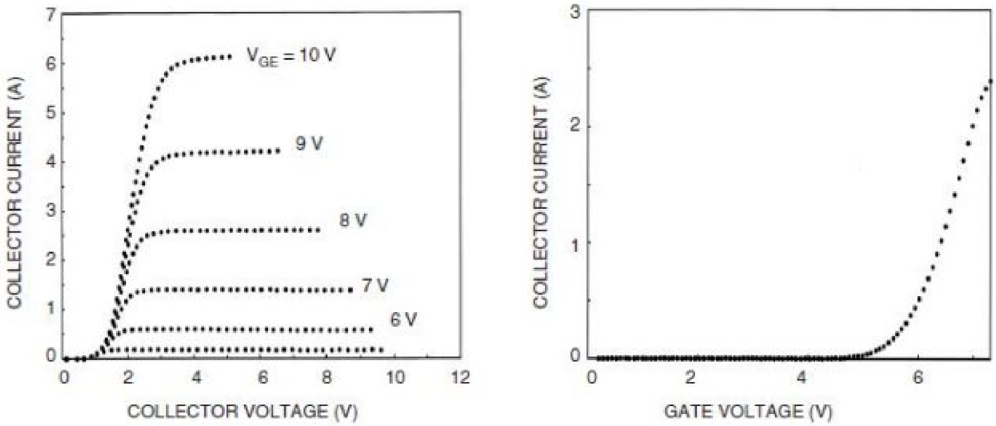
1.9 Insulated Gate Bipolar Transistor

Power BJTs have good on-state characteristics but have long switching times especially at turn-off. Since they are current-controlled devices, they require complex base drive circuits to provide the base current during on-state, which increases the power loss in the device. On the other hand power MOSFETs are voltage-controlled devices, which require very small current during switching period and hence have simple gate drive requirements. Power MOSFETs are majority carrier devices, which exhibit very high switching speeds. But the unipolar nature of the power MOSFETs causes inferior conduction characteristics as the voltage rating is increased above 200V. Therefore their on state resistance increases with increasing in applied voltage.

In order to improve the power device performance, a device which has low on-state drop and insulated gate is needed. This concept gave rise to the commercially available IGBTs with superior on-state characteristics, good switching speed and excellent safe operating area.

When a positive potential is applied to the gate and exceeds the threshold voltage an n channel is formed, which provides a path for electrons to flow into the n− drift region. The pn junction between the p+ substrate and n− drift region is forward biased and holes are injected into the drift region. The electrons in the drift region recombine with these holes to maintain space charge neutrality. The remaining holes are collected at the emitter, causing a vertical current flow between the emitter and collector.





IGBT: (a) forward characteristics and (b) transfer characteristics.

Figure 1.9: IGBT symbol and Characteristics

1.10 MOSFET

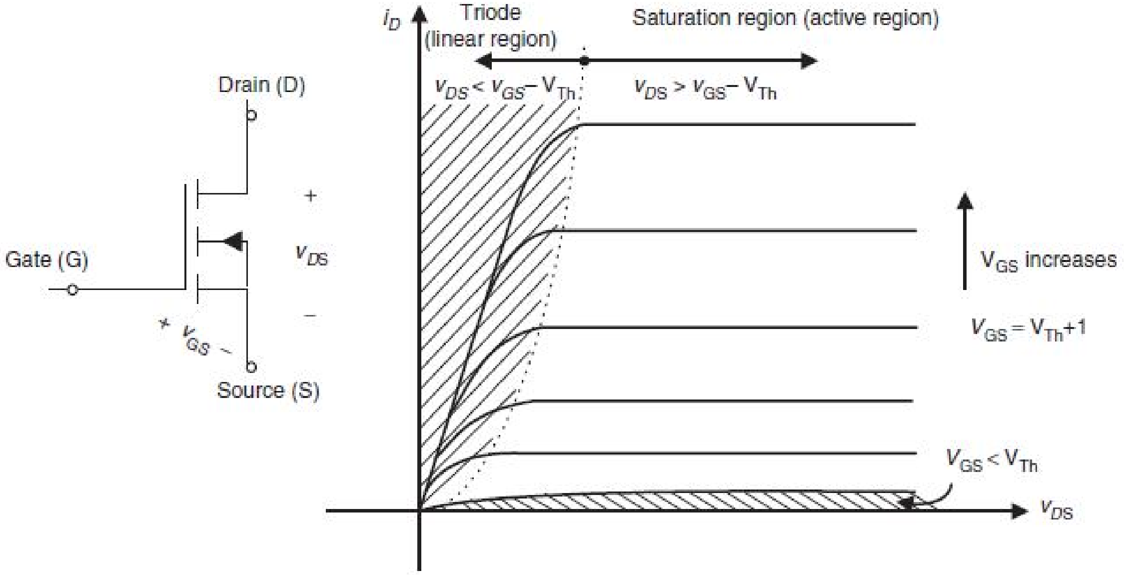


Figure 1.10: MOSFET symbol and Characteristics

Most of the MOSFET devices used in power electronics applications are of the n-channel, enhancement-type are shown in figure. For the MOSFET to carry drain current, a channel between the drain and the source must be created. This occurs when the gate-to-source voltage exceeds the device threshold voltage, V_{Th}. For $v_{GS} > V_{Th}$, the device can be either in the triode region, (constant resistance) region, or in the saturation region, depending on the value of v_{DS}. For the given v_{GS}, with small v_{DS} ($v_{DS} < v_{GS} - V_{Th}$), the device operates in the triode region (saturation region in the BJT), and for larger v_{DS}($v_{DS} > v_{GS} - V_{Th}$), the device enters the saturation region (active region in the BJT). For $v_{GS} < V_{Th}$, the device turns off, with drain current almost equals zero. Under both regions of operation, the gate current is almost zero. Due to this reason the MOSFET is known as a voltage-driven device, and it, requires simple gate control circuit. The characteristic curves in Fig. shows that there are three distinct regions of operation labeled as triode region, saturation region, and cut-off-region. The MOSFET will act as a switch when it is operated in saturation (ON Condition) and cutoff (OFF Condition) region. It will act as an amplifier when it is operated in linear region (triode region).

1.11 Commutation

The turn OFF process of an SCR is called commutation. The term commutation means the transfer of currents from one path to another. The commutation circuit does this job by reduces the forward current to zero so as to turn OFF the SCR or Thyristor.

To turn OFF the conducting SCR the following conditions must be satisfied.

- The anode or forward current of SCR must be reduced to zero or below the level of holding current.
- A sufficient reverse voltage must be applied across the SCR to regain its forward blocking state.

1.11.1 Methods of Commutation

The reverse voltage which causes to commutate the SCR is called commutation voltage. The commutation methods are classified into two major types. Those are 1) Forced commutation and 2) Natural commutation.

1.11.1.1 Natural Commutation

It happens only when the input is an AC Supply. If the SCR is connected to an AC supply, at every end of the positive half cycle the anode current goes through the natural current zero and also immediately a reverse voltage is applied across the SCR. These are the conditions to turn OFF the SCR.

This method of commutation is also called as source commutation, or line commutation, or class F commutation. This commutation is possible with line commutated inverters, controlled rectifiers, cyclo converters and AC voltage regulators because the input supply is AC.

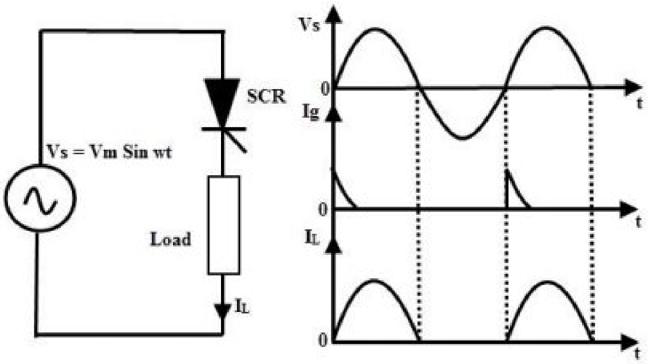


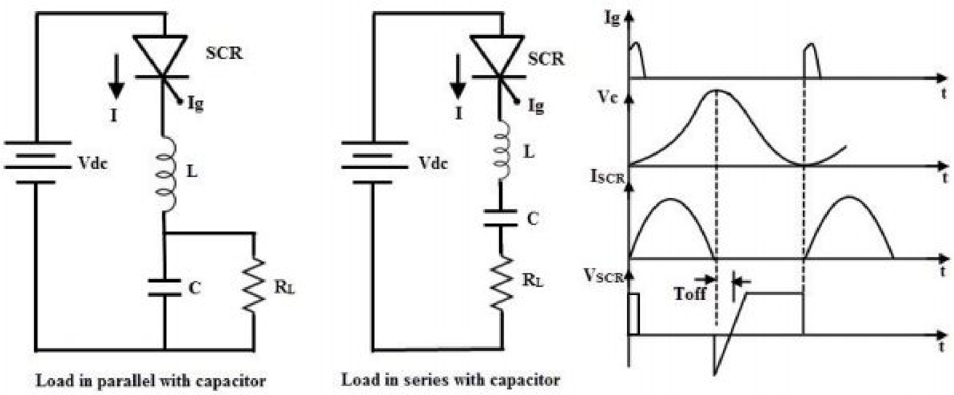
Figure 1.11: Natural Commutation

1.11.1.2 Forced Commutation

In case of DC circuits, there is no natural current zero to turn OFF the SCR. In such circuits, forward current must be forced to zero with an external circuit hence named as forced commutation. This commutating circuit consists of components like inductors and capacitors called as commutating components. These commutating components apply a reverse voltage across the SCR that immediately bring the anode current in the SCR to zero. Based on the zero current achievement forced commutation is classified into different types such as class A, B, C, D, and E.

1.11.1.3 Class A Commutation

This is also known as self commutation, or resonant commutation, or load commutation. In this commutation, the source of commutation voltage is in the load. This load must be an under damped R-L-C circuit so that natural zero of current is obtained. The commutating components L and C are connected either parallel or series with the load resistance R. The waveforms of SCR current, voltage and capacitor voltage are shown in figure.



Load in parallel with capacitor

Load in series with capacitor

Figure 1.12: Class A Commutation

The value of load resistance and commutating components are so selected that they form a under damped resonant circuit to produce natural zero. When the thyristor or SCR is triggered, the forward currents starts flowing through it and during this the capacitor is charged up to the value of E. Once the capacitor is fully charged (more than the supply source voltage) the SCR becomes reverse biased and hence the commutation of the device is taken place. The time for switching OFF the SCR depends on the resonant frequency which further depends on the L and C components.

1.11.1.4 Class B Commutation

This is also a self commutation circuit in which the commutation of SCR is achieved automatically by L and C components. In this, the LC resonant circuit is connected across the SCR but not in series with load as in case of class A commutation and hence the L and C components do not carry the load current.

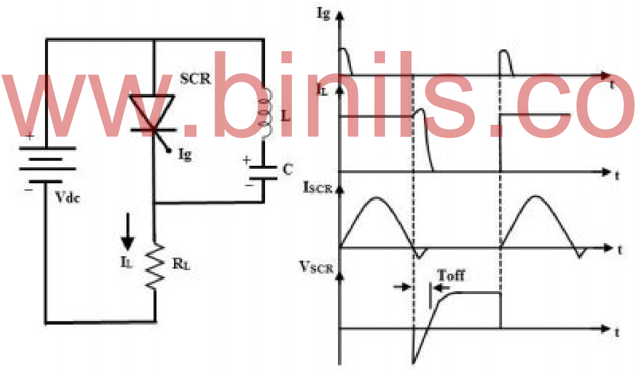


Figure 1.13: Class B Commutation

When the DC supply is applied to the circuit, the capacitor charges to a value of ‘E’ with an upper plate positive and lower plate negative. Once the SCR is turned ON, the capacitor is starts discharging through C+ – L – T – C-. When the capacitor is fully discharged, it starts charging with a reverse polarity. Hence a reverse voltage applied across the SCR which causes the commutating current I_C to opposes the load current I_L. When the commutating current Ic is higher than the load current, the SCR will automatically turn OFF and the capacitor charges with original polarity. In the above process, the SCR is turned ON for some time and then automatically turned OFF for some time. This is a continuous process and the desired frequency depends on the values of L and C. This type of commutation is mostly used in chopper circuits.

1.11.1.5 Class C Commutation

In this commutation method, the main SCR which is to be commutated is connected in series with the load. An additional or complementary SCR is connected in series with the resistor ‘R’. This method is also called as complementary commutation. In this, SCR turns OFF with a reverse voltage of a charged capacitor. The figure shows the complementary commutation with appropriate waveforms.

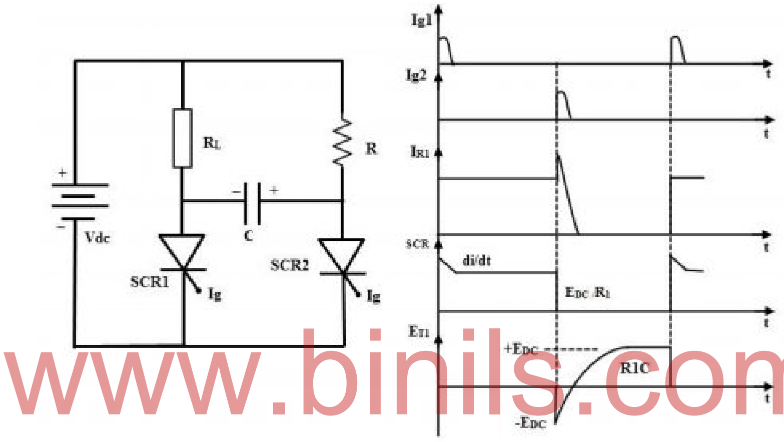


Figure 1.14: Class C Commutation

Initially, both SCRs are in OFF state so the capacitor voltage is also zero. When the SCR1 or main SCR is triggered, current starts flowing in two directions, one path is E+ – R1 – SCR1 – E- and another path is the charging current E+ – R2- C+ – C- SCR1 – E- . Therefore, the capacitor starts charging up to the value of E.

When the SCR2 is triggered, it is turned ON and simultaneously a negative voltage is applied across the SCR1. So this reverse voltage across the SCR1 immediately causes to turn OFF the SCR1. Now the capacitor starts charging with a reverse polarity through the path of E+ – R1- C+ – C- SCR2 – E-. If the SCR 1 is triggered, discharging current of the capacitor turns OFF the SCR2.

This commutation is mainly used in single phase inverters with a centre tapped transformers. The Mc Murray Bedford inverter is the best example of this commutation circuit.

This is a very reliable method of commutation and it is also useful in circuits even at frequencies below 1000Hz.

1.11.1.6 Class D Commutation

This is also called as auxiliary commutation because it uses an auxiliary SCR to switch the charged capacitor. In this, the main SCR is commutated by the auxiliary SCR. The main SCR with load resistance forms the power circuit while the diode D, inductor L and SCR2 forms the commutation circuit.

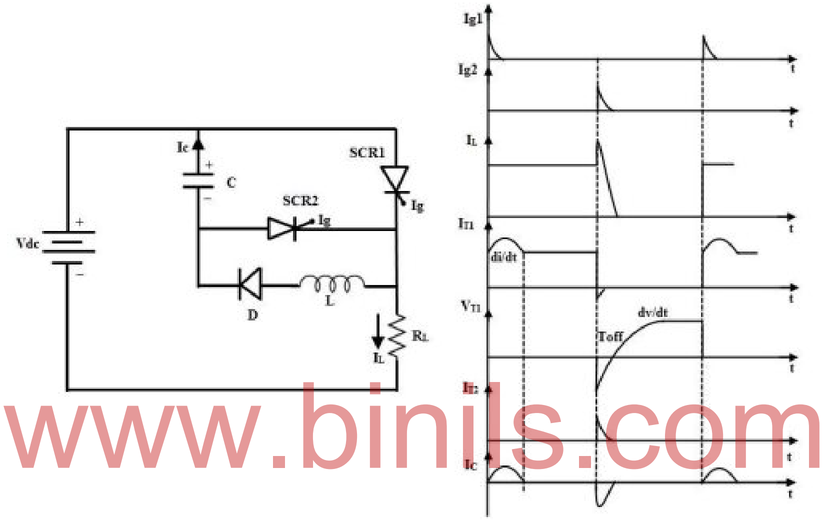


Figure 1.15: Class D Commutation

When the supply voltage E is applied, both SCRs are in OFF state and hence the capacitor voltage is zero. In order to charge the capacitor, SCR2 must be triggered first. So the capacitor charges through the path E+ – C+ – C- – SCR2- R- E-.

When the capacitor is fully charged the SCR2 becomes turned OFF because no current will flow through the SCR2 when capacitor is charged fully. If the SCR1 is triggered, the current will flows in two directions; one is the load current path E+ – SCR1- R- E- and another one is commutation current path C+ – SCR1- L- D- C.

As soon as the capacitor completely discharges, the inductor ‘L’ is fully charged. This inductor charges the capacitor in reverse direction. When inductor completely discharges the capacitor is charged fully. Now the capacitor is unable to discharge because of the reversed diode.When the SCR2 is triggered capacitor starts discharging through C+ – SCR2- SCR1- C-. When this discharging current is more than the load current the SCR1 becomes turned OFF.

Again, the capacitor starts charging through the SCR2 to a supply voltage E and then the SCR2 is turned OFF. Therefore, both SCRs are turned OFF and the above cyclic process is repeated. This commutation method is mainly used in inverters and also used in the Jones chopper circuit.

1.11.1.7 Class E Commutation

This is also known as external pulse commutation. In this, an external pulse source is used to produce the reverse voltage across the SCR. The circuit below shows the class E commutation circuit which uses a pulse transformer to produce the commutating pulse and is designed with tight coupling between the primary and secondary with a small air gap.

When the SCR is triggered, load current flows through the pulse transformer. If the SCR need to be commutated, pulse duration equal to the turn OFF time of the SCR is applied. If the pulse is applied to the primary of the pulse transformer, an emf or voltage is induced in the secondary of the pulse transformer.

This induced voltage is applied across the SCR as a reverse polarity and hence the SCR is turned OFF. The capacitor offers a very low or zero impedance to the high frequency pulse.

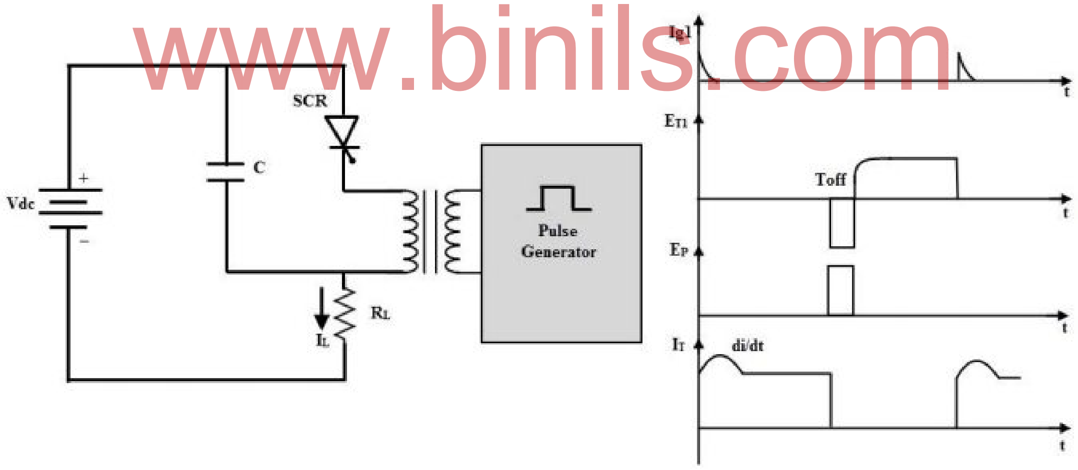


Figure 1.16: Class E Commutation

UNIT II

LINE COMMUTATED POWER CONTROL CIRCUITS

2.1 Line Commutated Converters

When the input AC supply voltage reverses the thyristor becomes reverse biased and hence turns off. There are several types of power converters which use ac line commutation. These are referred to as line commutated converters.

Different types of line commutated converters are

- Phase controlled rectifiers which are AC to DC converters.
- AC to AC converters
  - AC voltage controllers, which convert input ac voltage into variable ac output voltage at the same frequency.
  - Cyclo converters, which give low output frequencies.

All these power converters operate from ac power supply at a fixed supply voltage and at a fixed input supply frequency. Hence they use ac line commutation for turning off the conducting thyristors.

2.2 Principle of Phase Controlled Converter Operation

In a phase controlled rectifier circuit a high current and a high power thyristor device (SCR) for conversion of ac input power into dc output power is used. Phase controlled rectifier circuits are used to provide a variable AC voltage output voltage from a constant AC input voltage.

We can vary, the average value (dc value) of the output load voltage is varied (and hence the average dc load current) by varying the thyristor firing angle. Thyristor conduction angle δ is varied from 180^0 to 0^0 by varying the trigger angle α from 0^0 to 180^0, where thyristor conduction angle $\delta = (\pi - \alpha)$.

2.2.1 Applications of Phase Controlled Rectifiers

- DC motor control in steel mills, paper and textile mills employing dc motor
- drives.
- AC fed traction system using dc traction motor.
- Electro-chemical and electro-metallurgical process controls.
- Portable hand tool drives.
- Variable speed industrial drives.
- Battery charges.
- High voltage DC transmission.
- Uninterruptible power supply systems (UPS).

2.3 Controlled Rectifiers

Controlled rectifiers are line commutated ac to dc power converters which are used to convert a fixed voltage, fixed frequency ac power supply into variable dc output voltage.

