USING POWER SEMICONDUCTOR TO DRIVE THE THREE PHASE INDUCTION MOTORS

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ABSTRACT

Since Faraday discovered the phenomenon of mutual induction and invented the first electrical motor based on this phenomenon in the nineteenth century, electrical engineers and researchers development the materials which used in manufacture of the electrical motors as; the iron core, the conductor of the windings, insulation materials and so on. In that time, the AC motors were used to run the loads by constant speed. With development of power semiconductor devices and control theories, the AC motors were used to run the loads by varying speed. In this time, the DC motors were replaced by the AC motors. This book explained how frequency converters are used to control the speed of three-phase induction motors. These motors have been chosen due to their prevalence in many industrial applications such as transmission, pumps, fans, conveyors, refrigeration, air-conditioning, etc.

This book started by talking about the basic components of any driving system and reviewing how to choose the driving system, how to choose the electric motor and it explained the mechanical loads that are most famous in practical applications. It is talking about the types of the drive systems in the marketing. It explained the main principle parts of the three-phase induction motor. The performance characteristics of induction motors. Induction motor starting methods e.g., traditional and modern and how to overcome the problems of these methods. Also, speed converters and their parts have been fully explained. Methods of generating pulses were explained as, the 120 degree and 180 degree and the pulse width modulation method, and how to control the speed of induction motors by traditional methods and modern methods. The control systems with open loop and closed loop have also been explained and their advantages, disadvantages and applications are mentioned. The open loop scalar control and closed loop scalar control were explained in different mode of operation and how to improve it. The last chapter fully explained how to design the

frequency converter to drive the three-phase induction motor. It explained the printed circuit board through the Altium program. It explained the operation of this frequency converter under loads.

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CHAPTER (1)

VARIABLE SPEED DRIVES

When the humans need travel from town to town in any country, there many ways to transport them as the bus, van, taxi and metro. Most of these people prefer using the metro to reach their goal on time. This is because the metro is a modern transportation has drive system. This drive system can be controlled easily so, with this controller the driver of the metro can be controlled the speed of the motor to reach on time. So, when we need motion control, we need electrical drive system. The electrical drives system can control the motion of the load by controlling their motors speed. From this introduction for the electrical drive system lets define what is the meant by drive system.

Definition: The electrical drive system is defined as the system which is use for controlling the speed, torque and direction of an electrical motor. Each electrical drive system is different from other electrical drive systems, but there are some common features associated with all electrical drive systems.

Or: The system which is used for controlling the motion of an electrical machine, such type of system is called an electrical drive. In other words, the drive which uses the electric motor is called electrical drive. The electrical drive uses any of the prime movers like diesel or a petrol engine, gas or steam turbines, steam engines, hydraulic motors and electrical motors as a primary source of energy. This prime mover supplies the mechanical energy to the drive for motion control.

1-1 Elements of the drive systems:

The elements of the drive can be seen in Fig. 1-1. From this Fig. can be concluded that the main elements of the drive are:

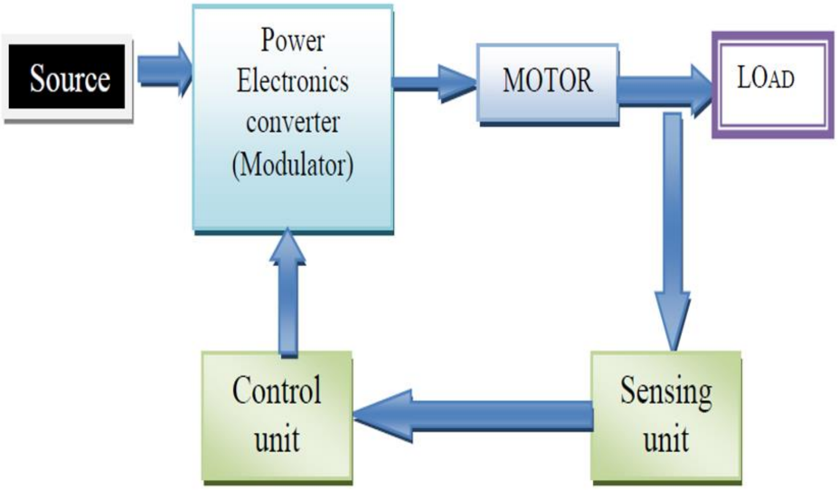


Fig. 1-1 Elements of the drive systems

1. The electrical source.
2. The power converter.
3. The motor.
4. The load.
5. The sensing unit.
6. The controlling unit.