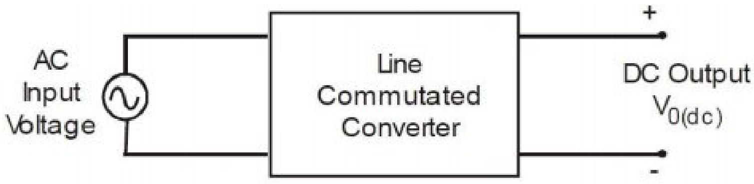


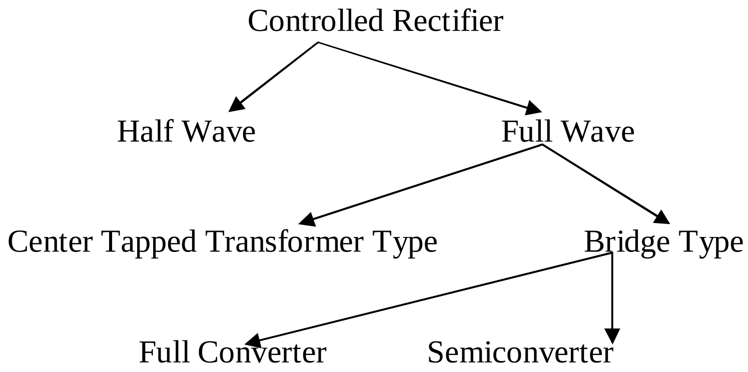
Figure 2.1: Controlled Rectifiers

2.3.1 TYPES OF CONTROLLED RECTIFIERS

Half wave controlled rectifier which uses a single thyristor device (which provides output control only in one half cycle of input ac supply, and it provides low dc output).

semi-converter (half controlled bridge converter, using two SCR’s and two diodes, to provide single quadrant operation).

full converter (fully controlled bridge converter which requires four SCR's, to provide two quadrant operation).



2.4 Single Phase Full Converter (Fully Controlled Bridge Converter)

The circuit diagram of a single phase fully controlled bridge converter is shown in the figure with a resistive and highly inductive load so that the load current is continuous and ripple free (constant load current operation). The fully controlled bridge converter consists of four thyristors T_1 , T_2 , T_3 and T_4 connected in the form of full wave bridge configuration as shown in the figure.

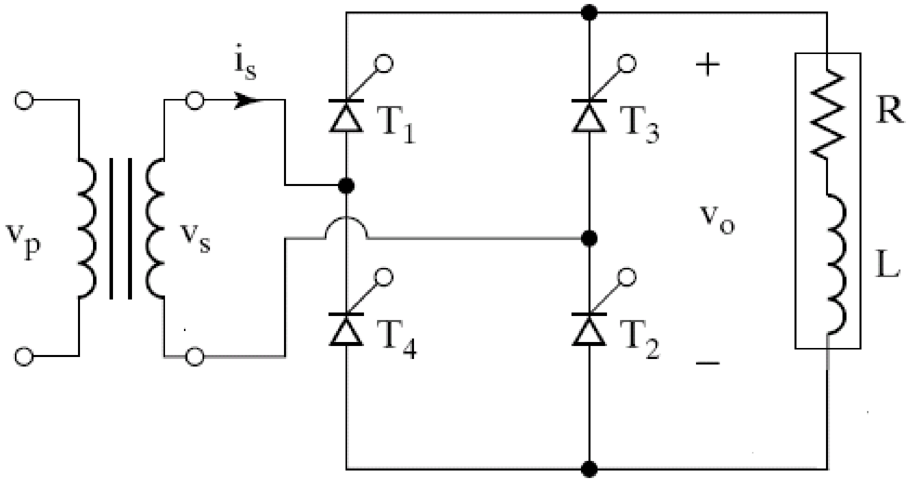
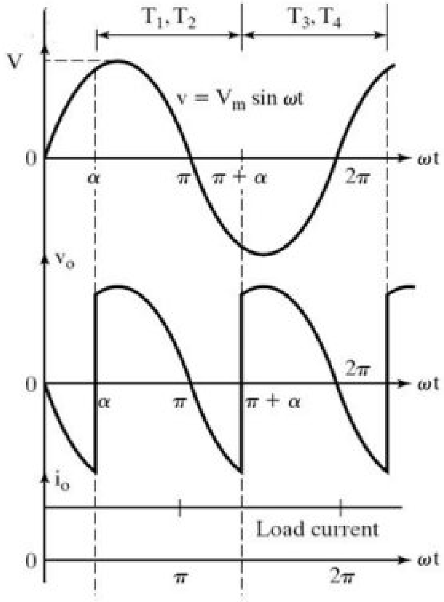


Figure 2.2: Single Phase Full Converter

Each thyristor is controlled and turned on by its gating signal and naturally turned off when a reverse voltage appears across it. During the positive half cycle the upper line of the transformer secondary winding is at a positive potential with respect to the lower end. The thyristors T_1 andT_2 are forward biased during the time interval $\omega t = 0$ to π . The thyristors T_1 andT_2 are triggered simultaneously at $\omega t = \alpha$; $(0 \leq \alpha \leq \pi)$. The load is connected to the input supply through the conducting thyristors T_1 andT_2. The output voltage across the load follows the input supply voltage. Due to the inductive load T_1 andT_2 will continue to conduct beyond $\omega t = \pi$, even though the input voltage becomes negative. $T1$ and $T2$ conduct together during the time period α to $(\pi + \alpha)$, for a time duration of π radians (conduction angle of each thyristor = 180^0) During the negative half cycle of input supply voltage from $\omega t = \pi$ to 2π the thyristors T_3 and T_4 are forward biased. T_3 and T_4 are triggered at $\omega t = (\pi + \alpha)$. As soon as the thyristors T_3 and T_4 are triggered a reverse voltage appears across the thyristors T_1 and T_2 . They naturally gets turned off and the load current is transferred from T_1 and T_2 to the thyristors T_3 and T_4. The output voltage across the load follows the supply voltage after $\pi + \alpha$ upto $(2\pi + \alpha)$. In the next positive half cycle when T_1 andT_2 are triggered, T_3 and T_4 are reverse biased and they gets turned off. The figure shows the waveforms of the input supply voltage, the output load voltage, the constant load current with negligible ripple and the input supply current.



igure 2.3: VI Characteristics of Single Phase Full Converter

$$V_{dc} = \frac{1}{\pi}\left[\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t . d(\omega t)\right]$$

$$= \frac{V_m}{\pi}\left[\int_{\alpha}^{\pi+\alpha} \sin\omega t . d(\omega t)\right]$$

$$= \frac{V_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi+\alpha}$$

$$= \frac{V_m}{\pi}\left[-\cos(\pi+\alpha)+\cos\alpha\right]$$

$$\cos(\pi+\alpha) = -\cos\alpha$$

Therefore $V_{O(dc)} = V_{dc} = \frac{2V_m}{\pi}\cos\alpha$

By varying the trigger angle α we can vary the output dc voltage across the load. Thus it is possible to control the dc output voltage by changing the trigger angle α. For trigger angle α in the range of 0 to 90 degrees (*i.e.*, $0 \leq \alpha \leq 90^{\circ}$), V_{dc} is positive and the average dc load current I_{dc} is also positive. The average or dc output power P_{dc} is positive, hence the circuit operates as a controlled rectifier to convert ac supply voltage into dc output power.

For trigger angle $\alpha > 90^{\circ}$, cosα becomes negative and hence the average dc output voltage V_{dc} becomes negative, but the load current flows in the same positive direction i.e., I_{dc} is positive . Hence the output power becomes negative. This means that the power flows from the load circuit to the input ac source. This is referred to as line commutated inverter operation. During the inverter mode operation for $\alpha > 90^{0}$ the load energy can be fed back from the load circuit to the input ac source.

2.5 Single Phase Dual Converter

In dual converter, two controlled rectifier are connected back to back. This arrangement, known as a dual converter configuration, allows four-quadrant operation of the drive. Converter 1 provides positive load current i_d , while Converter 2 provides negative load current. The motor can work in forward motoring, forward braking, reverse motoring, and reverse braking. These operating modes are shown in Fig.

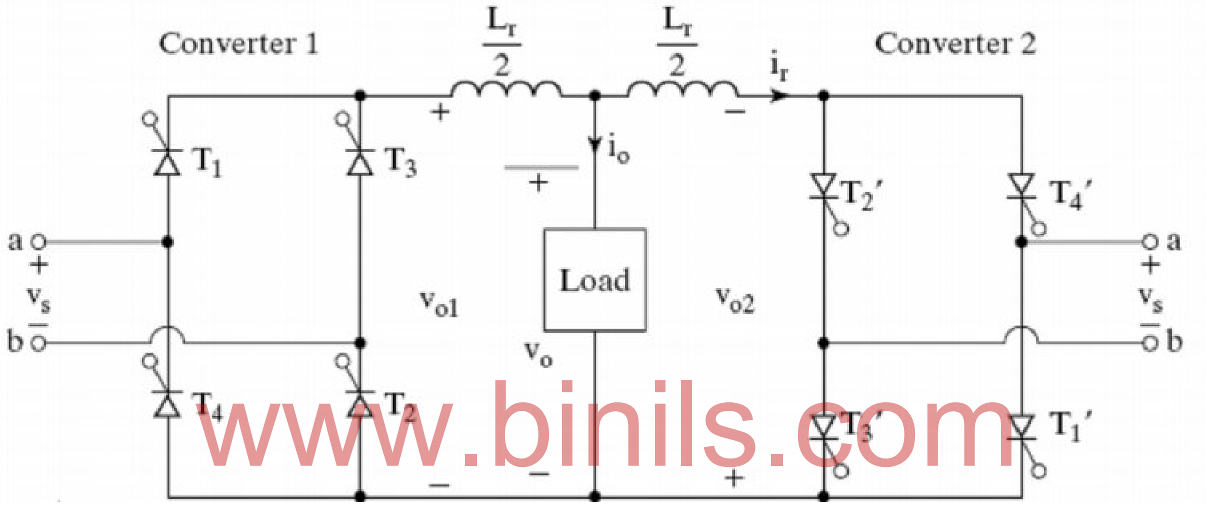


Figure 2.4: Single Phase dual Converter

In non circulating current mode, only one converter is switched on at a time while the second converter is switched off. When the converter 1 is switched on and the gate trigger signals are given to the gates of thyristors in converter. The average output voltage across the load, can be varied by adjusting the trigger angle α1 of the converter 1. If α1 is less than 90^0, the converter 1 operates as a controlled rectifier and converts the input ac power into dc output power to feed the load. $V dc$ and $I dc$ are both positive and the operation occurs in the first quadrant. The average output power $P dc = V dc \times I dc$ is positive. The power flows from the input ac supply to the load. When α1 is increased above 90^0 converter 1 operates as a line commutated inverter and $V dc$ becomes negative while $I dc$ is positive and the output power $P dc$ becomes negative. The power is fed back from the load circuit to the input ac source through the converter 1. The load current falls to zero when the load energy is utilized completely.

In circulating current mode of operation both the converters 1 and 2 are switched on and operated simultaneously. If converter 1 is operated as a controlled rectifier by adjusting the trigger angle α1 between 0 to 90^0 the second converter 2 is operated as a line commutated inverter by increasing its trigger angle α2 above 90^0. The trigger angles α 1 and α2 are adjusted such that they produce the same average dc output voltage across the load terminals.

$$\alpha\,1+\alpha\,2=180^0$$

The advantage of the circulating current mode of operation is that the load current can be reversed at a faster rate. The disadvantage of the circulating current mode of operation is that a current flows continuously in the dual converter circuit even at times when the load current is zero. Hence the current limiting inductors (reactors) are connected to limit the peak circulating current within specified value.

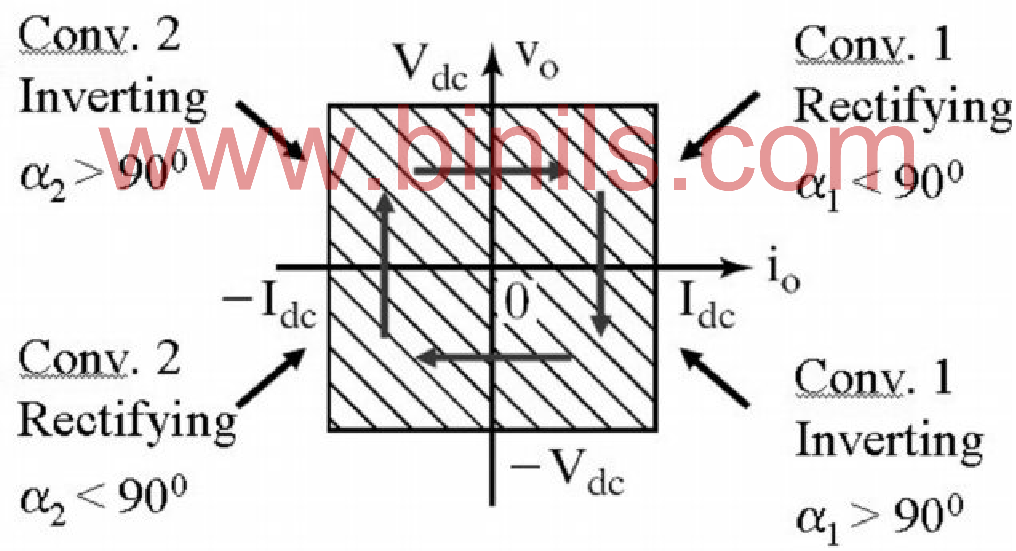


Figure 2.5: Rotation of Single Phase dual Converter

2.6 Three Phase Full Converter

Three phase full converter is a fully controlled bridge rectifier using six thyristors connected in the form of a full wave bridge configuration. All the six thyristors are controlled switches which are turned on at a appropriate times by applying suitable gate trigger signals. The three phase full converter is extensively used in industrial power applications upto about 120kW output power level, where two quadrant operation is required. The figure shows a three phase full converter with high inductive load. This circuit is also known as three phase full wave bridge or a six pulse converter. The thyristors are triggered at an interval of π/3.

$$V_{dc} = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha$$

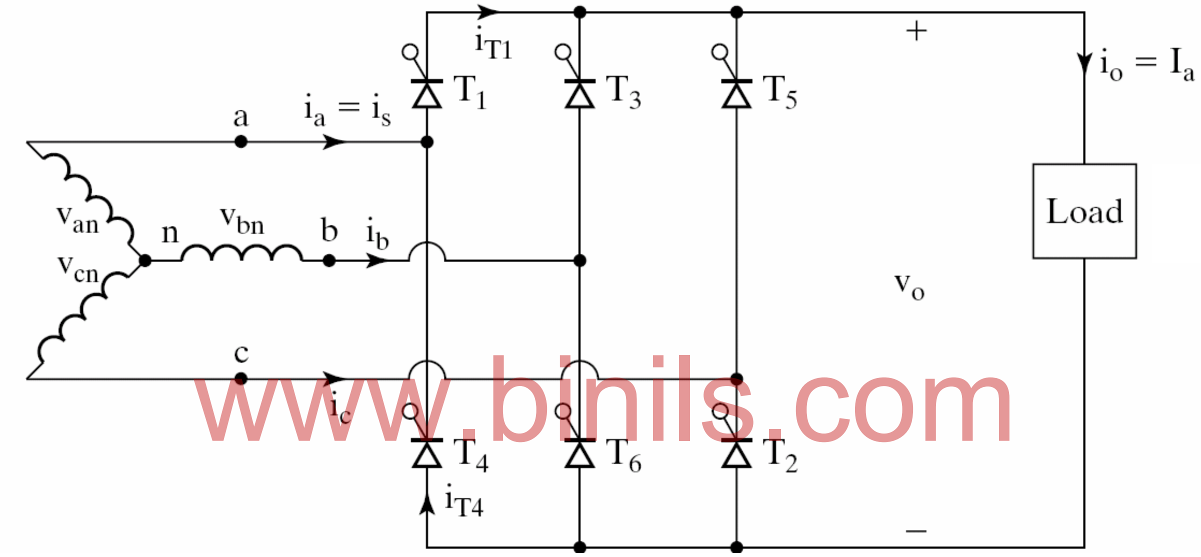


Figure 2.6: Three Phase Full Converter

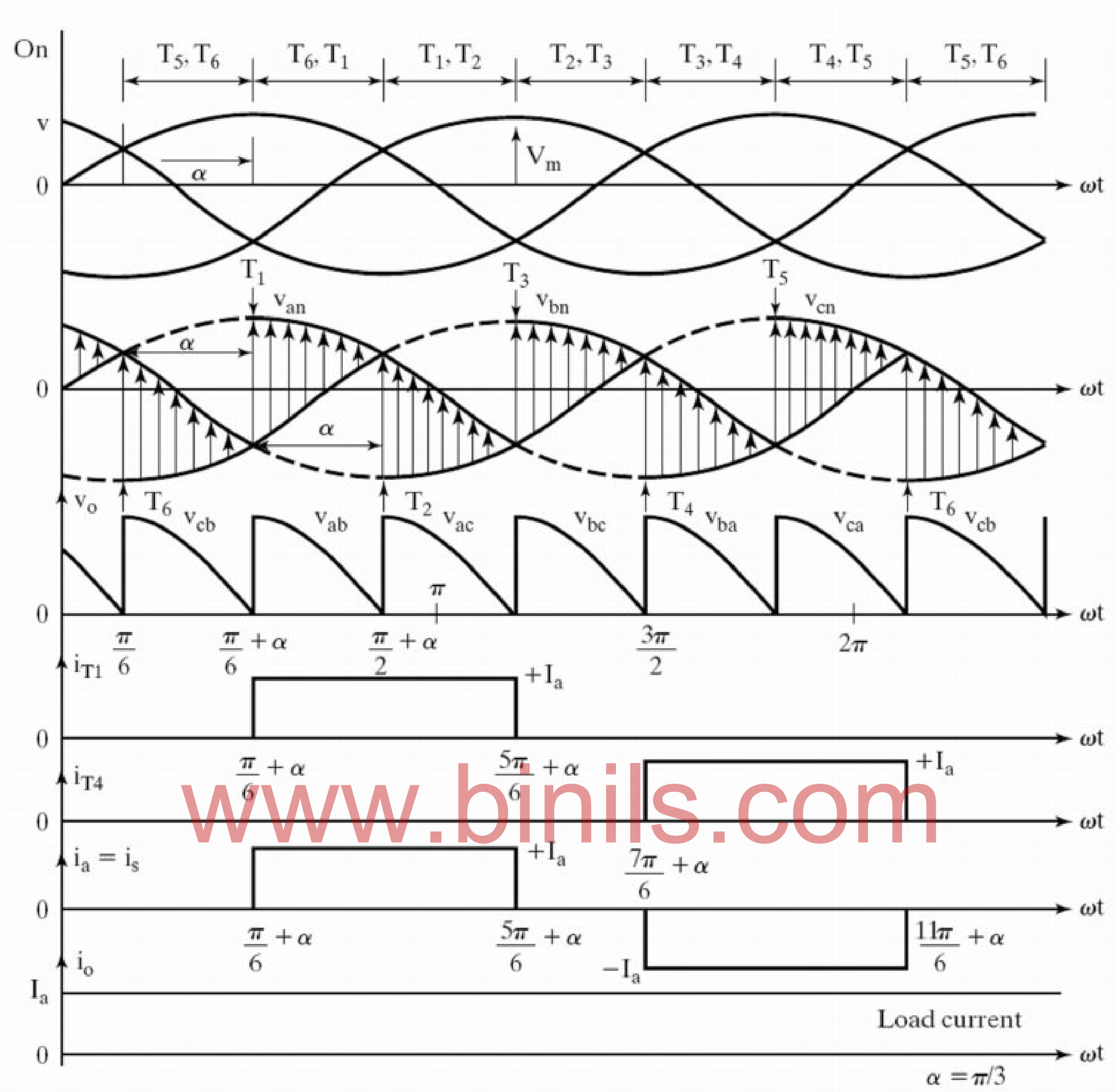


Figure 2.7: Characteristics of Three Phase Full Converter

2.7 Three Phase Dual Converters

In many variable speed drives, the four quadrant operation is generally required. Three phase dual converters are extensively used in such applications up to 2 kW level. Figure shows three phase dual converters where two three phase full converters are connected back to back across a common load.

The operation of a three phase dual converter is similar to that of a single phase dual converter system. The main difference between them is being that a three phase dual converter gives much higher dc output voltage and higher dc output power than a single phase dual converter system. But the drawback is that the three phase dual converter is more expensive and the design of control circuit is more complex.

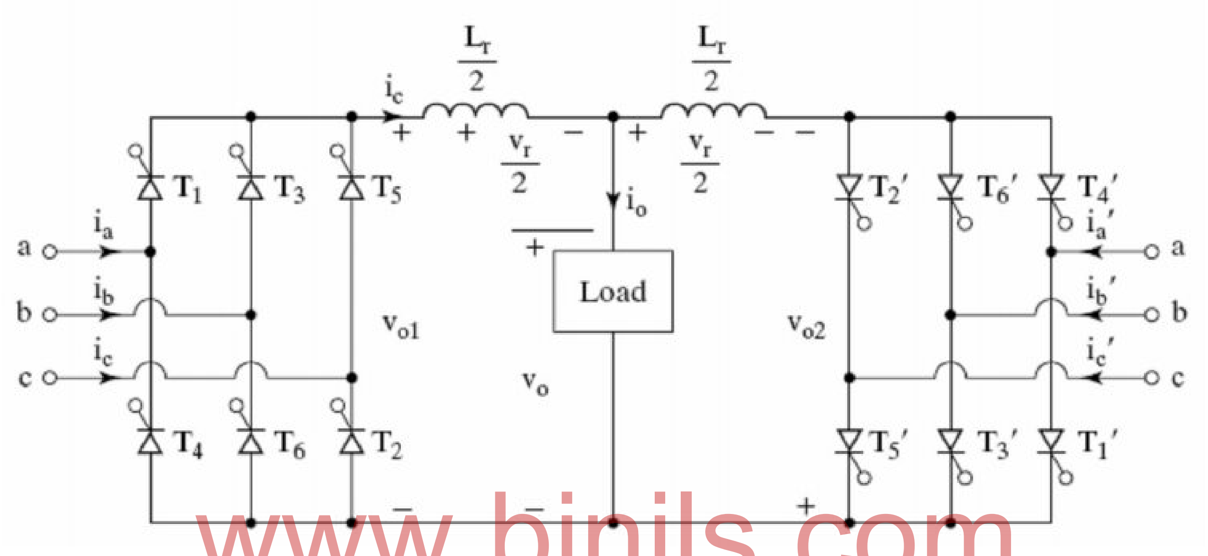


Figure 2.8: Three Phase Dual Converter

In non circulating current mode of operation only one converter is switched on at a time. When the converter number 1 is switched on and the gate signals are applied to the thyristors. The converter 1 converts the input ac supply and feeds a dc power to the load. Power flows from the ac supply to the load during the rectification mode. When the trigger angle $\alpha1$ is increased above 90^0 , $V\ dc$ becomes negative where as $I\ dc$ is positive because the thyristors of converter 1 conduct in only one direction. For $\alpha1 > 90^0$ converter 1 operates in the inversion mode & the load energy is supplied back to the ac supply. We obtain a reverse or negative load current when the converter 2 is switched ON. The average or dc output voltage and the average load current are controlled by adjusting the trigger angle $\alpha2$ of the thyristors of converter 2.

Both the converters are switched on at the same time in circulating current mode of operation. One converter operates in the rectification mode while the other operates in the inversion mode. Trigger angles $\alpha1$ & $\alpha2$ are adjusted such that $(\alpha1 + \alpha2) = 180^0$. When $\alpha1 < 90^0$, converter 1 operates as a controlled rectifier. When α2 is greater than 90^0 , converter 2 operates in the inversion mode. V_{dc}, I_{dc}, P_{dc} are positive. When $\alpha 2 < 90^0$, converter 2 operates as a controlled rectifier. When α1 is made greater than 90^0 , converter 1 operates as an Inverter. V_{dc} and I_{dc} are negative while P_{dc} is positive.

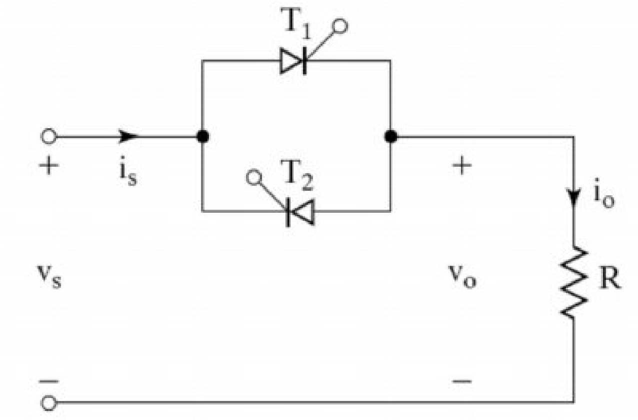
2.8 AC Voltage Controllers

An AC voltage controller is a converter that converts an AC voltage to Variable AC voltage. Such a converter is also called as AC-AC converter. The most common applications of AC voltage controllers are light-dimmer circuits and speed control of induction motors.

2.8.1 Single-Phase AC Voltage Controllers with R Loads

Positive half-cycle: *S*1 is forward biased and *S*2 is reverse biased. Before *S*1 conducts, the output voltage is zero and the voltage across the SCRs is the same as the source voltage. Suppose *S*1 is fired at α, then, the output voltage is equal to the input voltage and the voltage across the SCRs is zero. At π, *S*1 is turned off because of natural commutation.

Negative half-cycle: *S*2 is forward biased and *S*1 is reverse biased. Before *S*2 conducts, the output voltage is zero and the voltage across the SCRs is the same as the source voltage. Suppose *S*2 is fired at π +α, then, the output voltage is equal to the input voltage and the voltage across the SCRs is zero. At 2π, *S*2 is turned off because of natural commutation.



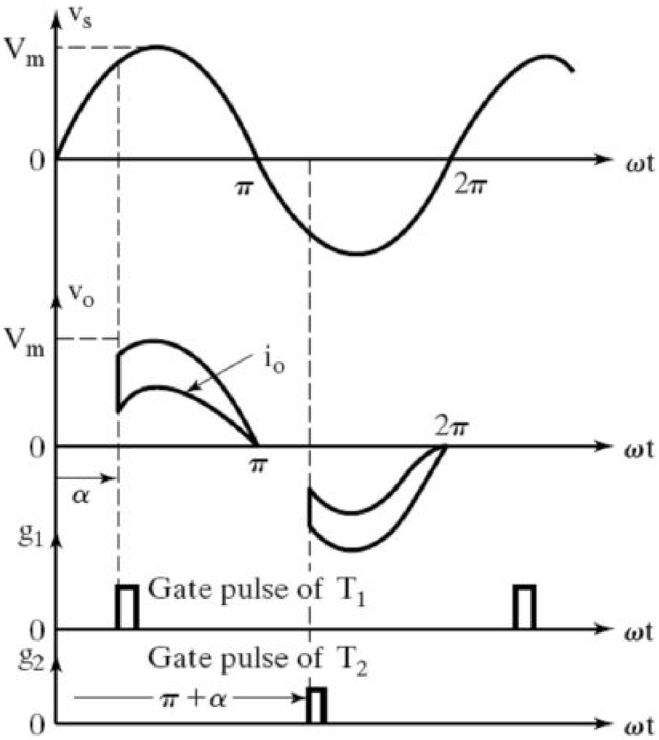


Figure 2.8: Single Phase AC Voltage Controller

2.9 Single Phase Full Wave Ac Voltage Controller (Bidirectional Controller) With RL Load

A single phase full wave ac voltage controller circuit (bidirectional controller) with an RL load using two thyristors T_1 and T_2 *are* connected in parallel and is shown in the figure.

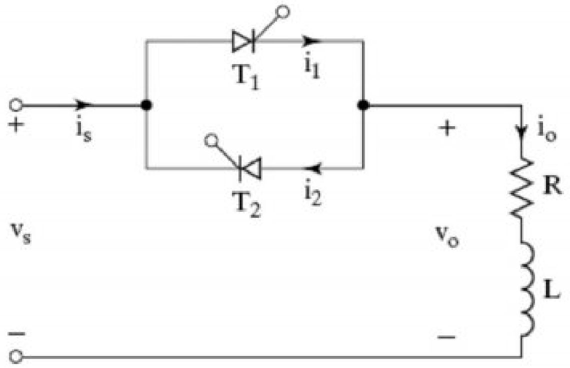


Figure 2.9: Bidirectional Controller with Single Phase AC Voltage Controller

The thyristor T_1 is forward biased during the positive half cycle of input supply. Let us assume that T_1 is triggered at $\omega t = \alpha$, by applying a suitable gate trigger pulse to T_1 during the positive half cycle of input supply. The output voltage across the load follows the input supply voltage when T_1 is ON. The load current i_0 flows through the thyristor T_1 and through the load in the downward direction. Due to the inductance in the load, the load current i_O flowing through T_1 would not fall to zero at $\omega t = \pi$. The thyristor T_1 will continue to conduct all the inductive energy stored in the load inductor L is completely utilized. The load current through T_1 falls to zero at $\omega t = \beta$, where β is referred to as the Extinction angle, (the value of ωt).

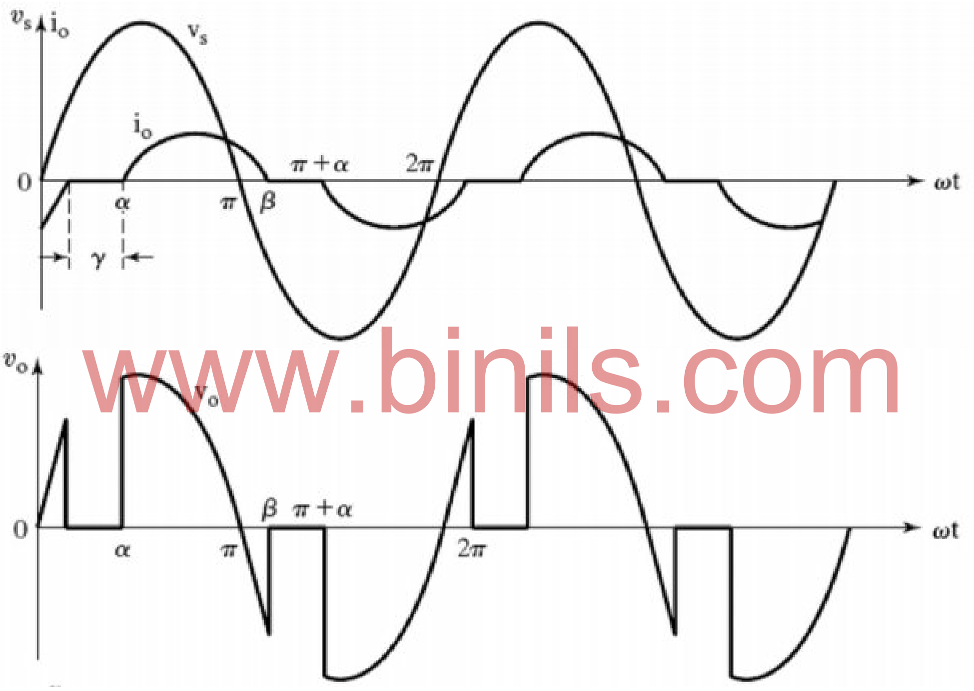


Figure 2.10: Graph of Single Phase AC Voltage Controller

2.10 Pulse Converters

For high power applications such as high voltage DC transmission and DC motor drives 12 pulse converters are used. It reduces output ripples.

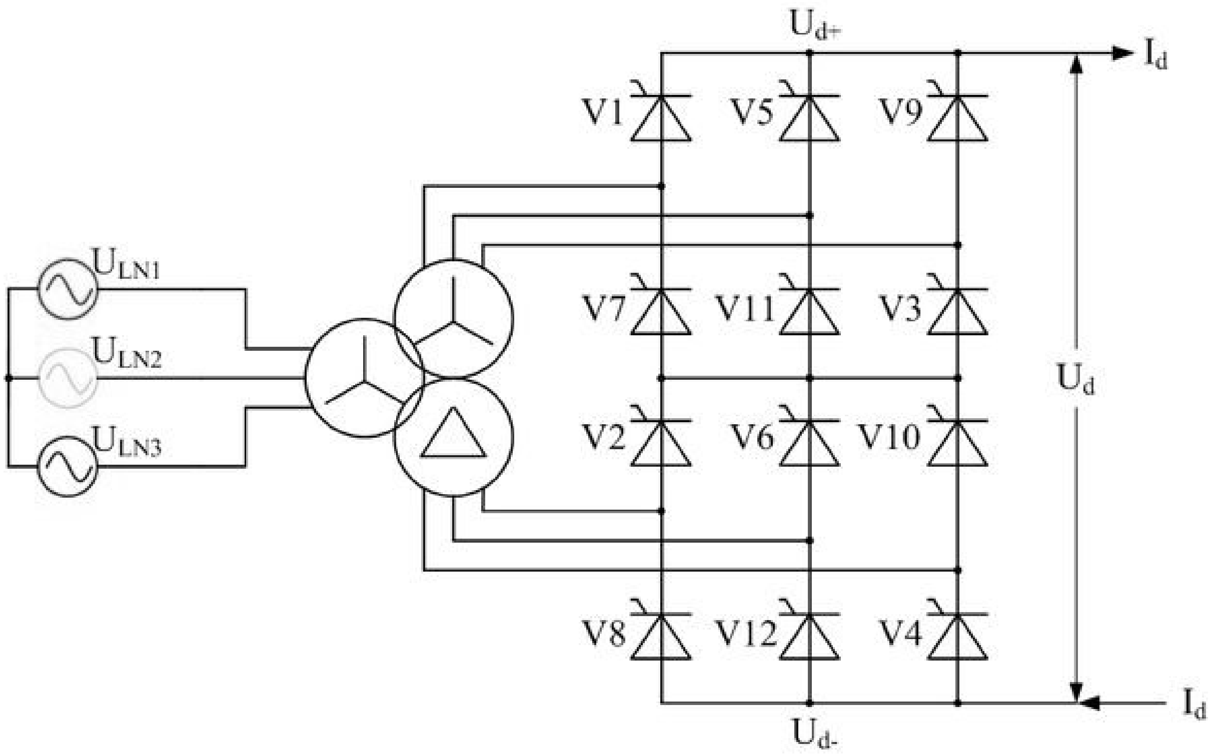


Figure 2.11: Pulse Converter

Secondary windings in star and delta configurations are connected to 3-phase bridges and the output connected either in parallel or series. The phase angle between star and delta secondary voltages is 30°. For instance in the case of a combined star/delta parallel system the difference between the two wave forms will be 30° (Fig. 9). This has the effect of introducing another set of waveforms displaced by 30° giving a 12-pulse output.

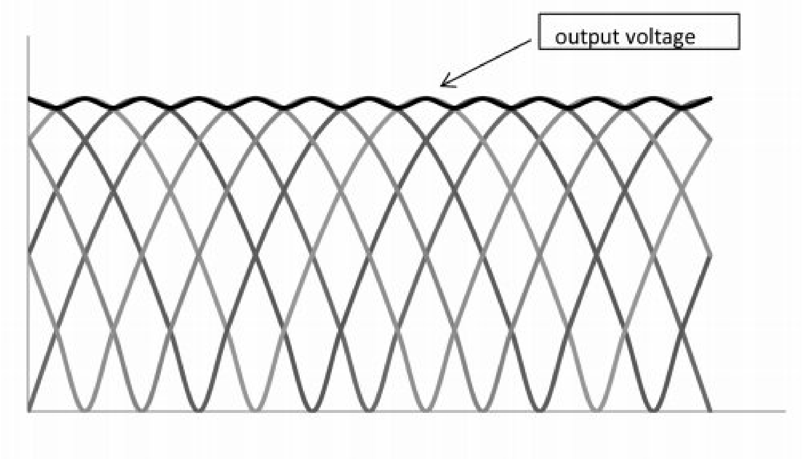


Figure 2.12: Graph Pulse Converter

2.11 Three Phase full wave controllers

The circuit of a three-phase, three-wire ac regulator (termed as ac to ac voltage converter) with balanced resistive (star-connected) load is shown in Fig. Two thyristors are connected back to back per phase, thus needing a total of six thyristors. The thyristors are fired in sequence starting from 1 in ascending order, with the angle between the triggering of thyristors 1 & 2 being 60° (one-sixth of the time period (T) of a complete cycle). The thyristors are fired or triggered after a delay of α from the natural commutation point.

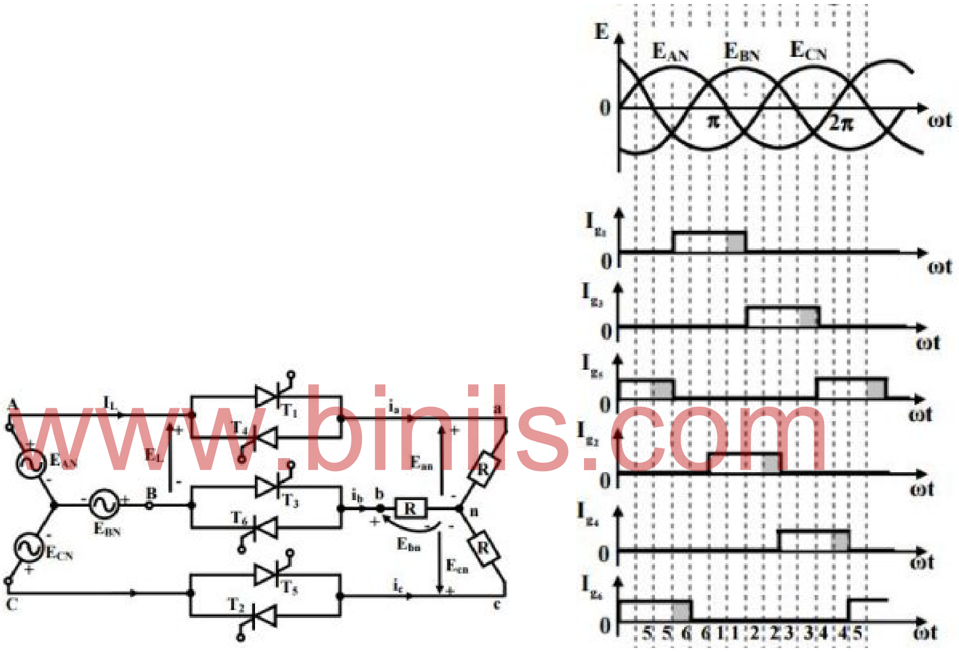


Figure 2.13: Three Phase Full Wave Converter

2.12 Cycloconverter

Cycloconverter converts power the AC Supply of one frequency into AC supply of different frequency.

2.12.1 Single Phase Cycloconverter

Single phase cycloconverter converts the supply frequency into its sub multiple frequency. Figure shows the centre tapped single phase to single phase cycloconverter circuit. To obtain one third of supply frequency, the triggering sequence is as follows:

$P_1P_2P_1$ and $N_1N_2N_1$.

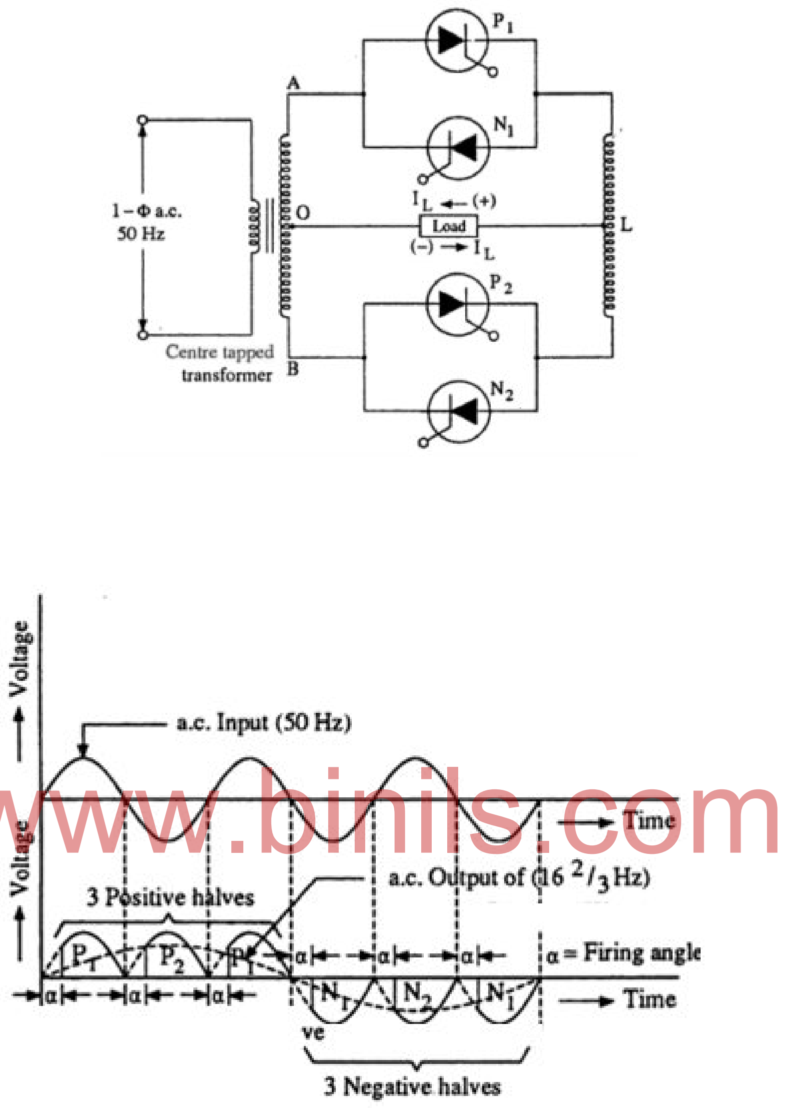


Figure 2.14: Single Phase Cyclo Converter

2.12.2 Three-phase to Three-phase Cyclo-converter

The circuit of a three-phase to three-phase cyclo-converter is shown in Fig. Two three phase half-wave (three-pulse) converters connected back to back for each phase. The total number of thyristors used is 18.

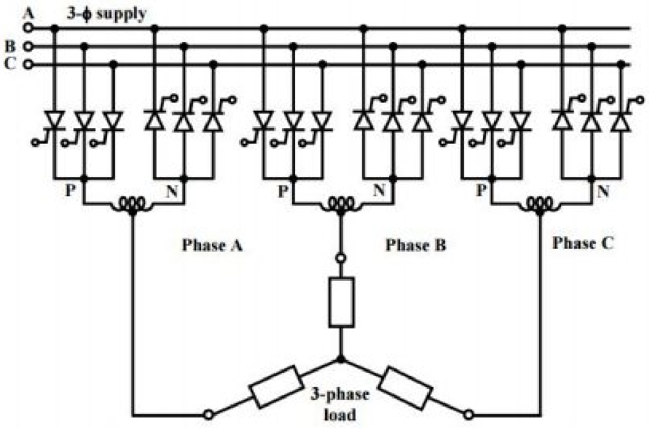


Figure 2.15: Three Phase Cyclo Converter

The firing sequence of the thyristors for the phase groups, B & C are same as that for phase group A, but lag by the angle 120º and 240º respectively. Thus, a balanced three-phase voltage is obtained at the output terminals. The average value of the output voltage is changed by varying the firing angles (α) of the thyristors.

UNIT - III

FORCED COMMUTATED POWER CONTROL CIRCUITS

3.1 DC-DC Converters

It converts a constant DC supply to a variable DC supply. They are commonly used in applications requiring regulated DC power, such as computers, medical instrumentation, communication devices, television receivers, and battery chargers. They are also a part of a regulated variable DC voltage for DC motor speed control applications.