These elements of the drive system can be explained as the follows;

Firstly, electrical source:

The electrical source is a supply of the power. This power can be defined as the rate of energy consumed in a unit time. Electrical power can be classified as AC Power or DC Power depending upon the direction of the flow of energy. Here AC stands for alternating current and DC stands for direct current. Power which is a result of current flowing in alternating direction is termed as AC Power and one which is a result of current flowing in only one direction is called DC Power. The electrical source or the electrical power feeds the electrical drive system by energy. The electrical power can be classified into two main types. These types are;

1- Alternating current (AC sources).
2- Alternating Current may be single phase or three three-phase, 50Hz or 60 Hz, 240V/415V, 220V/380V, 120V/90V, 11kV/415V, etc.
3- Direct current (DC sources).

Direct current sources have many different types of the level DC voltage as 6V, 12V, 24V, 230V, etc.

Extensive industrial installation usually has more than one type of power sources at different voltages and frequencies, Commercial airplanes, for examples, may have a 400Hz AC sources in additional a 270Vsources.

Secondly, the power converter:

The power converter interfaces the motor with the power source and provides the motor with adjustable voltage, current and/or frequency. The main function of the power converters is to transform the waveform of a power sources to that the required by an electric motor in order to achieve the desired performance. Also, the power converter Selects the mode of operation of the motor, i.e. Motoring or Braking.

There are many types of the power converters. These types can be classified into;

1. DC to AC converter (inverter). The output of this converter is frequency, current/voltage can be adjusted according to the application

2. DC to DC converter (DC chopper). The output of this converter is variable magnitude of voltage.

3. AC to DC converter (rectifier). The output of this converter is variable magnitude of dc voltage, input is single or three-phase AC voltage.

4. AC to AC converter (AC chopper). The output of this converter is frequency and AC variable voltage, the input is constant frequency and ac voltage.

Thirdly, the electrical motor:

The electrical motors are used worldwide in many residential, commercial, industrial, and utility applications. Motors transform electrical energy into mechanical energy. the motor may be part of a pump or fan, or connected to some other form of mechanical equipment such as a winder, conveyor, or mixer.

Electric motors have of various types as

1- DC motors

The DC motors can be divided in four types – shunt wound DC motor, series wound DC motor, compound wound DC motor and permanent magnet DC motor.

2- AC motors

AC motors are of two types – induction motors and synchronous motors. Now synchronous motors are of two types – round field and permanent magnet. Induction motors are also of two types – squirrel cage and wound motor.

3- Special motor

Besides all above motors, there are some types of the motor called special motor as, stepper motors and switched reluctance motors are also considered as the parts of drive system.

<u>The basic criterion in selecting an electric motor for a given drives application:</u>

1. Power level and performance required by the loads during steady state and dynamic operation.

   Ex: In application for which a high starting torque is needed a DC series motor might be a better choice than an AC induction motor. In Constant speed applications, synchronous motor be more suitable than induction or DC motors.
2. Environmental factors (determine the motor type)

   Ex: In food processing, chemical industries, aviation, where the environment must be clean and free from arcs, DC motor cannot be used unless they are encapsulated.
3. The cost of the electric motors.

In general, brushless dc motors are more expensive, whereas squirrel cage induction motors are the cheaper

4. The function of converters (wave forms)

Ex: If the power source is an AC type and the motor is a DC machine. The converter transforms the ac waveform to DC. (stability, efficiency and performance of motor that using this converter.

Fourthly, the mechanical loads:

The mechanical load has many components. These components are;

1. Friction Torque (TF)

The friction torque (TF) is the equivalent value of various friction torques referred to the motor shaft.

2. Windage Torque (Tw)

When a motor runs, the wind generates a torque opposing the motion. This is known as the winding torque.

3. Torque required to do useful mechanical work (Tm)

Classifications of Various Types of Loads

Most of the industrial loads can be classified into the following two categories:

(i) Load torques varying with time:

- Constant continuous type loads: Loads operating continuously for the same loading (same torque) conditions for a long time.
- Continuous variable loads: Loads varying and having duty cycle.
- Pulsating loads: Loads of machines with crank shafts.
- Impact loads: Regular repetitive load peaks such as in rolling mills,

forging hammer, etc.

- Short time loads (e.g. hoists).

(ii) Load torques varying with speed:

- Load torques which are independent of speed (e.g. Cranes).
- Load torques proportional to speed (Generator type load).
- Load torques proportional to square of the speed (Fan type load).
- Torque inversely proportional to speed (Constant power type load).

Load Torque-Speed Characteristics:

Speed-torque characteristics of the load must be known to calculate the acceleration time and to select the proper type of motor to suit the load. The load speed-torque characteristics of industrial loads are generally nonanalytical function $T_L = f(\omega)$. However, some of them may be approximated to an analytic form such as the following empirical formula $T_L = CT_r(\frac{n}{n_r})^k$

Where C is proportional constant, T_L is the load torque, T_r is the rated torque, n_r is the rated speed, n is motor speed, k is exponential coefficient representing the torque dependency speed.