The switch mode power supply has several functions :

1. Step down an unregulated DC input voltage to produce a regulated DC output voltage using a buck or step-down converter.
2. Step up an unregulated DC input voltage to produce a regulated DC output voltage using a boost or step-up converter.
3. Step down and then step up an unregulated DC input voltage to produce a regulated DC output voltage using a buck–boost converter.
4. Buck or Boost the DC input voltage using a Cúk converter.

One method of controlling the output voltage employs switching at a constant frequency. Hence the switching time period remains constant ($T=t_{on}+t_{off}$), and the on-duration of the switch is adjusted to control the average output voltage. This method is called as pulse-width modulation (PWM). Here the duty ratio *d* is defined as the ratio of the on-duration to the switching time period. $d = \frac{t_{on}}{T}$.

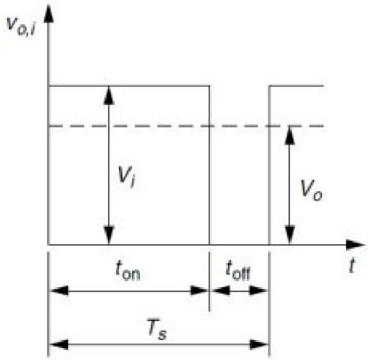


Figure 3.1: ON-OFF Condition

In the other control method, T_{on} or T_{off} of the switch is varied. This method is mainly used in force-commutated thyristor converter circuits.

3.2 Step-Down (Buck) Converter

A step-down converter produces an average output voltage, which is lower than the DC input voltage *V*in. The basic circuit of a step-down converter is shown in Fig. In continuous-conduction mode of operation, assuming an ideal switch, when the switch is on for the time duration *t*on, the inductor current passes through the switch, and the diode becomes reverse biased. This results in a positive voltage (*V*in-*Vo*) across the inductor, which, in turn, causes a linear increase in the inductor current *iL*. When the switch is turned off, because of the inductive energy storage, *iL* continues to flow. This current flows through the diode and gets discharged. Average output voltage can be calculated in terms of the switch duty ratio as:

$$V_{0\cdot ave} = \frac{t_{on}}{T} V_{in}$$

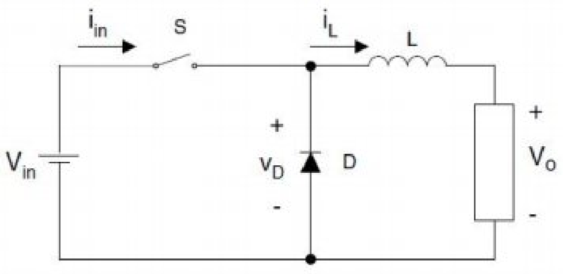


Figure 3.2: Step down converter

3.3 Step-Up (Boost) Converter

In this converter, the output voltage is always greater than the input voltage. When the switch is on, the diode is reversed-biased, thus isolating the output stage. The input voltage source charges the inductor. When the switch is off, the output stage receives energy from the inductor as well as the input source. In the continuous-conduction mode of operation, considering *d* as the duty ratio, the input–output relation is as follows:

$$V_{0\cdot ave} = \frac{1}{1-d} V_{in}$$

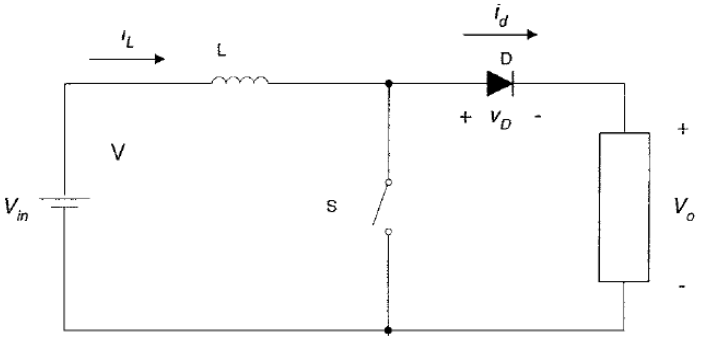


Figure 3.3 Step Up converter

3.4 Buck–Boost Converters

Schematic of the buck–boost converter circuit (in one of its simplest forms) is shown below in Fig. The main power switch is shown and the switch will be a BJT or power MOSFET, or any other device that could be turned on (and off) in a controlled fashion. The DC output voltage value can be chosen to be higher or lower than the input DC voltage. The circuit operation can be explained using inductor current, i_L, and the capacitor voltage, $v_{C.}$ Two differential equations in terms of these variables, the output voltage, v_O, and the source voltage, v_S, are shown below.

$$\frac{di_L}{dt} = \frac{v_s}{L}$$

$$\frac{dv_C}{dt} = \frac{v_0}{R_L C}$$

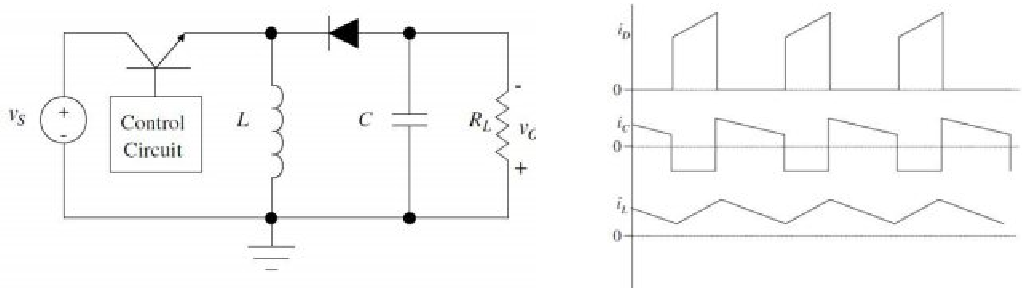


Figure 3.4 Buck Boost converter

Note that the inductor is receiving energy from the source and being charged up, while the capacitor is being discharged into the output load, R_L, and the output voltage is falling.

3.5 Cúk Converter

The Cúk converter is a switched-mode power supply and it was invented by Dr. Slobodan Cúk. The basic non isolated Cúk converter is a SMPS with two inductors, two capacitors, a diode, and a transistor switch as illustrated in Fig. The transfer capacitor, *Ct* , stores and transfers energy from the input to the output. The average value of the inductor voltages for steady-state operation is zero. As a result, the voltage across the transfer capacitor is assumed to be the average value in steady state and is the sum of the input and output voltages. The inductor currents are assumed to be continuous for steady-state operation.

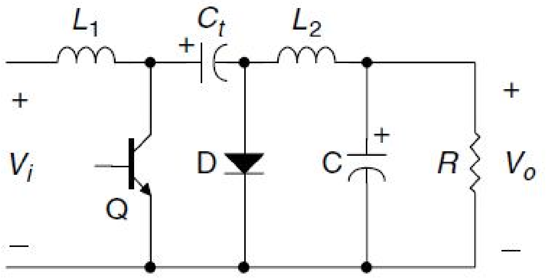


Figure 3.5 Cuk converter

3.6 Pulse Width Modulated Inverters

Fixed DC power can be converted into AC power at desired output voltage and frequency by using a power electronics converter , called an inverter. The objective of inverter and UPS is to produce a sinusoidal AC output whose magnitude and frequency can be controlled. The applications of inverters are for adjustable-speed AC drives, HVDC transmission lines etc.

There are two common types of inverters, i) Voltage Source Inverters and ii) Current Source Inverters. When an inverter has a DC source with a small or negligible resistance, which means the inverter has a stiff DC voltage source at its input terminal, it is called a VSI or voltage fed inverter. When the input DC source has high resistance, which means the DC source is a stiff DC current source, the inverter is called a CSI or current fed inverter

3.7 Single Phase Full Bridge Inverter

A single phase bridge inverter is shown in Figure below. The analysis of the single phase inverter is done by considering the following assumptions and conventions.
1) In the figure The current entering node is considered to be positive.
2) The switches S1, S2, S3 and S4 are unidirectional, i.e. they conduct current in one direction.

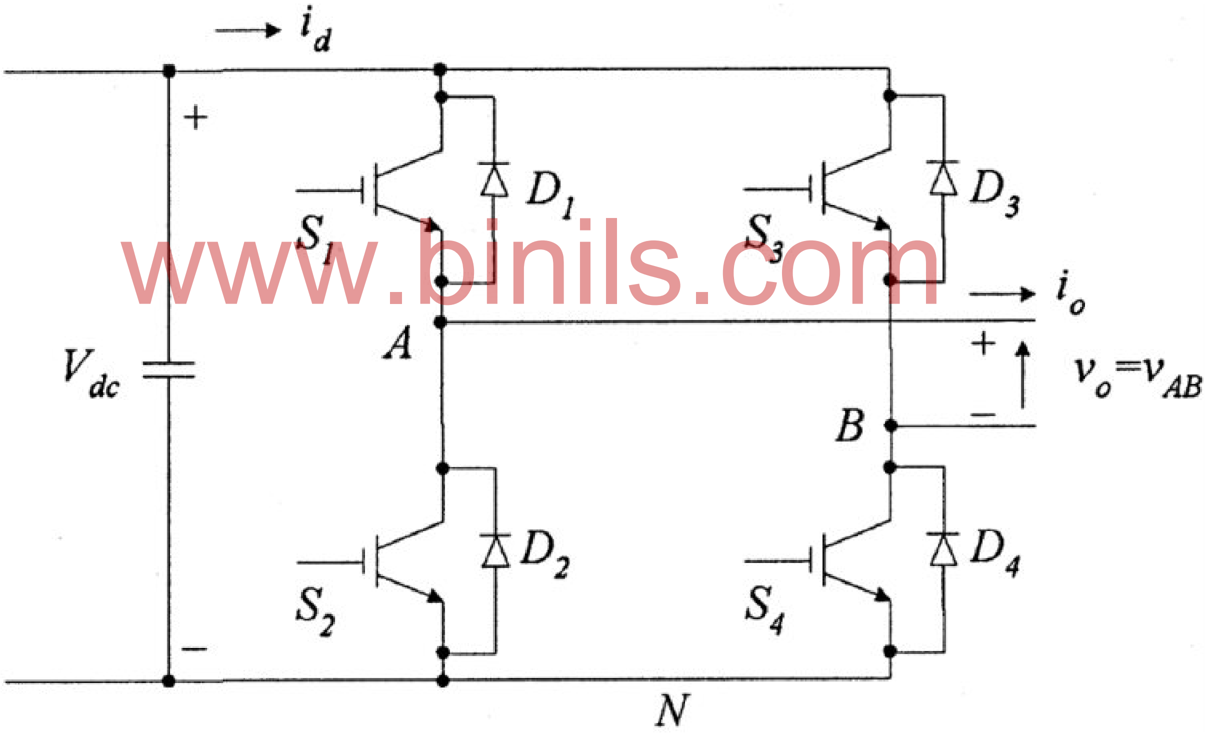


Figure 3.6: Single Phase Full Bridge Inverter

When the two switches S_1 and S_4 are turned on, the voltage at the output is equal to the DC bus voltage V_{dc}. Similarly, when the switches S_2 and S_3 are turned on the output voltage is equal to - V_{dc}.

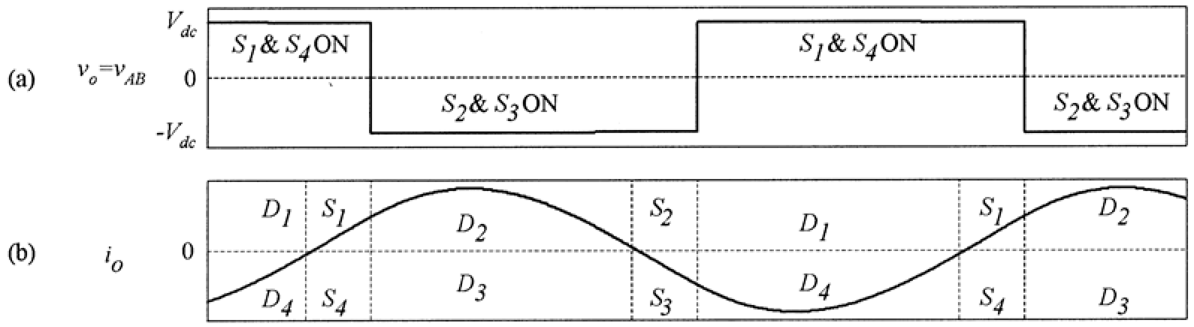


Figure 3.7: Switch Condition of Single Phase Full Bridge Inverter

3.8 Three Phase DC-AC Converters (Inverter)

Three phase inverters are normally used for high power applications. The advantages of a three phase inverter are:

- The frequency of the output voltage waveform depends on the switching rate of the swtiches and hence can be varied over a wide range.

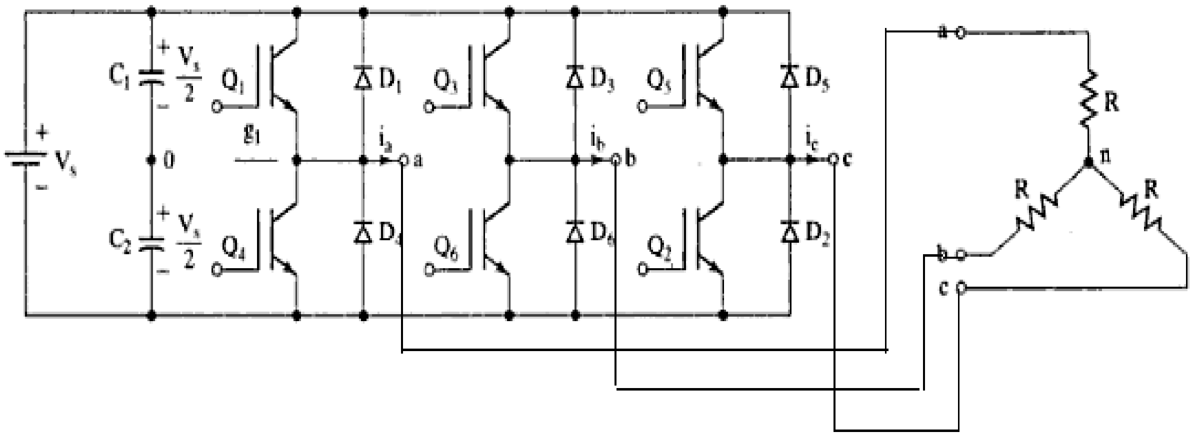
- The direction of rotation of the motor can be reversed by changing the output phase sequence of the inverter.

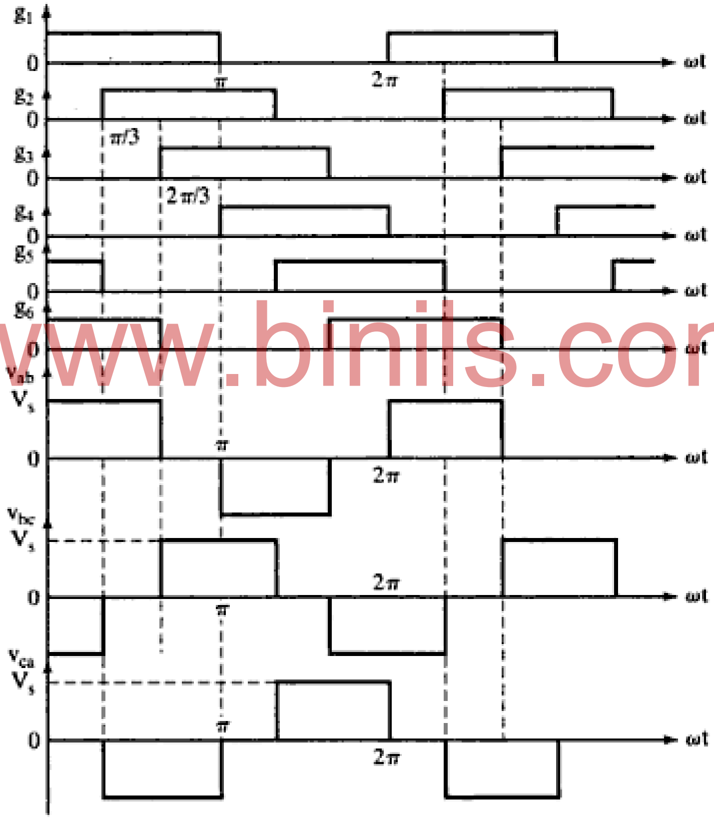
- The ac output voltage can be controlled by varying the dc link voltage.

A Three phase inverter can be obtained from a configuration of six transistors and six diodes as shown. Two types of control signals can be applied to the switches. They are 180˚ conduction and 120˚ conduction.180 ˚ conduction has better utilization of switches and is preferred method. In 180˚conduction mode each switch conducts for 180˚ and in 120˚conduction mode each transistor conducts for 120˚.

3.8.1 180^o CONDUCTION MODE

In 180^0 conduction scheme, each device conducts for 180^0. They are turned ON at regular interval of 60^0 in the sequence Q_1,Q_2,Q_3,Q_4,Q_5,Q_6.The output terminals A B and C of this bridge are connected to the terminals of a 3-phase star or delta connected load.


C1
+ Vs/2 −
Q1
g1
D1
Q3
D3
Q5
D5
+
Vs
−
0
ia
a
ib
b
ic
c
C2
+ Vs/2 −
Q4
D4
Q6
D6
Q2
D2
a
R
n
R
R
b
c


g1
0
π
2π
ωt
g2
0
π/3
ωt
g3
0
2π/3
ωt
g4
0
ωt
g5
0
ωt
g6
0
ωt
vab
Vs
0
π
2π
ωt
vbc
Vs
0
2π
π
ωt
vca
Vs
0
π
2π
ωt

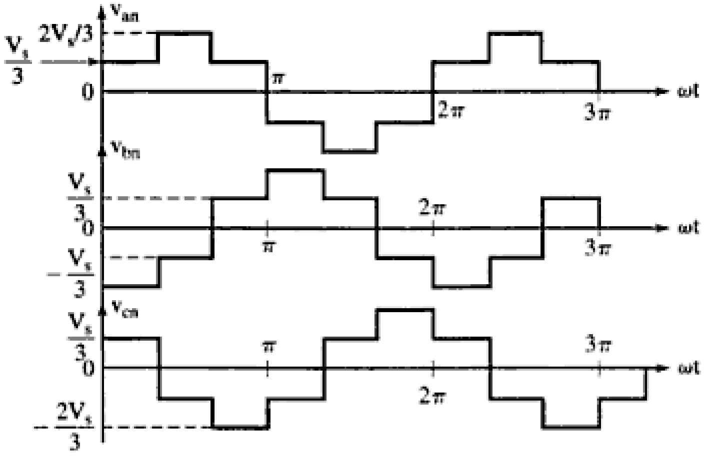


Figure 3.8: Conduction mode and Switch Condition of Three Phase Inverter

3.8.2 120^0 CONDUCTION MODE

In 120^0 conduction scheme each device conducts for 120^0.It is preferable for a delta connected load because it provides a six step waveform across any phase. As each device conducts for 120^0, only two devices are in conduction state at any instant.

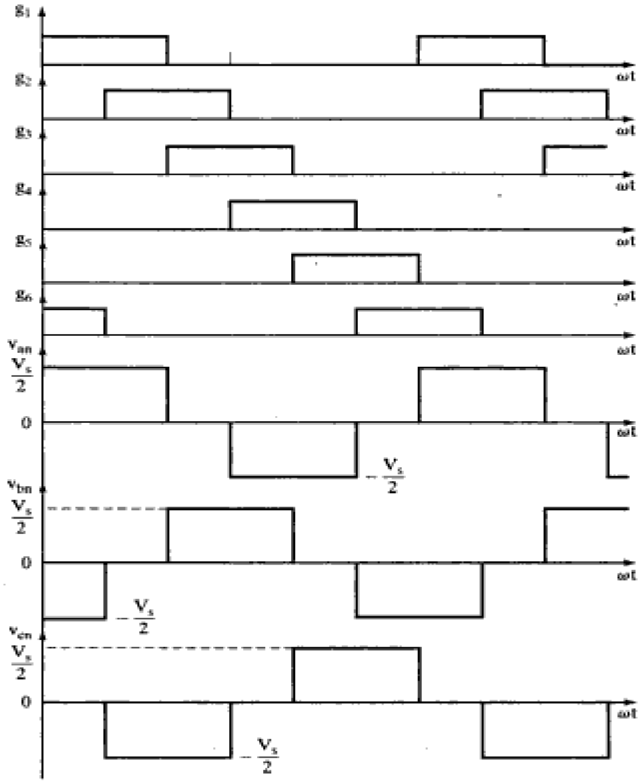


Figure 3.9: Conduction mode and Switch Condition of Three Phase Inverter

3.9 Different PWM Techniques

PWM techniques are characterized by constant amplitude pulses. The width of these pulses is, however, modulated to obtain output voltage control and to reduce its harmonic content. Different PWM techniques are as under.

- Single-pulse width modulation
- Multiple-pulse width modulation
- Sinusoidal-pulse width modulation

3.9.1 Single-Pulse Width Modulation

In single pulse-width modulation, there is only one pulse per half-cycle and the width of the pulse is varied to control the inverter output voltage.

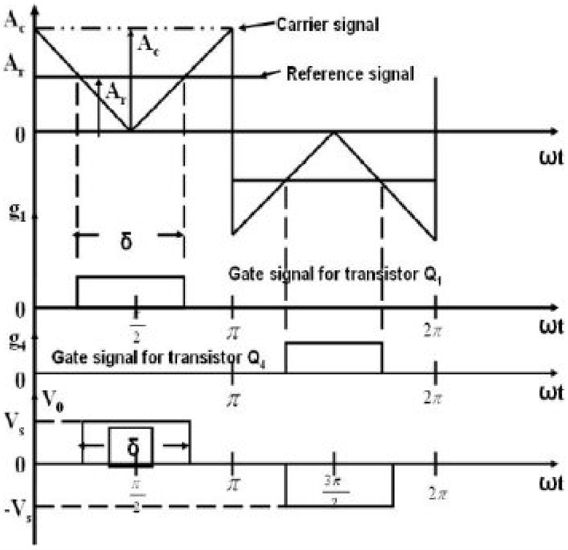


Figure 3.10: Single Pulse Width Modulation

Figure shows the generation of gating signals. The gating signals are generated by comparing a rectangular reference signal of amplitude, Ar, with a triangular carrier wave of amplitude, Ac. The frequency of the reference signal determines the fundamental frequency of the output voltage. The ratio of Ar to Ac is the control variable and defined as the modulation index.