1- Constant Torque characteristics: $T_L = k$

Most of the working machines that have mechanical nature of work like shaping, cutting, grinding or shearing, require constant torque irrespective of speed, (See Fig.1-2). Similarly cranes during the hoisting and conveyors handling constant weight of material per unit time also exhibit this type of characteristics. By applying the imperial formula, we find that, the value of k takes zero.

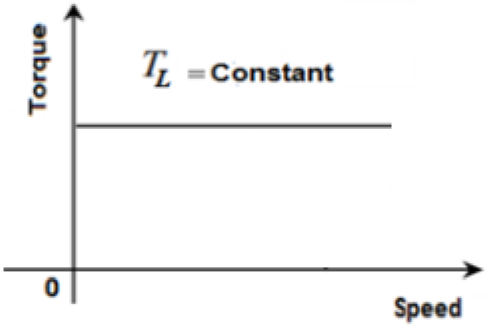


Fig. 1-2 Torque speed characteristics for constant load torque

2- Torque Proportional to speed: ***TL= kω***

Separately-excited DC generators connected to a constant resistance load; eddy current brakes have speed-torque characteristics given by *TL= kω*. This can be seen in Fig. 1-3. From empirical formula, the value k of takes one.

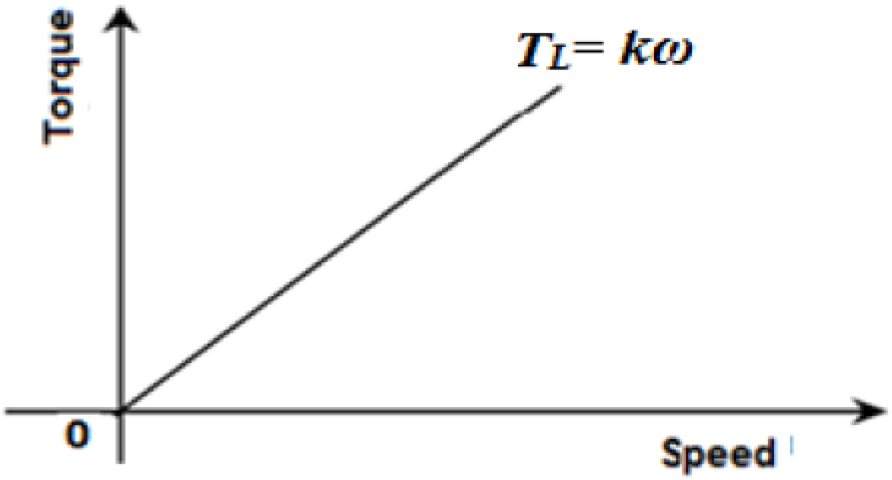


Fig. 1-3 Torque speed characteristics for load torque proportional to speed

3- Torque proportional to square of the speed: ***TL= kω***^{2}

Another type of load met in practice is the one in which load torque is proportional to the square of the speed, e.g.: Fans, rotary pumps, compressors and ship propellers. From imperial formula k takes two. The characteristics of this load can be seen in Fig. 1-4.

4- Torque Inversely proportional to speed: $T_L \alpha \frac{1}{\omega}$

In this type of the loads and from imperial formula k takes mins one the torque is inversely proportional to motor speed. Certain types of the load are working by this method as; lathes, boring machines, milling machines, steel mill coiler and electric traction load exhibit hyperbolic speed-torque characteristics as shown in Fig.1-5.

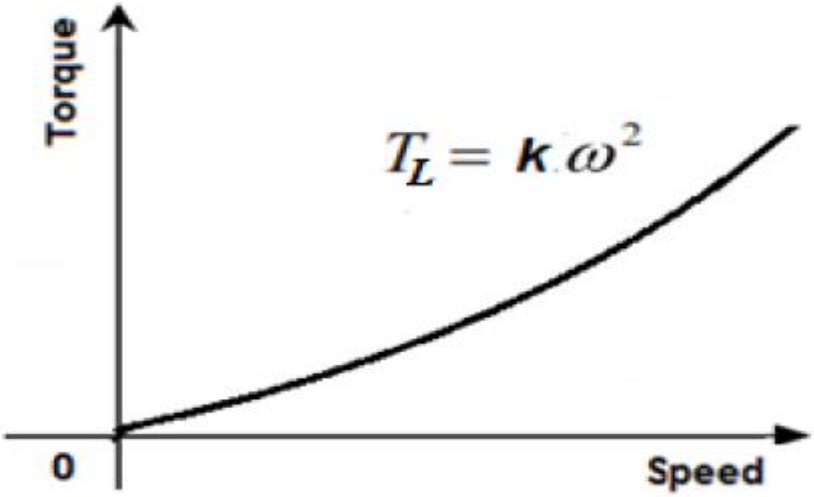


Fig. 1-4 Torque speed characteristics for load torque proportional to squared speed

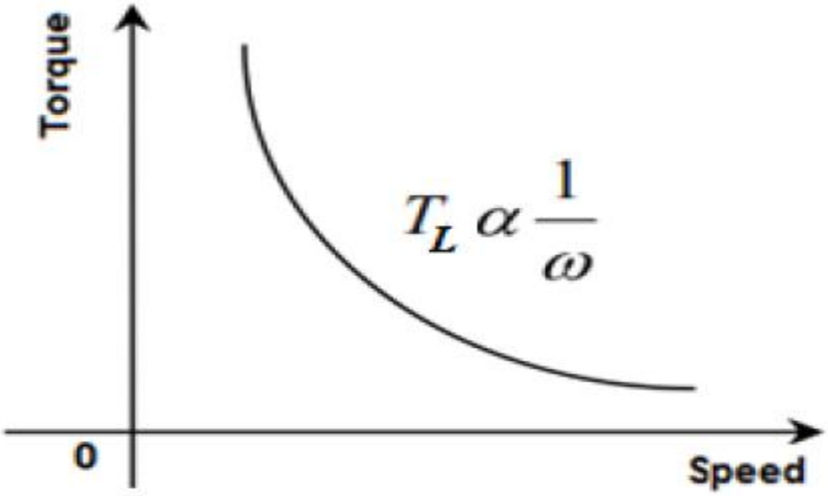


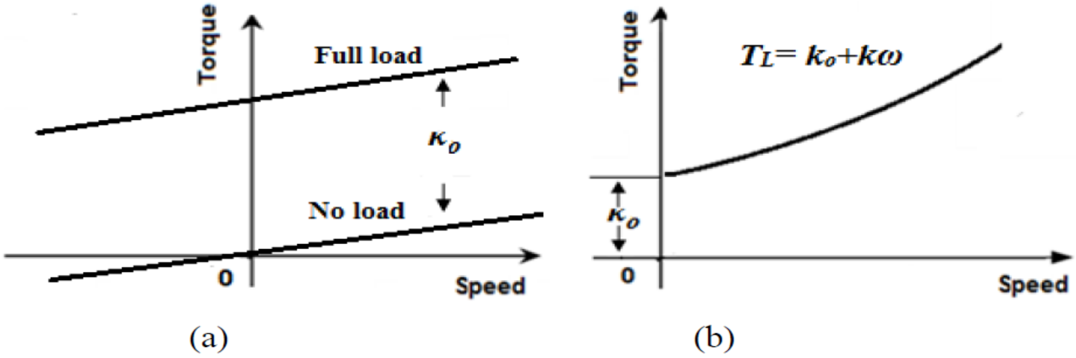
Fig. 1-5 Torque speed characteristics for load torque inversely proportional to speed

5. Torque polinomialy related to the speed:

For the particular characteristics of Fig.1-6 each example may be approximated to a polynomial form:

T_L= ko+kω for a hoist or elevator (Fig.1-6a)

T_L= ko+k_1 ω+$k_2$$\omega^2$+ ...... for a compressor (Fig.1-6b)



(a) (b)

Fig.1-6 Torque approximated to a polynomial form

Fifthly, sensing unit:

The sensing unit may be one sensor or more. The sensor is a type of device which detects and then responds according to some input received from the physical environment. The input can be in any form like heat, light, pressure, moisture, motion, current, voltage and other environmental factors. And then the sensor device does some processing on the collected input and generates an output that is in a human-readable form. The sensor devices can be used in home appliances, industries, and other sectors.

Sixly, controller unit:

Controller for a power modulator matches the motor and power converter to meet the load requirements.

1-2 Classification of Electric Drives:

Electric drives may be classified as follows:

1. According to Mode of Operation

- Continuous duty drives
- Short time duty drives
- Intermittent duty drives

2. According to Means of Control

- Manual
- Semi-Automatic
- Automatic

3. According to Number of machines -motor drive

- Individual drive
- Group drive
- Multi-motor drive

4. Another main classification of electric drive is

- DC drive
- AC drive

Because this course is for AC drive so, the following table is compared to the DC drive and AC drive.