The amplitude modulation index or simply modulation index is

$$M = \frac{A_r}{A_c}$$

3.9.2 Multiple -Pulse-Width Modulation

The harmonic content can be reduced using several pulses in each half-cycle of output voltage. The generation of gating signals for turning on and off of transistors is shown in figure, by comparing a reference signal with a triangular carrier wave. The frequency of reference signal sets the output frequency, fo, and the carrier frequency, fc, determines the number of pulses per half-cycle. The modulation index controls the output voltage. This

type of modulation is also known as uniform pulse-width modulation (UPWM).

The number of pulses per half-cycle is found from

$$p = \frac{f_c}{2f_o} = \frac{m_f}{2}$$

where $m_f = f_0/f_c$ is defined as the frequency modulation ratio.

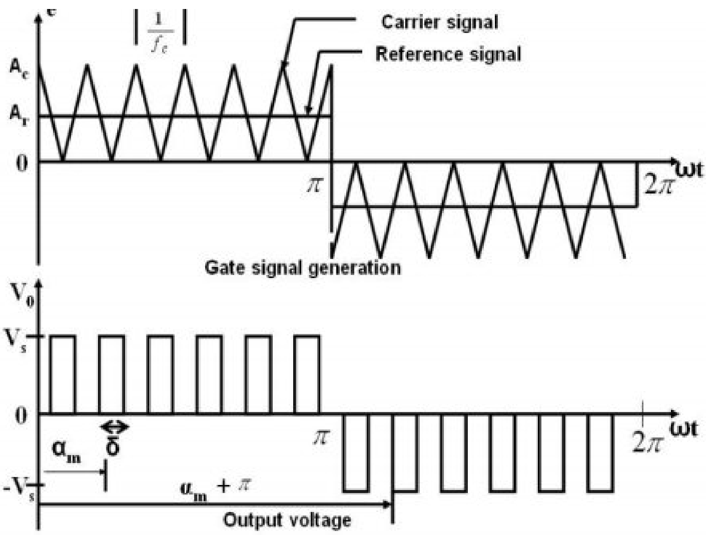


Figure 3.11: Multiple Pulse Width Modulation

3.9.3 Sinusoidal Pulse Width Modulation

In SPWM, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the centre of the same pulse. The distortion factor and lower-order harmonics are reduced significantly. The gating signals as shown in figure are generated by comparing a sinusoidal reference signal with a triangular carrier wave of frequency, fc. This type of modulation is commonly used in industrial applications and abbreviated as SPWM. The frequency of the reference signal, fr, determines the output frequency fo. The peak amplitude, Ar, controls the modulation index m, and then in turn the RMS output voltage,
Vo. The number of pulses per half cycle depends on the carrier frequency.

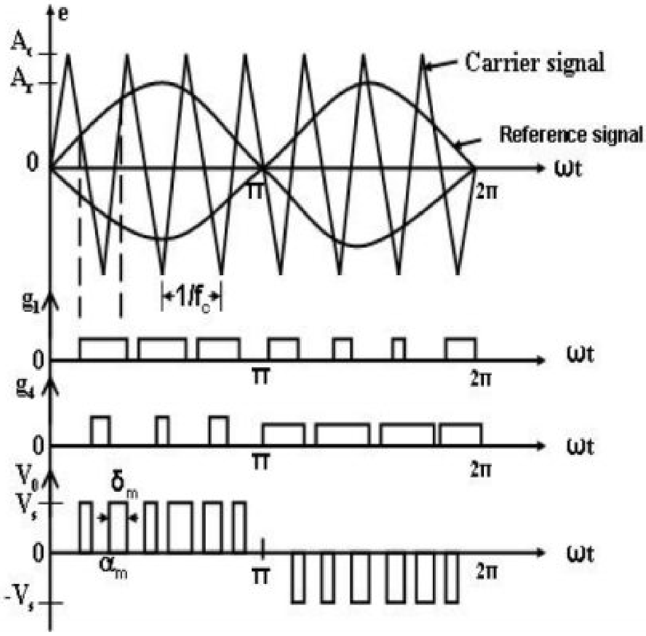


Figure 3.12: Sinusoidal Pulse Width Modulation

3.10 Three Phase SPWM Inverter

Here for three phase PWM the three modulating sine waves are of 0^0,120^0 and 240^0. The carrier wave is 00 for all three phase. This modulation technique, also known as PWM with natural sampling, is called sinusoidal PWM because the pulse width is a sinusoidal function of the angular position in the reference signal.

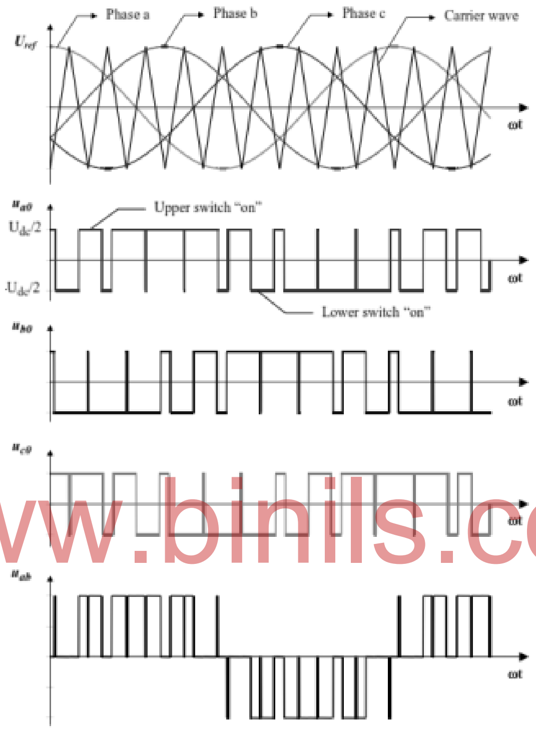


Figure 3.13: Three Phase SPWM Inverter

UNIT IV

APPLICATIONS OF POWER ELECTRONICS

4.1 Switched Mode Power Supply (SMPS)

The ‘Switched Mode Power Supply’ owes its name to the dc-to-dc switching converter which converts unregulated dc input voltage to regulated dc output voltage. The switch employed is turned ‘ON’ and ‘OFF’ (referred as switching) at a high frequency. During ‘ON’ mode the switch is in saturation mode with negligible voltage drop. During ‘OFF’ mode the switch is in cut-off mode with negligible current through the collector and emitter terminals. On the contrary the voltage regulating switch, in a linear regulator circuit, always remains in the active region.

As shown in Figure, the bridge is used to generate a high-frequency square wave that is fed to an isolation transformer. Operation at high frequency reduces the size of the transformer and of the filter components. Power densities in excess of 50W per in^3 are commonly available in some commercially available SMPS.

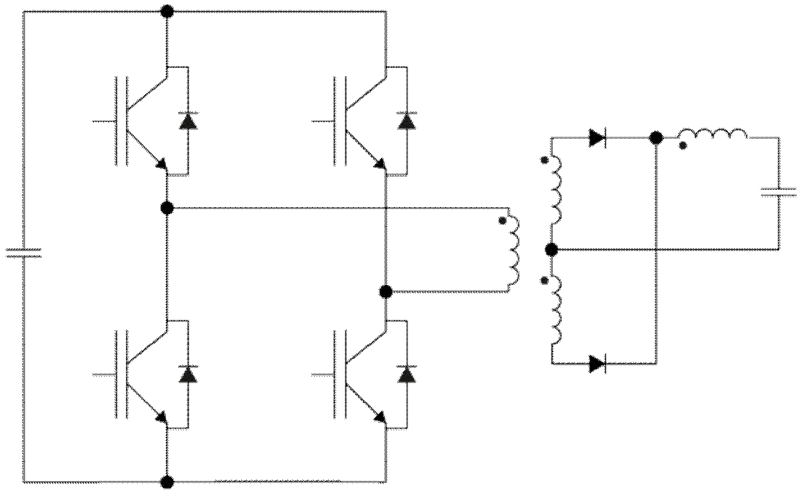


Figure 4.1: SMPS

4.2 Uninterruptible Power Supply Systems

There are two distinct types of uninterrupted power supplies, namely, (i) on-line UPS and (ii) off-line UPS. In the on-line UPS, whether the mains power is on or off, the battery operated inverter is ON all the time and supplies the ac output voltage. In off-line UPS, the inverter is off when the mains power is present. The inverter turns on only when the mains supply goes off.
The block diagrams of on-line UPS, off-line UPS are given in fig.

A UPS generally consists of a rectifier, battery charger, a battery bank and inverter circuit. First it converts the commercial ac input into dc suitable for input to the battery bank and the inverter. The rectifier should have its input protected and should be capable of supplying power to the inverter when the commercial supply is either slightly below the normal voltage or slightly above.

4.2.1 Online UPS

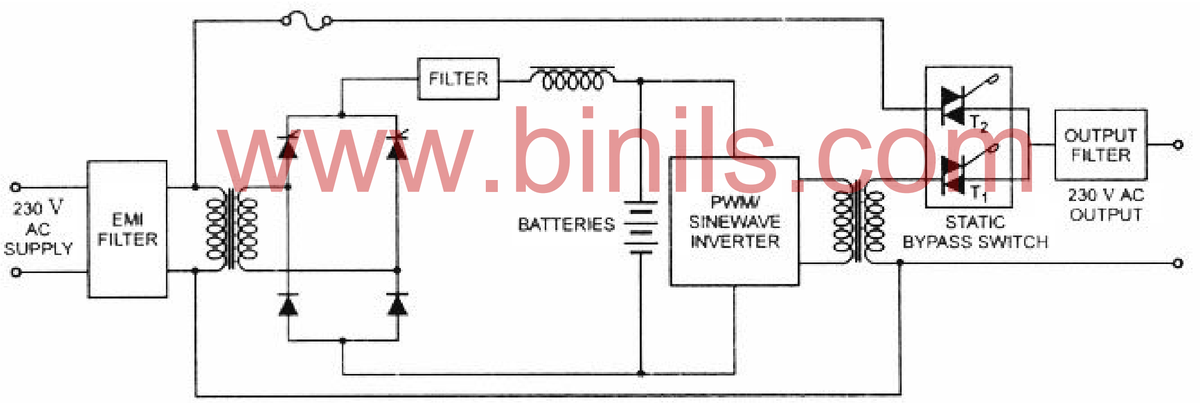


Figure 4.2: Online UPS

In case of On-line UPS, the battery operated inverter works continuously whether the mains supply is present or not. Triac T_1 is on for all the times while Triac T_2 has been provided to bypass the UPS inverter, only when a fault develops in the UPS inverter. When the mains supply fails, the UPS supplies power from the batteries. However, once the mains power resumes, the batteries will get charged again. The switching times of these supplies is considered to be zero. Usually sealed maintenance free batteries are used and the running time of the inverter is low (approximately 10 to 30 minutes).

4.2.2 Off Line UPS

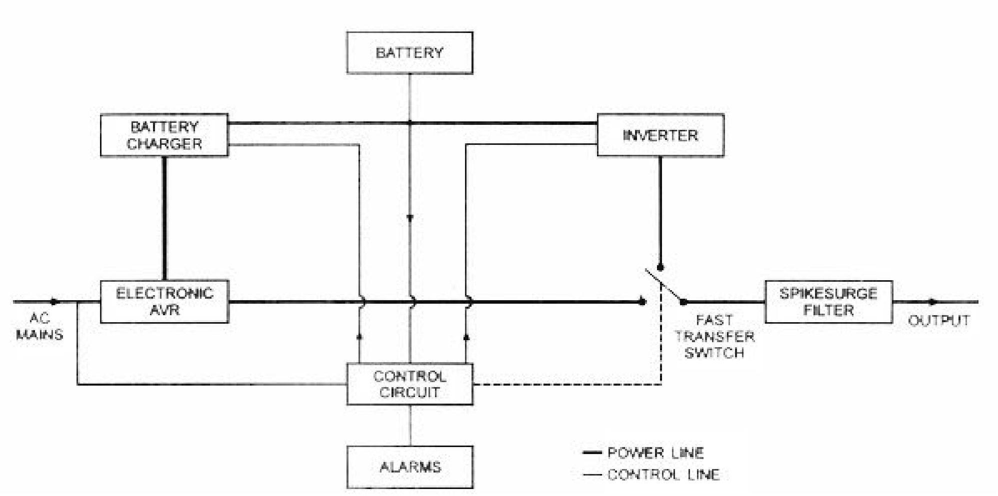


Figure 4.3: Off line UPS

In the case of Off-Line UPS, the inverter is off when the mains power is on and the output voltage is derived directly from the mains. The inverter turns on only when the mains supply fails. Its switching time is less than 5 ms. These UPS are generally used with PCs or computers or other appliances where a small duration (5 ms or less) interruption in power supply can be tolerated. Usually, sealed batteries or lead-acid batteries are used. The running time of UPS supplies is also low (about 10 to 30 minutes).

4.2.3 Static AC Circuit Breaker

Thyristor, being bistable device is widely used for switching off power signals owing to their long life, high operation speed and freedom from other defects associated with mechanical and electro-mechanical switches.

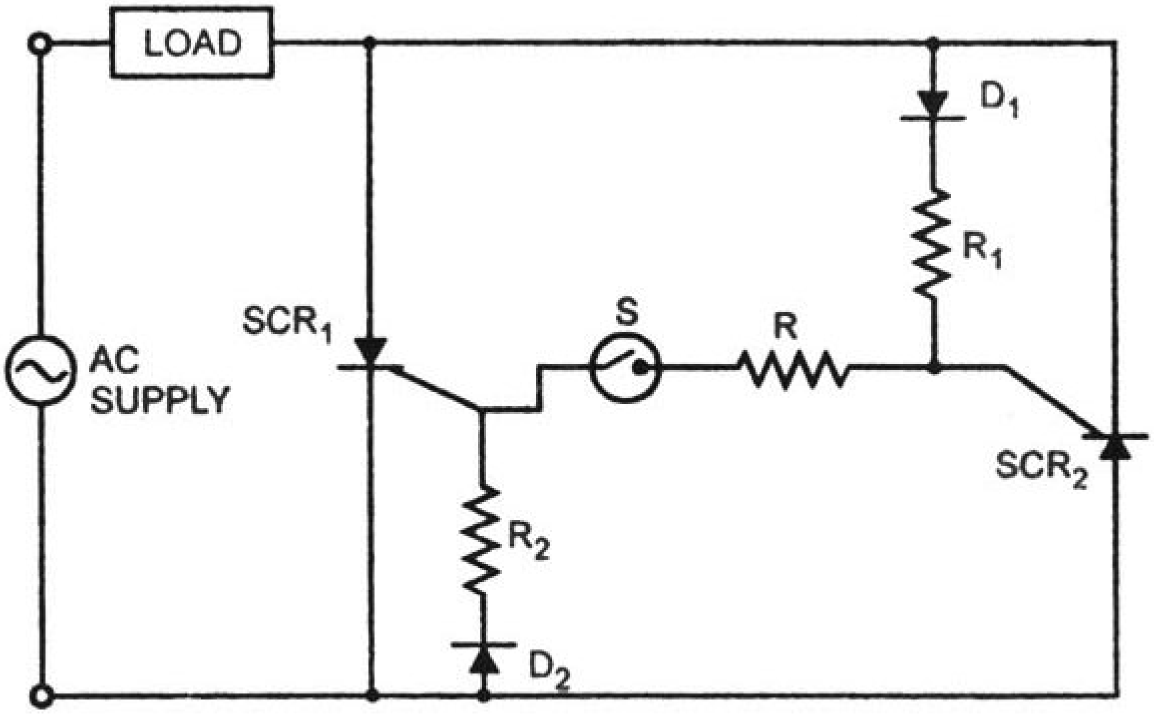


Figure 4.4: Static AC Circuit Breaker

Figure shows a circuit in which two SCRs are used for making and breaking an ac circuit. The input voltage is alternating and the trigger pulses are applied to the gates of SCRs through the control switch S. Resistance R is provided in the gate circuit to limit the gate current while resistors R1 and R2are to protect the diodes D1 and D2 respectively.

For starting the circuit, when switch S is closed, SCR1 will fire at the beginning of the positive half-cycle (the gate trigger current is assumed to be very small). It will turn-off when the current goes through the zero value. As soon as SCR1 is turned-off, SCR2 will be fire since the voltage polarity is already reversed and it gets the proper gate current. The circuit can be broken by opening the switch S. Opening of gate circuit poses no problem, as current through this switch is small. As no further gate signal will be applied to the SCRs, the SCRs will not be triggered and the load current will be zero. The maximum time delay for breaking the circuit is one half-cycle. Thus several hundred amperes of load current can be switched on/off simply by handling gate current of few mA by an ordinary switch. The above circuit is also called the static contactor breaker because it does not have any moving part.

4.3 AC Solid State Relay

The AC type Solid State Relay turns “ON” at the zero crossing point of the AC sinusoidal waveform, prevents high inrush currents when switching inductive or capacitive loads while the inherent turn “OFF” feature of Thyristors and Triacs provides an improvement over the arcing contacts of the electromechanical relays.

Resistor-Capacitor (RC) snubber network is generally required across the output terminals of the SSR to protect the semiconductor output switching device from noise and voltage transient spikes when used to switch highly inductive or capacitive loads. In most modern SSR’s this RC snubber network is built as standard into the relay itself reducing the need for additional external components.

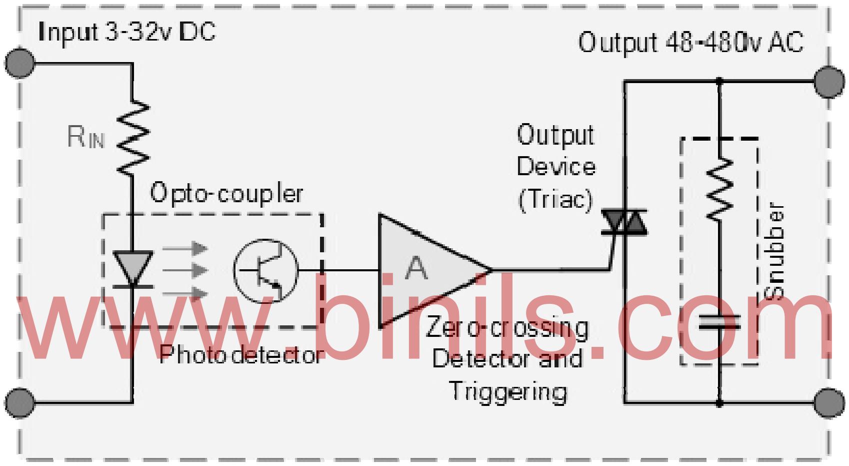
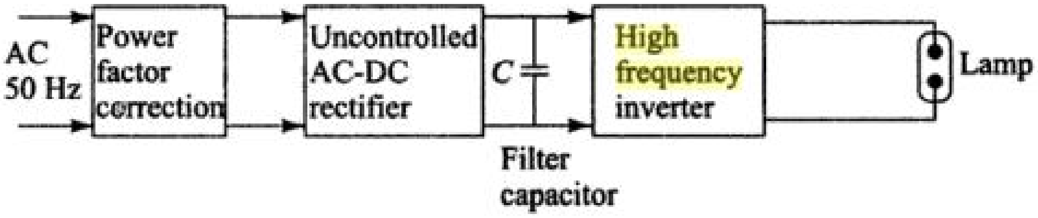


Figure 4.5: High frequency fluorescent lighting

All gas discharge lamps, including fluorescent lamps, require a ballast to operate. The ballast provides a high initial voltage to initiate the discharge, then rapidly limits the lamp current to safely sustain the discharge.



.

The uncontrolled ac-dc converter with filter is followed by a high frequency inverter. Resonant inverter can be used here. The switching frequency of the inverter lies in the range of 25 KHz to 40 KHz. The current from the source has a very poor power factor, hence, the power factor correction is necessary.

4.4 Induction Heating

Induction heating is a non-contact heating process. It uses high frequency electricity to heat materials that are electrically conductive. Since it is non-contact, the heating process does not contaminate the material being heated. It is also very efficient since the heat is actually generated inside the workpiece. This can be contrasted with other heating methods where heat is generated in a flame or heating element, which is then applied to the workpiece. For these reasons Induction Heating lends itself to some unique applications in industry.

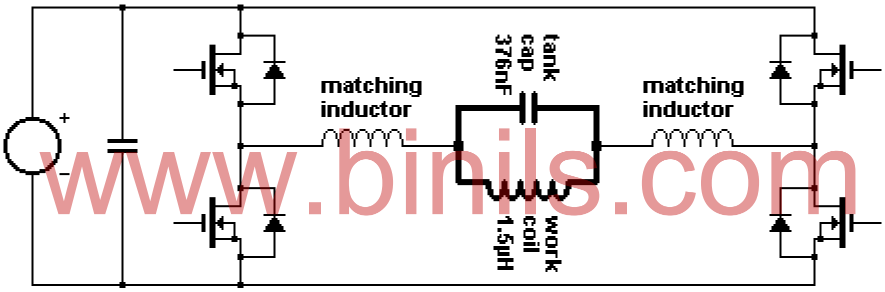


Figure 4.6: Induction Heating

In high power designs it is common to use a full-bridge (H-bridge) of 4 or more switching devices. In such designs the matching inductance is usually split equally between the two bridge legs so that the drive voltage waveforms are balanced with respect to ground. The DC-blocking capacitor can also be eliminated if current mode control is used to ensure that no net DC flows between the bridge legs.