1-3 Advantages of the drive system:

A modern variable speed electrical drive system is a static system using power semiconductor devices such as thyristors (SCRs) and power transistors. These systems have replaced the old pneumatic or hydraulic drives as well as electromechanical and other forms of control to electronic control using SCR's drive which has the following advantages:

1. Basic operation is simple and reliable.

2. Saving in space and capital cost.

3. Low starting current.

4. Accelerating and braking time can be controlled

5. Higher efficiency.

6. Better speed response.

7. Low maintenance cost and long life.

8. Braking power can be transformed into electrical power and feedback to the main supply.

DC drive	AC drive
Well established technology	The power circuit and control circuit are complex
Requires frequent maintenance	Less Maintenance
The commutator makes the motor bulky, costly and heavy	No commutator problems exist in these motors and they are inexpensive, particularly squirrel-cage induction motors
Speed and design ratings are limited due to commutations	Fast response and wide speed range
Poor power factor	Good line power factor
Environmentally sensitive	Environmentally insensitive

Table 1-1 Comparing between DC electrical drives and AC electrical drives

1-4 Applications of Electrical Drives:

Electric drives are used in several industrial applications such as:

1- Paper mills.
2- Steel mills.
3- Cement mills.
4- Textile mills.
5- Sugar mills.
6- Electric traction systems.
7- Electrical vehicles.
8- Petrochemical industries.

1-5 Choice of Electrical Drives:

The choice of an electrical drive depends on a number of factors. Some important factors are:

- Steady state operation requirements: (nature of speed-torque characteristics, speed regulation, speed range, efficiency, duty cycle, quadrants of operation, speed fluctuations, rating etc).

- Transient operation requirement (values of acceleration and deceleration, starting, braking, speed reversing).

- Requirement of sources:(types of source, its capacity, magnitude of voltage, power factor, harmonics etc).

- Capital and running cost, maintenance needs, life periods.

- Space and weight restrictions.

- Environment and location.

- Reliability.

1-6 Traction system:

A system which causes the propulsion of vehicle or railway vehicle in which tractive or driving force is obtained from various devices such as diesel engine drives, steam engine drives, electric motors, etc. is called as traction system.

The traction system can be classified as non-electric and electric traction systems.

1- Non-electric Traction System:

A traction system that doesn’t use electrical energy for the movement of vehicle or railway vehicle at any stage is referred as non-electric traction system.

The steam engine drive is the best example of a non-electric traction system and it is the first locomotive system used before the invention of actual electric traction systems. This can be seen in Fig. 1-7. This may use coal or petroleum as fuel, liberates thermal energy to produce the steam pressure and then it is converted into kinetic energy so that mechanical movement of the vehicle is produced. This may use coal or petroleum as fuel, liberates thermal energy to produce the steam pressure and then it is converted into kinetic energy so that mechanical movement of the vehicle is produced as seen in Fig. 1-8.

Fig. 1-7 The steam locomotive system uses the superheated steam to produce mechanical energy for the movement of vehicle.

The disadvantages of steam locomotive systems, such as, low fuel efficiency, poor technical performance, maintenance of a large number of water supply facilities, and high maintenance cost makes them to be replaced by alternative traction systems and hence the electric traction.

The types of non-electric traction systems:

a. Steam engine drive-based vehicles (used for railways)

b. Internal combustion (IC) engine drive-based vehicles (used for road transport)

c. Maglev trains

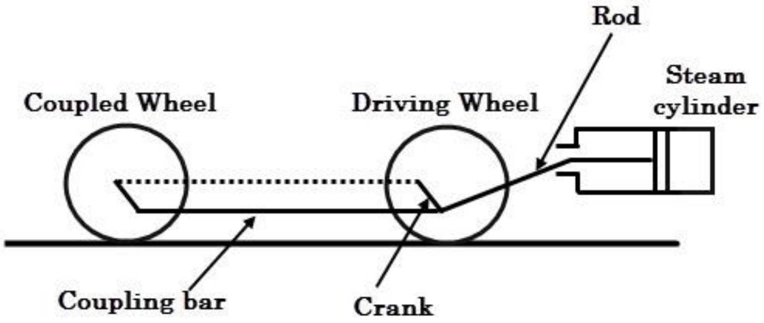


Fig. 1-8 to operate the locomotive through the steam

2- Electric Traction System

Electric traction involves the use of electricity at some stage or all the stages of locomotive movement. This system includes straight electrical drive, diesel electric drive and battery-operated electric drive vehicles.

In this, electrical motors are used for producing the vehicle movement and are powered by drawing electricity from utilities or diesel generators or batteries. This can be seen in Fig. 1-9.

Advantages of the electric traction systems:

a. Cheapness. It is cheapest method of all other methods of traction.

b. Cleanliness. It is free from smoke and flue gasses

c. Maintenance cost. Maintenance and repair cost is about 50% of steam traction system.

d. Starting time. It can be started without loss of time.

e. High starting torque. This system uses of DC and AC series motors which has a very high starting torque.

f. Braking. In electric traction, regenerative breaking is used which feeds back 40%of the energy.

g. Saving in high grade coal. No coal is required for electric traction.

Fig. 1-9 Example of the electric traction system

Disadvantages of the electric traction systems:

a. Higher initial expenditure.

b. Failure of supply is a problem.

c. Additional equipments are required for breaking purposes.

d. The electrically operated vehicles have to move only on electrified track.

e. Interference with telegraphs and telephone lines.

Supply Systems for Electric traction:

1- D.C system

2- A.C system

- Single phase

    - Three phase
4. Composite system
    - Single phase AC to DC
    - Single phase to three phase

Factors affecting energy consumption:

1. Distance between the stops.
2. Train resistance
3. Acceleration and retardation.
4. Gradient
5. Train equipment.

Traction motors:

1. DC series motor
2. Ac series motor
3. Three phase induction motor

Traction motor electrical features:

1. High starting torque
2. Simple speed control
3. Regenerative braking
4. Better commutation
5. Capability of withstanding voltage fluctuations.

Mechanical features

1. Light in weight.
2. Small space requirement.
3. Robust and should be able to withstand vibration.

Traction motor control:

1- Rheostat control
2- Series parallel control
3- Field control
4- Buck and boost method
5- Thyristor control
  - Phase control
  - Chopper control

Braking:

Electric braking:

1- Plugging or reverse current braking
2- Rheostatic braking
3- Regenerative braking

Mechanical braking:

1- Compressed air brakes
2- Vacuum brakes

Magnetic track brakes:

Recent trends in electric traction:

1- Tap changer control
2- Thyristor control
3- Chopper control
4- Microprocessor control

CHAPTER (2)

THREE PHASE INDUCTION MOTOR

Electric motor: it is a device which converts electrical energy into mechanical energy. The working principle of an electric motor depends on the magnetic field and electric field interaction. There are two types of electric motors DC and AC motors.

DC motor: it feeds DC power supply as self-excited DC motor and separately excited DC motor. Self-excited DC motor includes other types of the DC motor as series DC motor, shunt DC motor and compound DC motor.

AC motor: it is a motor feeding from the AC power supply as synchronous motor and induction motor. These motors feed from AC single phase power supply or from AC three phase power supply. The synchronous motor is called double excited because it feeds from two power supplies one of them feeds the rotor part and the other power supply feeds the part but the induction motor is single excited because it feeds the stator only power supply. This course focus on the three-phase induction motor.

The three-phase induction motor is the most widely used electrical motor in industrial. Almost 80% of the mechanical power used by industries is provided by three phase induction motors because of its simple and rugged construction, low cost, good operating characteristics, the absence of commutator and good speed regulation. In three phase induction motor, the power is transferred from stator to rotor winding through induction. The induction motor is also called a synchronous motor as it runs at a speed other than the synchronous speed.

2-1 Three Phase Induction Motor Construction:

Like any other type of electrical motor, a three-phase induction motor constructs from two main parts, namely the rotor part and stator part:

Stator part: As its name indicates a stationary part of induction motor. It consists of three main parts. These parts are stator frame, stator core and stator winding.

Firstly, the stator frame:

It is the outer part of the three-phase induction motor. Its main function is to support the stator core and the field winding. It acts as a covering, and it provides protection and mechanical strength to all the inner parts of the induction motor. The frame is either made up of die-cast or fabricated steel. The frame of three phase induction motor should be strong and rigid as the air gap length of three phase induction motor is very small. Otherwise, the rotor will not remain concentric with the stator, which will give rise to an unbalanced magnetic pull.

Fig. 2-1 The stator frame

Secondly, the stator core:

The main function of the stator core is to carry the alternating flux. In order to reduce the eddy current loss, the stator core is laminated. These laminated types of structure are made up of stamping which is about 0.4 to 0.5 mm thick. All the stamping is stamped together to form stator core, which is then housed in stator frame. The stamping is made up of silicon steel, which helps to reduce the hysteresis loss occurring in the motor. The stator core can be seen in Fig. 2-2.