4.5 Electric Welding

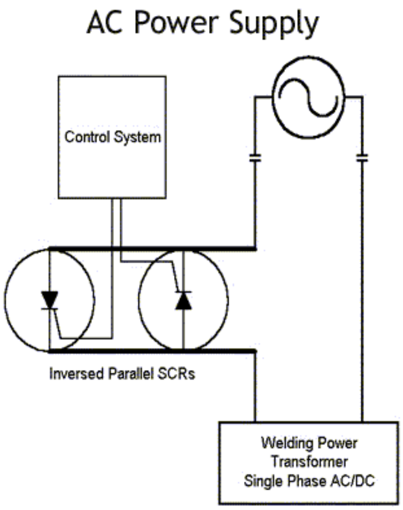


Figure 4.7: Electric Welding

The low frequency welding control utilizes an inverse parallel pair of Silicone Controlled Rectifiers (SCR) to control the output of the welding power transformer. SCRs are turned on by pulsing a gate with a voltage signal. The welding control uses predictive algorithms to determine the best point to pulse the gate of the SCRs during the half cycle of the alternating current supply. The SCRs are turned off only when the alternating current supply is below the threshold point called "minimum holding current". This occurs near the zero crossing point of the AC power supply.

4.6 HVDC Transmission

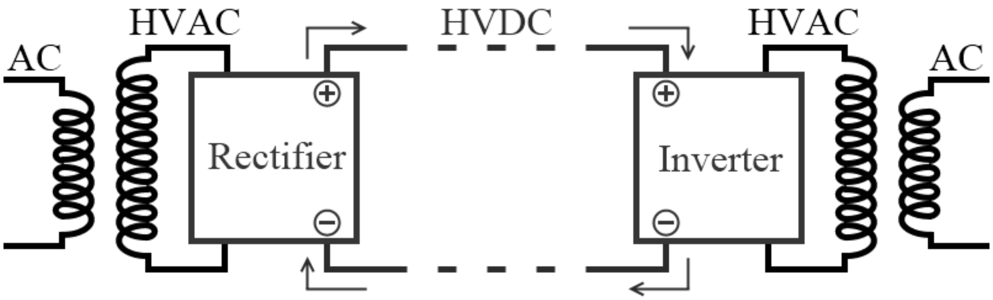
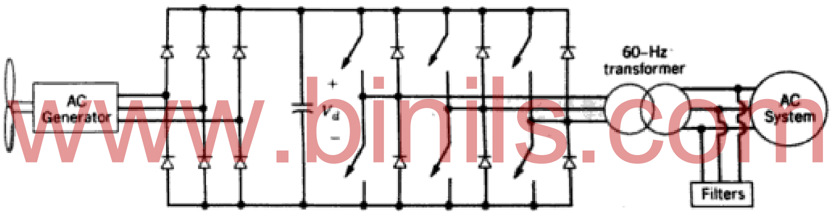


Figure 4.8: HVDC Transmission

A high voltage direct current (HVDC) power system uses D.C. for transmission of bulk power over long distances. For long distance power transmission, HVDC lines are less expensive, and losses are less as compared to AC transmission. It interconnects the networks that have different frequencies and characteristics.

In generating substation, AC power is generated which can be converted into DC by using a rectifier. In HVDC substation or converter substation rectifiers and inverters are placed at both the ends of a line. The terminal substation, which converts AC into DC is called a rectifier terminal, while the terminal substation which converts DC into AC is called an inverter terminal. The DC is flowing with the overhead lines and at the user end again DC is converted into AC by using inverters, which are placed in converter substation. The power remains the same at the sending and receiving ends of the line. DC is transmitted over long distances because it decreases the losses and improves the efficiency.

Wind and small hydropower interconnection



4.7 Static VAR Compensator

Static Var Compensator is “a shunt-connected static Var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage)”. SVC is based on thyristors without gate turn-off capability. The operating principal and characteristics of thyristors realize SVC variable reactive impedance. SVC includes two main components and their combination: Thyristor-controlled and Thyristor-switched Reactor (TCR and TSR); and Thyristor-switched capacitor (TSC).

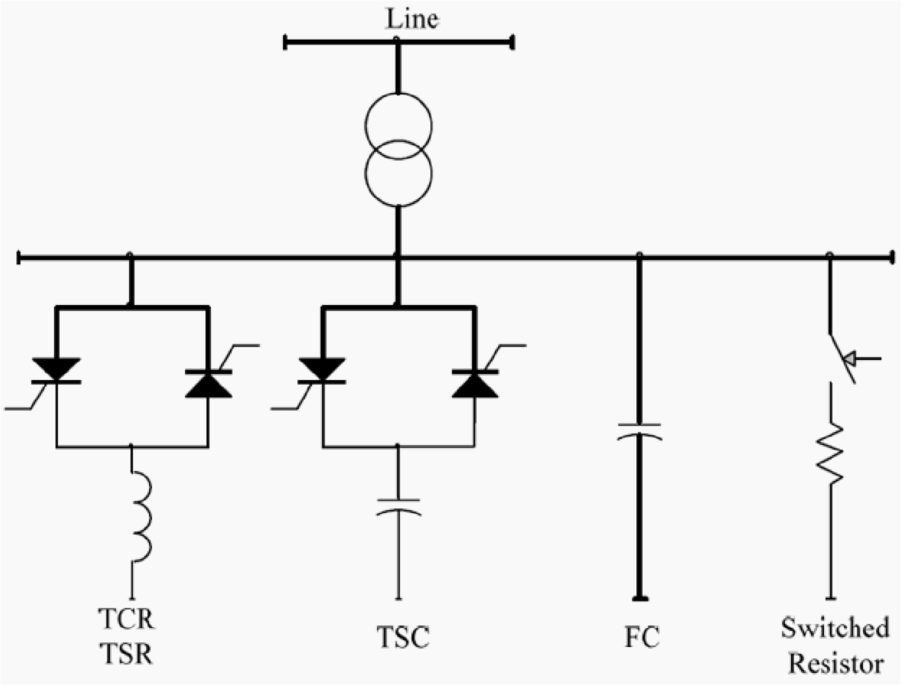


Figure 4.9: Static VAR Compensator

4.8 Thyristor Controlled Inductor

Thyristor controlled reactor consist reactor L placed in series with the thyristor. This reactor is the controlled element of the TCR, and it controls the thyristor. TCR consists two opposite poled thyristor which conducts every alternate half cycles of the supply.

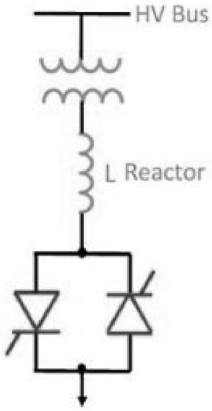


Figure 4.10: Thyristor Controlled Inductor

In TCR the duration of current flowing through the reactor is controlled by the firing angle of the thyristor. For every half cycle, the thyristor is given a triggering pulse by the controlled circuit. It is used in EHV (Extra High Voltage) lines for providing lagging VARs during the low load or load rejection.

4.9 Thyristor Switched Capacitor

The thyristor switched capacitor is used in EHV lines for providing leading VARs during heavy loads. The current through the capacitor can be varied by controlling the firing angles of back to back thyristor connected in series with the capacitor.

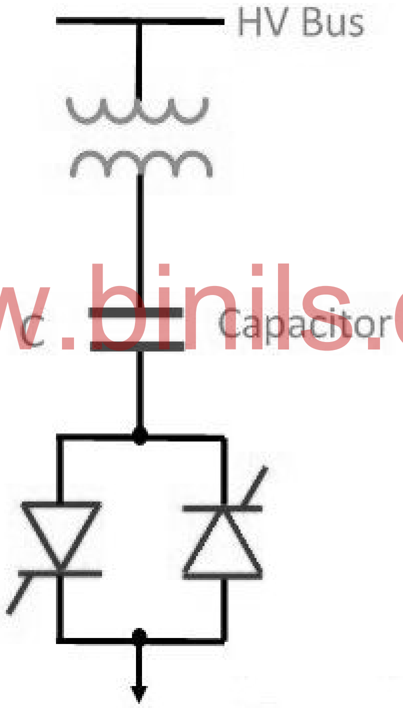


Figure 4.11: Thyristor Switched Capacitor

When the voltage at a bus reduces below the reference value, the static VAR compensator used TSC for injected capacitive volt-amperes and when the voltage at the bus rise above the reference value, inductive VAR are to be injected to lower the bus voltage by using TCR.

UNIT V

MOTOR DRIVE APPLICATIONS

5.1 DC Motor with a Separately Excited Field Winding

Under no load conditions, the speed of dc shunt motor is given by

$$n = \frac{V}{k_E \varphi}$$

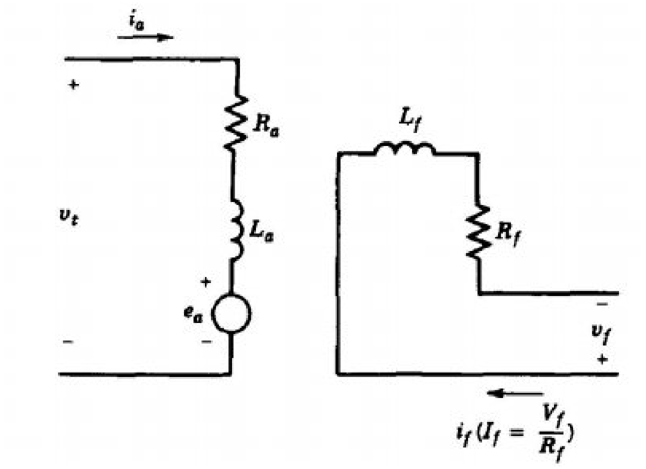
Where n=speed; V= armature voltage and φ= field flux

The motor can operate at any speed up to base speed, and at any torque (current) up to the rated value by appropriate choice of armature voltage. This full flux region of operation is indicated by the shaded area in Figure. This region is referred to as the 'constant torque' region of the torque–speed plane.

To run faster than base speed the field flux must be reduced. The operation with reduced flux is known as 'field weakening' region.

The speed of dc shunt motor is controlled as follows:

- Below base speed, the field flux is kept at maximum. The speed is set by varying the armature voltage. Full torque is available at any speed.
- Above base speed, the armature voltage is at maximum and the flux is reduced in order to raise the speed. The maximum torque available reduces in proportion to the flux.



Separately excited dc motor - equivalent circuit

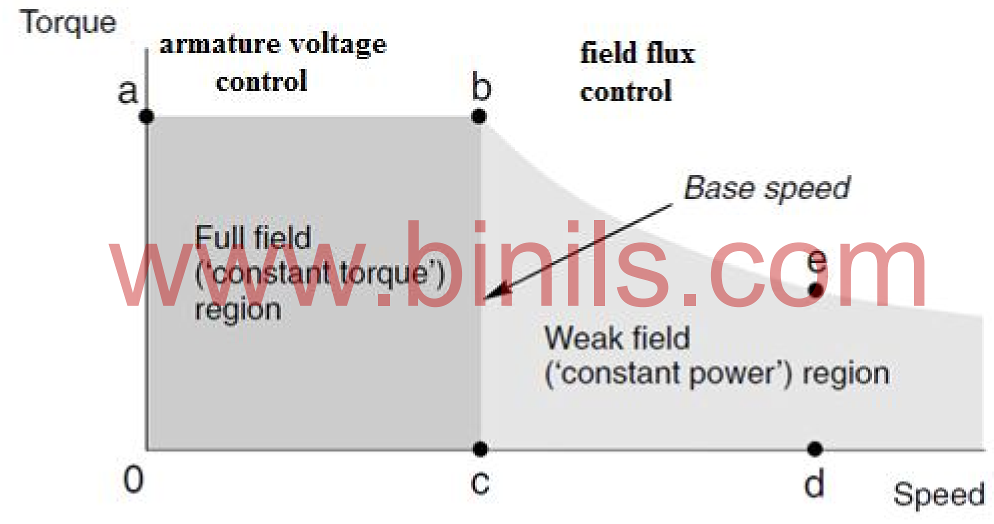


Figure 5.1 Separately excited dc motor - equivalent circuit

5.2 Line frequency controlled converters

In many adjustable dc drives, especially in large power ratings, it may be economical to utilize a line frequency controlled converters.

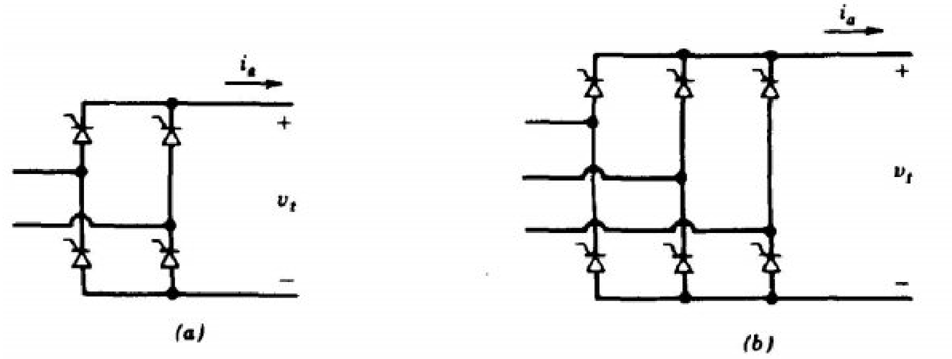


Figure 5.2: Line frequency controlled converters

a) Single phase b) three phase

The output of these line frequency converters, also called the phase controlled converters, contains an ac ripple that is a multiple of 50 Hz line frequency. Because of this low frequency ripple, an inductance in series with the motor armature may be required to keep low ripple current. This will minimize its effect on armature heating and ripple in torque and speed.

A disadvantage of line frequency converters is the longer dead time to the changes in the speed control. So line frequency converters are not suitable for servo drive applications. Moreover, the voltage of line frequency converter is reversible but not current. The current reversal is required for braking.

For reverse drive control and regenerative braking, dual converters or converter with reversing contactor can be used.

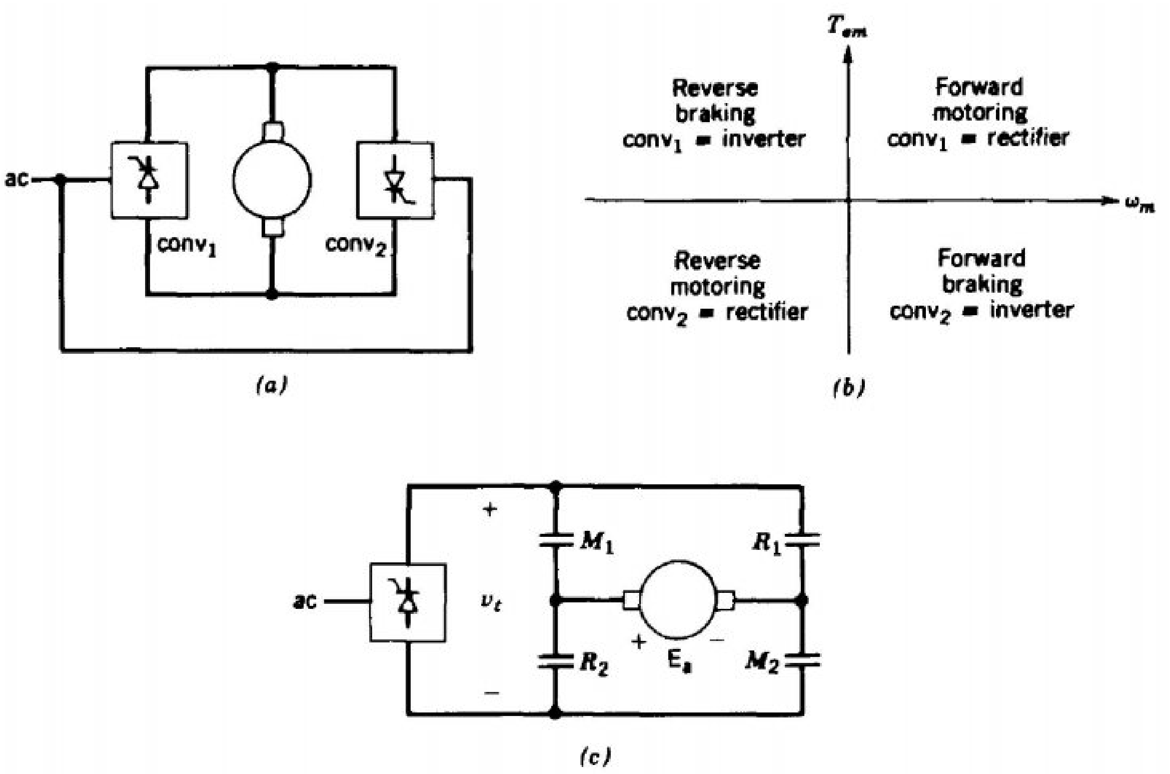
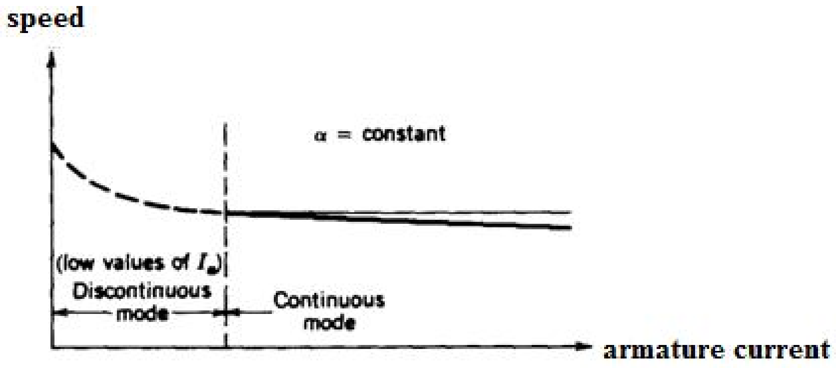


Figure 5.2: Driver Line frequency controlled converters

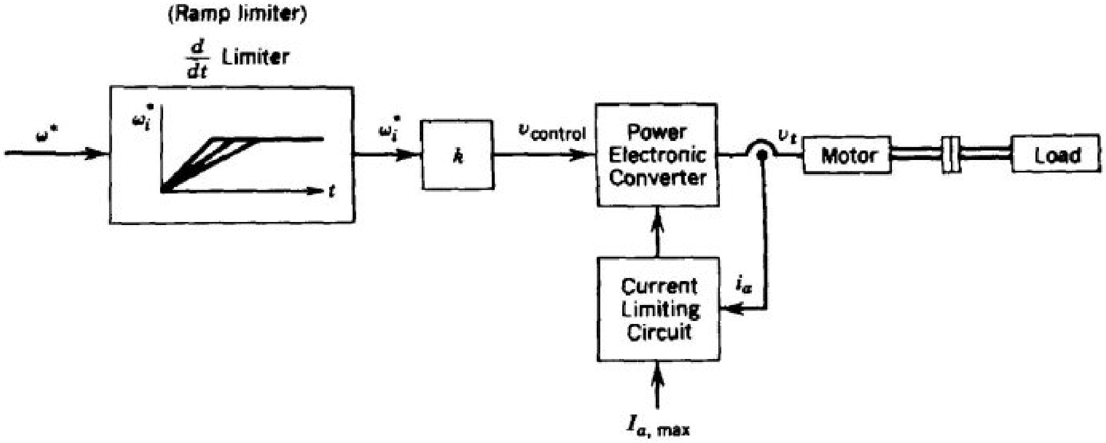
5.3 Effect of Discontinuous Armature Current

In line frequency controlled converters, the armature current may be discontinuous at light load condition. For a fixed firing angle α, the discontinuous current causes the output voltage to go up. This voltage rise causes the motor speed to rise at low armature current. With a continuously flowing armature current, the voltage drop is due to IaRa and commutation voltage drop in ac side inductance. These effects results in poor regulation under on open loop operation.



5.4 Control of Adjustable Speed Drives

The type of control used depends on the drive requirements. An open-loop control is shown in figure.



5.4.1 Open loop control

A d/dt limiter allows the speed command to change slowly, thus preventing the rotor current from exceeding its rating. The slope of the d/dt limited can be adjusted to match the motor – load inertia. The current limiter in such drives may be just a protective measure, whereby if the measured current exceeds its rated value, the controller shuts the drive to off.

5.4.2 Closed loop Control:

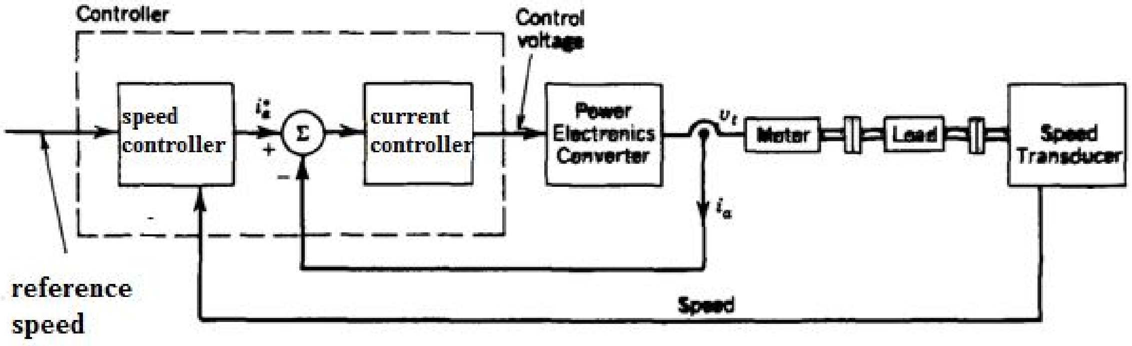


Figure 5.3: Closed loop control

Figure shows closed loop control of dc motor. The outer loop is speed control and the inner loop is current control. The speed transducer measures the actual speed and the reference speed and it is compared with actual speed. Speed controller generates current set value. The current set value is compared with actual current and the current controller generates control voltage to trigger the power electronic converter.