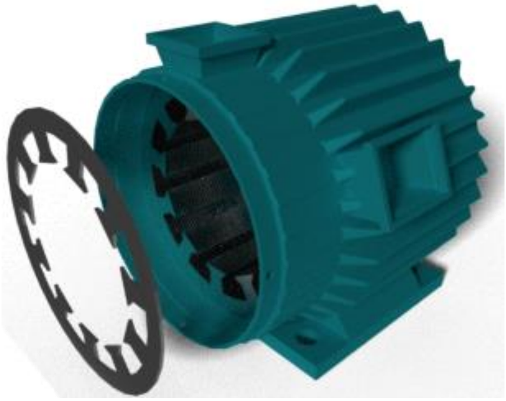


Fig. 2-2 Stator core inside the stator frame

Thirdly, the stator winding:

The slots on the periphery of the stator core of the three-phase induction motor carry three phase windings. We apply three phase AC supply to this three-phase winding.

The three phases of the winding are connected either in star or delta depending upon which type of starting method we use. We start the squirrel cage motor mostly with star-delta starter and hence the stator of squirrel cage motor is delta connected. The winding wound on the stator of three phase induction motor is also called field winding, and when this winding is excited by three phase AC supply, it produces a rotating magnetic field. Fig. 2-3 shows all parts of the stator.

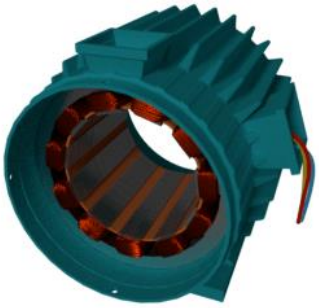


Fig. 2-3 All parts of the stator

Rotor part: The rotor is a rotating part of induction motor. The rotor is connected to the mechanical load through the shaft.

The rotor of the three-phase induction motor is further classified as, squirrel cage rotor and slip ring rotor or wound rotor or phase wound rotor.

Depending upon the type of rotor construction used the three-phase induction motor are classified as:

1- Squirrel cage induction motor
2- Slip ring induction motor or wound induction motor or phase wound induction motor.

2-2 Squirrel Cage Three Phase Induction Motor:

The rotor of the squirrel cage three phase induction motor is cylindrical and have slots on its periphery. The slots are not made parallel to each other but are bit skewed (skewing is not shown in the figure of squirrel cage rotor besides) as the skewing prevents magnetic locking of stator and rotor teeth and makes the working of the motor more smooth and quieter. The squirrel cage rotor consists of aluminum, brass or copper bars (copper bras rotor is shown in the figure beside). These aluminum, brass or copper bars are called rotor conductors and are placed in the slots on the periphery of the rotor. The rotor conductors are permanently shorted by the copper, or aluminum rings called the end rings. To provide mechanical strength, these rotor conductors are braced to the end ring and hence form a complete closed circuit resembling like a cage and hence got its name as squirrel cage induction motor. The squirrel cage rotor winding is made symmetrical. As end rings permanently short the bars, the rotor resistance is quite small, and it is not possible to add external resistance as the bars get permanently shorted. The absence of slip ring and brushes make the construction of Squirrel cage three-phase induction motor very simple and robust and hence widely used three phase induction motor. These motors have the advantage of adopting any number of pole pairs. Fig. 2-4 shows the rotor of the squirrel cage induction motor from externally also, Fig. 2-5 shows a squirrel cage induction rotor having aluminum bars short circuit by aluminum end rings. Fig 2-6 shows sectional view of overall squirrel cage induction motor.