5.5 Switch-Mode DC-DC Converters

If a four quadrant operation is needed then a switch mode converter is utilized. The full bridge dc-dc converter shown in figure is used.

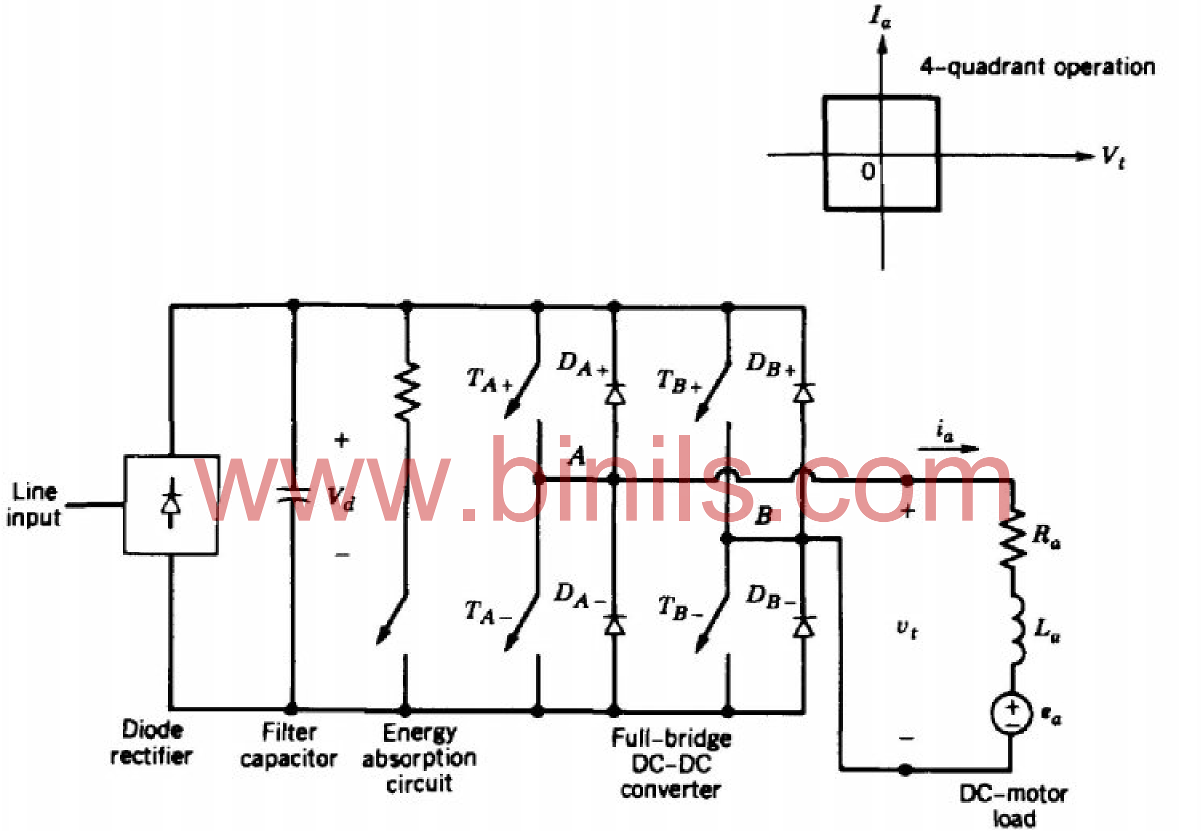


Figure 5.4: Switch-Mode DC-DC Converters

If braking is needed, then the two quadrant converter shown in figure **a** is used.

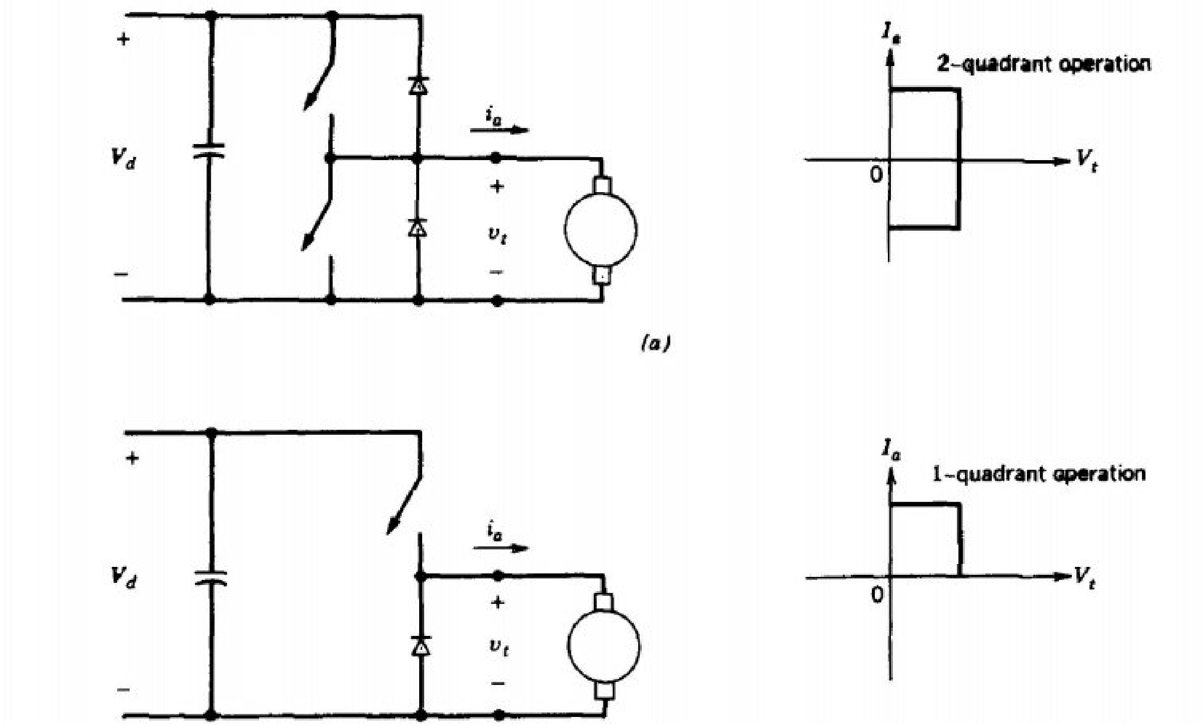


Figure 5.5: a)Two quadrant operation b) single quadrant operation

It consists of two switches, where one of the switches is ‘ON ‘at any time, to keep the output voltage independent of the direction of I_a. The armature current will get reversed during the braking mode of operation. Here the power flows from the dc motor to V_d. The output voltage V_t can be controlled in magnitude, but it always remains unipolar.

For a single quadrant operation where the speed remains unidirectional and braking is not required then the step down converter as shown in figure **b** is used.

5.6 Induction Motor Drives

5.6.1 Introduction

Induction motor with squirrel cage rotor, are the workhorse of the industry because of their low cost and rugged construction. When operated directly from the 50 Hz line voltages, an induction motor operates nearly at constant speed. However by means of power electronics converters, it is possible to vary the speed of the induction motor. The induction motor drives can be classified into two broad categories based on their applications:

1. Adjustable speed drives - One important application of these drives is in process control by controlling the speed of fans, compressors, pumps and blowers.
2. Servo control – by means of sophisticate control, induction motor can be served as servo drives in computer peripherals, machine tools and robotics.

5.6.1 Basic Principle of Induction Motor Operation

The stator of an induction motor consists of three phase windings distributed in the stator slots. These three windings are displaced by 120º in space, with respect to each other. The squirrel cage rotor consists of a stack of insulated laminations. It has conducting bars inserted through it which are electrically shorted at each end of the rotor by end rings.

If a balanced set of three phase sinusoidal voltage at a frequency $f=\omega/2\pi$ are applied to the stator, it results in a balanced set of currents, which establishes a flux density distribution B_{ag} in the air gap with the following properties:

1. It has a constant amplitude
2. It rotates with a constant speed, also called the synchronous speed, of ω_s radians per second. In terms of revolution per minute (rpm), the synchronous speed is, $N_s=120F/P$ rpm.

The air gap flux φ_{ag} rotates at a synchronous speed relative to the stationary stator windings. As a consequence, a counter emf, called the air gap voltage E_{ag} is induced in each of the stator phases at a frequency f.

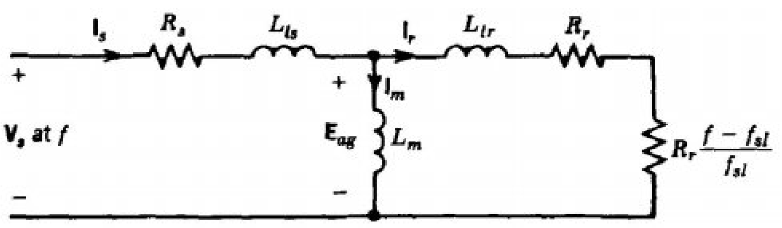


Figure 5.5: Equivalent Circuit of Induction Motor

The airgap voltage $E_{ag} = kf\varphi_{ag}$ (eqn.2)

The torque in an induction motor is produced by interaction of the air gap flux and the rotor currents. If the rotor is rotating at the synchronous speed, there will be no relative motion between φ_{ag} and the rotor, and hence there will be no induced rotor voltages, rotor currents and torque. At any other speed ω_r of the rotor in the same direction of the air gap flux rotation, the motor is slipping with respect to the air gap flux.

Torque, $T = k\varphi_{ag}I_r = k\varphi_{ag}{}^2 f_{sl}$ (eqn.3)

For normal motor parameters, except for low values of operating frequency f,

Applied voltage, $V_s = E_{ag} = kf\varphi_{ag}$ (eqn.4)

The slip frequency $f_{sl} = sf$ (eqn.5)

The following important observations can be drawn from these relations:

1. The synchronous speed can be varied by varying the frequency f of the applied voltages (eqn.1).
2. With small f_{sl}, except at low values of f, the slip s is small and the motor speed varies approximately linearly with the frequency f of the applied voltages (eqn.5).
3. For the torque capability equal to the rated torque at any frequency, Q_{ag} should be kept constant (eqn.3) and equals to its rated value. Here Vs is varied proportional to frequency ‘f’.

From the above statements it can be concluded that the motor speed can be varied by controlling the applied frequency f, by keeping air gap flux constant at its rated value. Here the applied voltage is varied in proportions with ‘f’ so that V/F remains constant.

Induction Motor Characteristics at rated (line) frequency and rated voltage

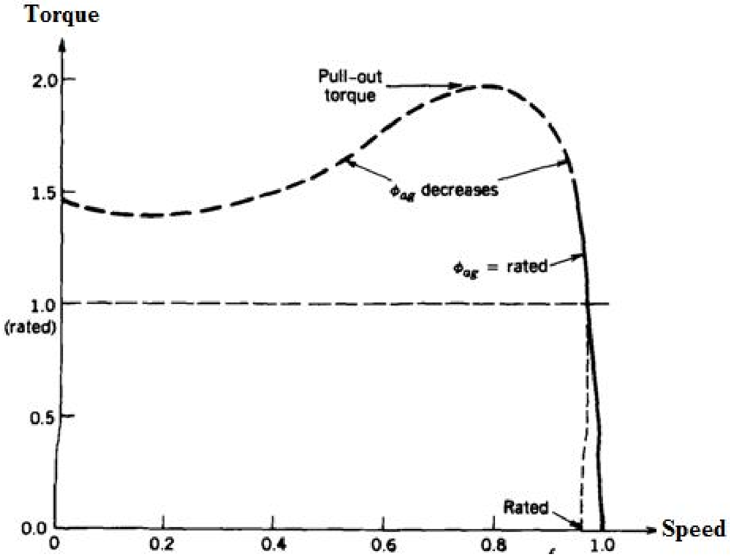


Figure 5.6: Speed – Torque characteristics

The speed torque curve of an induction motor is a plot of speed on the x-axis and torque on the y-axis. When the motor is started, the initial torque is about 150% of the rated torque. This is the torque required by the motor to overcome the inertia at standstill. As the motor picks up speed the torque drops to the pull-up torque. If the pull-up torque of a motor is less than the torque requirement of the load the motor will stall and over heat. The full load torque is the torque produced by a motor operating at the rated speed and load. Exceeding the full load torque causes reduction in the life of the motor. When the motor is run on no load, the rotor speed reaches the synchronous speed. The slip becomes zero and the motor runs at zero torque.

5.6.3 Speed Control by Varying Stator frequency and voltage

1. **Torque Speed characteristics**

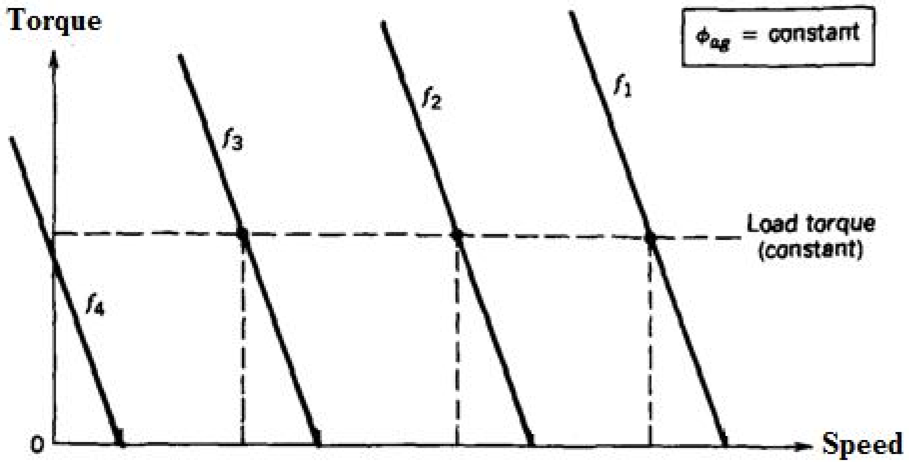


Figure 5.6: Speed Torque characteristics with constant air gap flux and constant load torque

The speed torque characteristics shifted horizontally in parallel for different values of frequency f is shown in figure. Consider two frequencies f_1 and f_2. The synchronous speeds n_{s1} and n_{s2} are in proportion to f_1 and f_2. If an equal load torque is to be delivered at both these frequencies, slip should be equal. Therefore, in the speed torque characteristics equal torque and equal slip speeds (at f_1 and f_2) result in parallel but shifted horizontally.

2. **Start up considerations**

For a solid-state inverter driven induction motor, it is an important to keep the large starting current during start-up. This can be achieved by considering the following relationship:

For a constant φ_{ag} ,

$$Ir = kf_{sl} \qquad \text{(eqn.6)}$$

From equation (3) and (6), torque and rotor current are plotted in figure to show how the motor can be started at a small applied frequency f (=f_{start}). Since at start-up f_{sl} equals f_{start}, the rotor current can be limited by selecting appropriate f_{start}. The stator current is limited, due to constant φ_{ag} with constant magnetizing current.

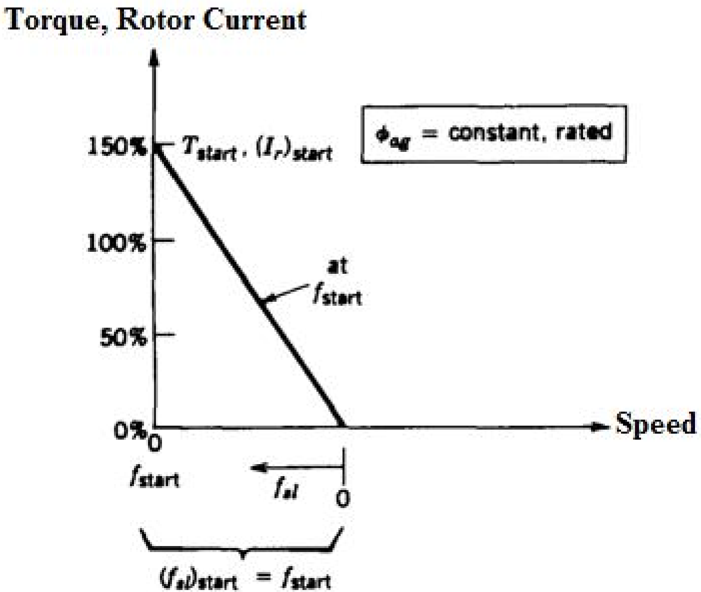
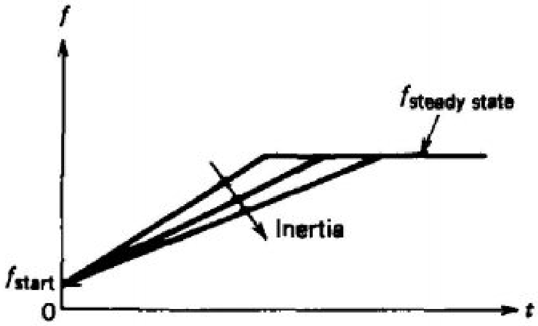


Figure 5.7: Torque and Rotor Current

Frequency at start-up

In practice, the stator frequency is increased continuously at a preset rate, as shown in figure which does not let the stator current exceed a specified limit. This rate is decreased for higher inertia loads to allow the rotor speed to catch up.



Ramping of frequency at start-up

5.6.4 Voltage Boost required at low frequencies

The effect of stator resistance cannot be neglected at low value of operating frequency . For constant φ_{ag},

$$V_s \approx kf + R_s I_r \qquad \text{(eqn.7)}$$

Equation (7) shows that the additional voltage required to compensate voltage drop across R_s to keep φ_{ag} constant does not depend on the supply frequency, f but depends on I_r .

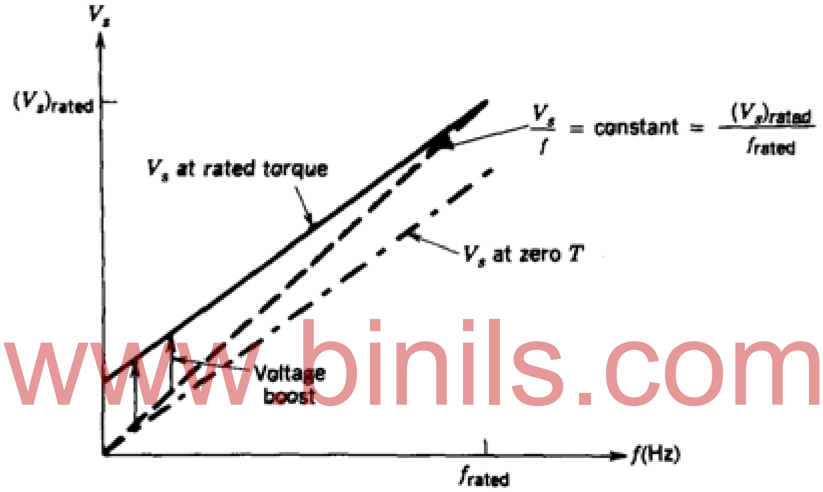


Figure 5.8: Voltage boost required to keep φ_{ag} constant

Figure shows that to keep φ_{ag} constant, a much higher percentage of voltage boost is required. It is needed at low operating frequencies due to the voltage drop across R_s. At large values of f, voltage drop across R_s can be neglected. The voltage required at no load is shown by a short- long dashed line.

5.6.5 Induction Motor Capability below and above the rated speed

Speed control by means of frequency (and voltage) variation allows the capability to operate the motor not only at below the rated speed but also at above the rated speed. This capability is very attractive in many applications, since most induction motors, are of rugged construction. It can be operated up to twice the rated speed without mechanical problems.

However, the torque and power capabilities as a function of rotor speed need to be clearly established.

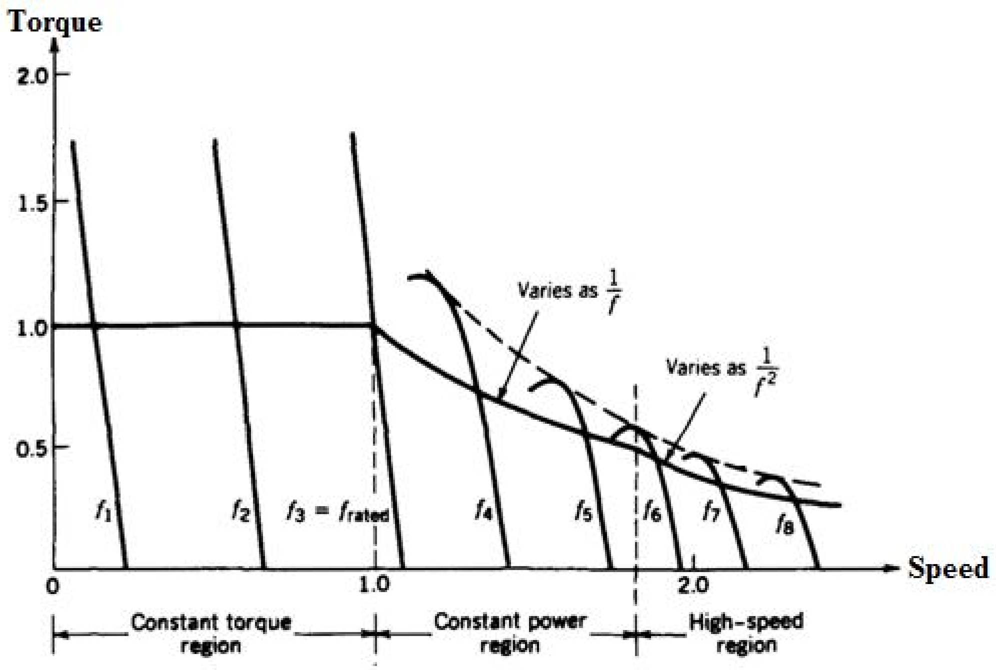


Figure 5.9: Induction motor Characteristics and capabilities

In the region of speed below its rated value, φ_{ag} is maintained constant by controlling V_s/f. If φ_{ag} is maintained constant, the motor can deliver its rated torque. Therefore, this region (below the rated speed) is called the constant torque region.

By increasing the frequency above its nominal (rated) value, it is possible to increase the motor speed beyond the rated speed. By keeping the V_s at its rated value, increasing the frequency f results in a reduced V_s/f and hence reduced φ_{ag} and torque. In this region speed*torque = power is constant. Therefore, this region (above the rated speed) is called the constant power or constant HP region.

With V_s equal to its rated value, beyond certain speed (nearly $2*n_s$), torque approaches to pullout torque. Torque declines with $1/f^2$.

5.6.6 Variable frequency Converter Classifications

The variable frequency converters, which act as an interface between utility power system and the induction motor, must satisfy the following basic requirements:

1. Ability to adjust the frequency according to the desired output speed.
2. Ability to adjust the output voltage so as to maintain a constant air gap flux in the constant torque region.
3. Ability to supply a rated current on a continuous basis at any frequency.

Figure illustrates the basic concept where the utility input is converted into dc by means of either a controlled or an uncontrolled rectifier and then inverted to provide three phase voltages and currents to the motor, adjustable in magnitude and frequency.

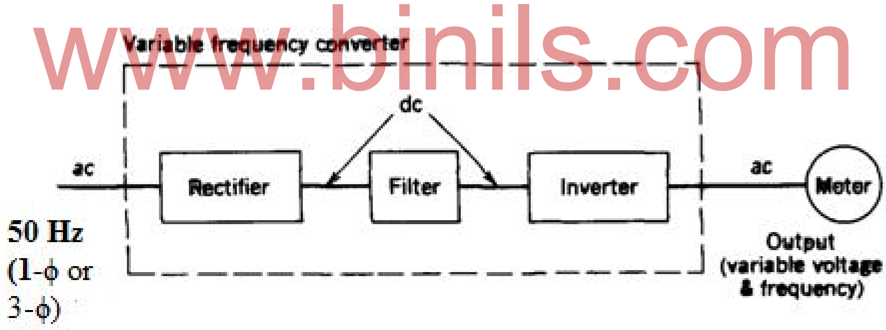


Figure 5.10: Variable frequency converter

Variable frequency converters can be classified based on the type of rectifier and inverter used.

1. Pulse width modulated voltage source inverter (PWM-VSI) with a diode rectifier.
2. Square wave voltage source inverter (square-VSI) with a thyristor rectifier.
3. Current source inverter (CSI) with a thyristor inverter.

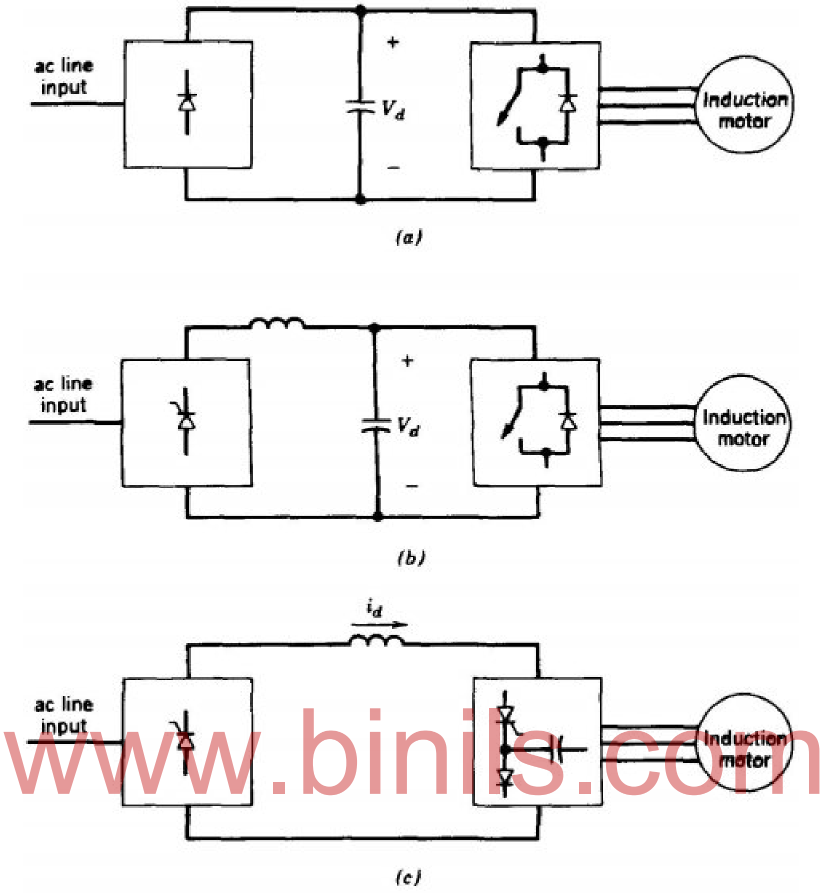


Figure 5.11: a)PWM-VSI with a diode rectifier b) square wave VSI with a controlled rectifier c) CSI with a controlled rectifier

Figure (a) shows the PWM-VSI with a diode rectifier and (b) shows the square wave-VSI inverter where a controlled rectifier is used at the front end and the inverter operates in a square wave mode (also called the six step). The line voltage may be single phase or three phase. In both VSI converters, large dc bus capacitor is used to make the input to the inverter with very small internal impedance. Figure (c) shows the schematic of CSI drive in which a line commutated converter is used at the front end. Because of a large inductor in the dc link, the input to the inverter appears as a dc current source. The inverter utilizes the thyristors, diodes and capacitors for forced commutation.

5.7 Variable frequency PWM-VSI Drives

Figure (a) shows a schematic of PM-VSI drive, assuming a three phase utility input. PWM inverter controls both the magnitude and frequency of the voltage output. Therefore, at the input, an uncontrolled diode bridge rectifier is generally used.

One possible method of generating the inverter switch control signal is by comparing three sinusoidal control voltages (at the desired output frequency and proportional to the output voltage magnitude) with a triangular waveform at a selected switching frequency as shown in figure (b).

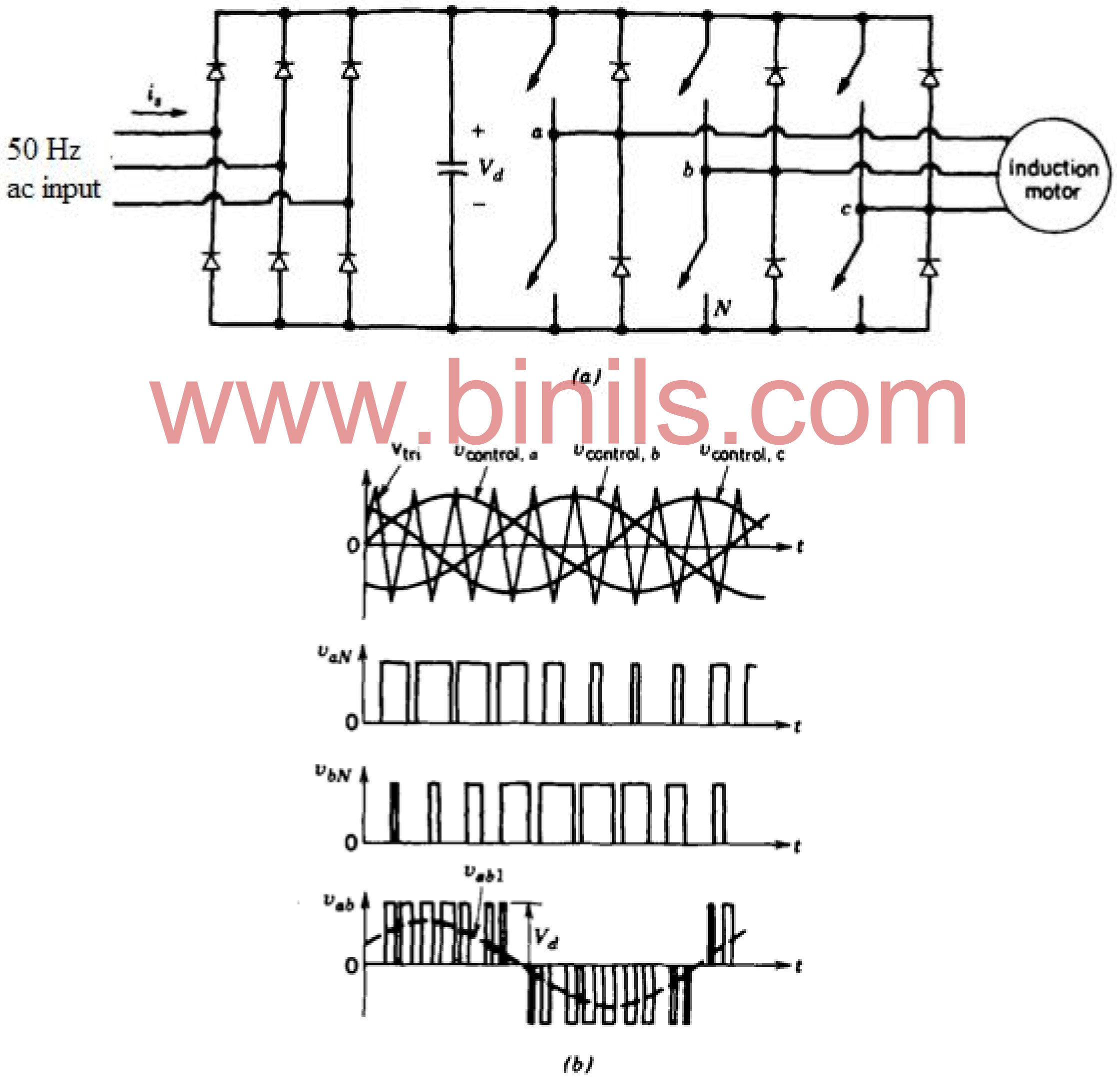


Figure 5.12: a) PWM-VSI schematic b) waveform

5.8 Line frequency Variable-Voltage Drives

In some applications, it may be cheaper to use line frequency variable – voltage drives. In induction motor, the torque is proportional to square of the supply voltage.

$$T = kV_s^2 \qquad \text{(eqn. 8)}$$

Based on equation (8), Figure shows the motor speed-torque curves at various values of V_s. The load torque of a fan or pump-type load varies approximately as the square of the speed. Therefore a small torque is required at low speeds, and as figure shows, the speed can be controlled over a wide range.

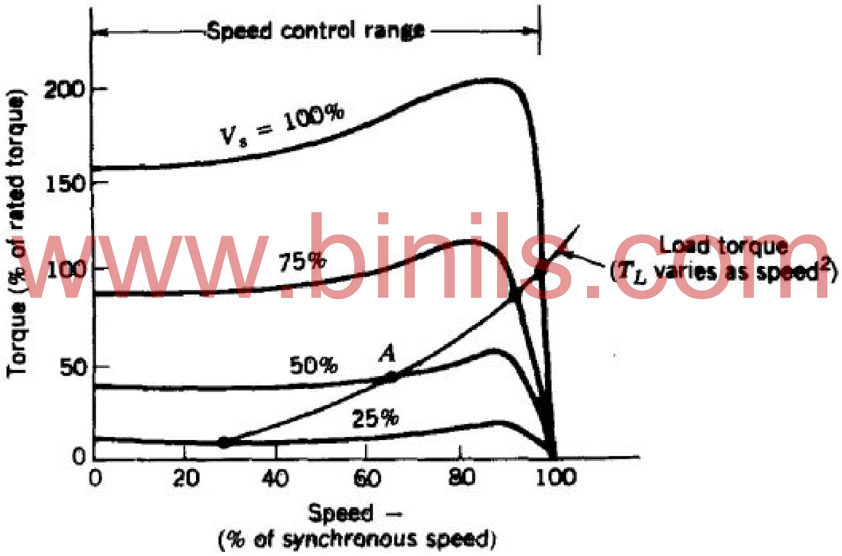


Figure 5.13: Speed Control Range

A practical circuit for controlling the stator voltage of a three phase induction motor is shown in figure. It consists of three pairs of back-to-back connected thyristors.

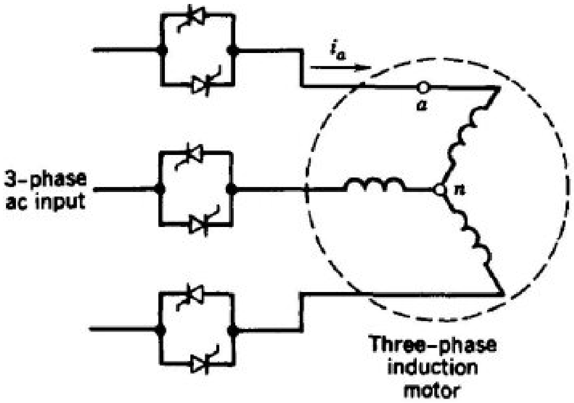


Figure 5.14: Stator Voltage Control Circuit

5.8.1 Reduced Voltage Starting ("Soft Start") of Induction Motors

The circuit used for stator voltage control can also be used in constant-speed drives to reduce the motor voltage and hence current at start-up. If the torque developed at reduced voltage is sufficient to overcome the load, the motor accelerates. During starting, the firing angles of the thyristors are high. During the steady state operation, each thyristor conducts for an entire half cycle. Then, these thyristors are shorted by mechanical contactors to eliminate the power loss in the thyristors.

5.9 Speed Control by Static Slip-Power Recovery

From the induction motor equivalent circuit, it is possible to obtain speed-torque characteristics for various values of rotor resistances. In a wound-rotor induction motor, the rotor resistance can be varied by adding an external resistance through the slip rings. The speed of operation can be continuously varied by varying the rotor resistance.

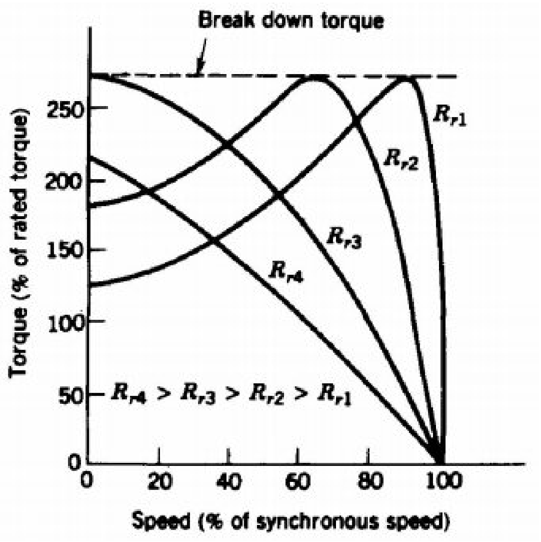


Figure 5.15: Speed control by rotor resistance

In the static slip power recovery scheme, the slip power is saved without dissipating in the external resistance. The resistances are simulated by means of a diode rectifier and the energy recovered is fed back to ac supply by means of a line commutated inverter.

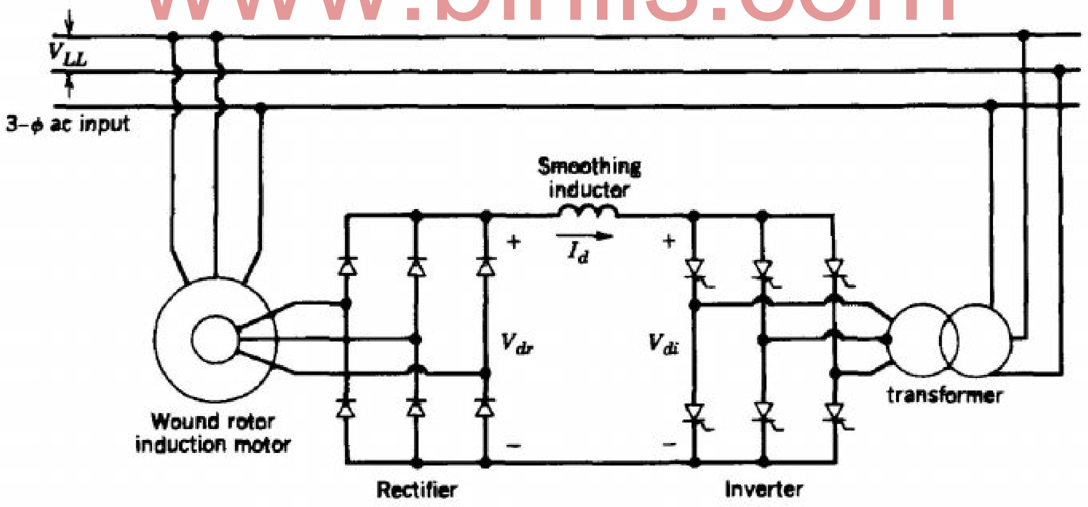


Figure 5.16: Static slip power recovery scheme

POWER ELECTRONICS MODEL QUESTION PAPER-1

PART-A

1. Mention the major areas of applications of power electronics.
2. What is firing angle of SCR?
3. Mention the control methods for varying duty ratio.
4. State the advantages of using pulse transformer in trigger circuit.
5. What do you mean by constant power region?
6. Expand IGBT and draw its symbol.
7. Mention the applications of three phase inverters.
8. Mention the voltage control techniques commonly used for three phase inverter and what drawback does it cause?

PART-B

9. Briefly write a note on classification of thyristor rating.
10. Give a brief note on polarized snubber circuit.
11. What is the necessity for adding two diodes in single phase bidirectional controllers?
12. Draw the input and output waveforms of half wave controlled rectifier with resistive load.
13. Briefly explain the Buck converter
14. Write a brief note on high frequency electronic ballast..
15. Draw the schematic of AC solid state relay using an optocoupler.
16. Write a note on stator voltage control.

PART-C

17. Explain briefly the three operating modes of SCR

    (OR)

    Discuss the effect of armature current in discontinuous mode of phase controlled converters
18. Explain the operation of three phase bidirectional controller.
19. Write a note on important specification of SCR
20. Explain the operation of class E commutation using thyristor.
21. Explain the operation of single phase full converter
22. Explain the operation of synchronized UJT triggering circuit with a neat diagram.
23. Explain the operation of single phase cyclo converter with a neat diagram.
24. Explain the operation of Buck-Boost converter.
25. Draw the schematic of single phase bridge inverter with its output waveforms.
26. Draw the circuit diagram of full bridge SMPS.
27. Explain the operation of voltage source series resonant inverter for induction heating.
28. Explain thyristor controlled inductor.

29. Draw the circuit diagram of separately excited DC motor and its operating regions and explain.
30. Explain the operation of PWM-VSI drives.
31. Explain the operation of slip ring motor speed control using slip power recovery scheme.

POWER ELECTRONICS MODEL QUESTION PAPER-2

PART-A

1. Define switching speed of a semiconductor devices.
2. Define chopper. What are the applications of chopper?
3. Define commutation. What are the types of commutation?
4. Define cyclo converters. Give the applications.
5. Define inverter gain. Mention the commonly used techniques to vary the inverter gain.
6. What is the need of UPS? Mention the types of UPS.
7. Draw the block diagram of AC circuit breaker.
8. List the advantages of using no break UPS configuration.

PART-B

9. List the types of power electronic circuits.
10. Write a note on class F commutation.
11. Draw the circuit diagram of three phase dual converter.
12. Draw the input and output waveform of single phase half bridge inverter.
13. List the types of techniques used for voltage control of three phase inverter.
14. Compare on line UPS and off line UPS.
15. Draw the torque speed curves for a wound rotor induction motor.
16. Draw the schematic diagram of current source parallel resonant inverter for induction heating.

PART-C

17. Explain the operation of SCR.

    (OR)

    Discuss the effects of dv/dt and snubber circuits
18. Explain RC firing circuit
19. Explain Class D commutation.
20. Draw the circuit diagram of three phase full converters with its output waveforms.
21. Draw the circuit diagram, input and output waveforms of three phase cycloconverter.
22. Explain the operation of Boost converter.
23. Explain the operation of single phase half bridge inverter.
24. Explain the principle of single pulse width modulation.
25. Explain the operation of optocoupler with photo SCR.
26. Write a note on thryristor-switched capacitors.
27. Explain the operation of AC solid state relay using a pulse transformer.
28. Draw the block diagram for interconnection of wind/hydro power generator to the utility system and explain.
29. Explain single phase dual converter

30. Draw the torque speed characteristics of induction motor and explain the various regions
31. Explain the operation of stator voltage control in induction motor.

POWER ELECTRONICS MODEL QUESTION PAPER-3

PART-A

1. What is the other name for intelligent module?
2. Define latching current and holding current
3. Expand SCR and draw its symbol.
4. What is natural commutation?
5. Give the applications of inverter
6. List two advantages of HVDC transmission over AC transmission system.
7. Write the classification of variable frequency converter.
8. What is the need for soft start in induction motor?

PART-B

9. Explain the use of RC snubber circuit in thyristor converters.
10. Calculate the average DC output voltage of half-wave controlled rectifier with resistance load.
11. Give the advantages of operation of dual converters with circulating current.
12. What are the advantages of using free wheeling diode?
13. Draw the circuit diagram of CUK converter.
14. Draw the schematic diagram of welding with series regulator and explain.
15. Write a brief note on static var controller.
16. Draw the speed vs torque characteristics of induction motor drives.

PART-C

17. Draw the block diagram of a typical HVDC transmission system and explain briefly.

    (OR)

    Draw the schematic of welding with step down dc-dc converter and explain.
18. Explain the operation of three phase to single phase cyclo converter.
19. With a neat diagrams, explain 12 pulse converter.
20. Explain the operation of fiber optic cable based DBC.
21. Explain the operation of resistance trigger circuits.
22. Explain the operation of class B commutation.
23. Explain the principle of single phase thyristor converter.
24. Explain the operation of continuous conduction mode of step up converter.
25. Draw the schematic diagram of 180^0conduction mode of three phase inverter with its waveforms.
26. Explain the operation of sinusoidal pulse width modulation.
27. Explain the operation of no break UPS configuration.
28. Explain the operation of switch mode welder.
29. Explain the four quadrant operation of a DC motor drive.

30. Write the basic DC motor speed equation and draw the speed torque characteristics of DC shunt motor mentioning the armature and field control region.
31. Draw the circuit and output waveforms of stator voltage control.