Fig. 2-4 Rotor of squirrel cage induction motor from externally

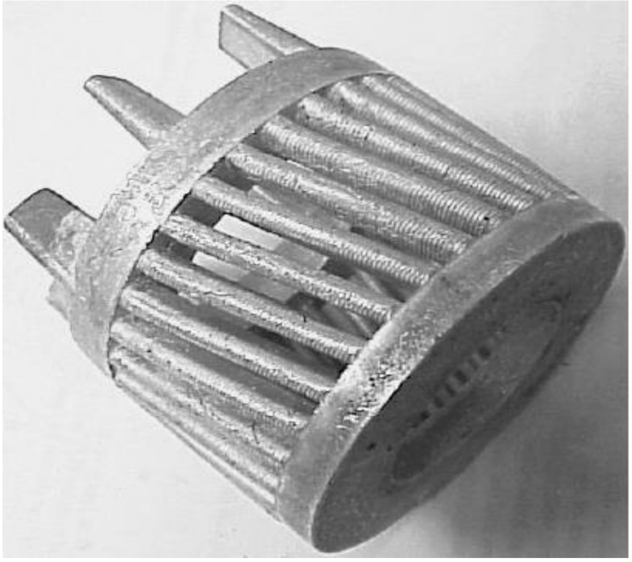


Fig. 2-5 Rotor bar and rings of squirrel cage induction motor from internally

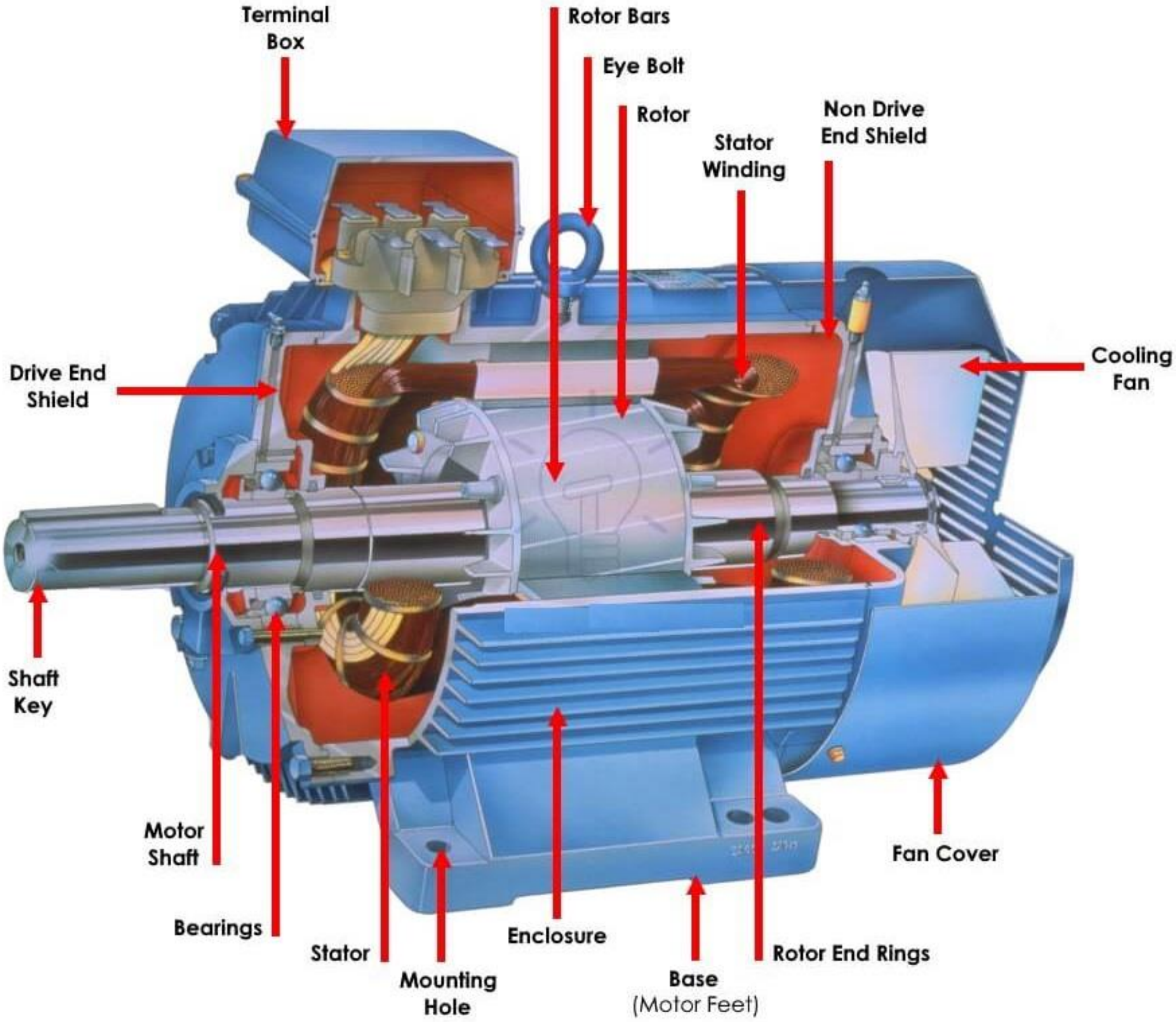


Fig. 2-6 Sectional view of overall of squirrel cage induction motor

2-3 Advantages of Squirrel Cage Induction Rotor:

Its construction is very simple and rugged.

As there are no brushes and slip ring, these motors require less maintenance.

2-4 Applications of Squirrel Cage Induction Rotor:

We use the squirrel cage induction motors in lathes, drilling machine, fan, blower printing machines, etc.

2-5 Slip Ring or Wound Rotor Three Phase Induction Motor:

In this type of three phase induction motor the rotor is wound for the same number of poles as that of the stator, but it has less number of slots and has fewer turns per phase of a heavier conductor. The rotor also carries star or delta winding similar to that of the stator winding.

The rotor consists of numbers of slots and rotor winding are placed inside these slots. The three end terminals are connected together to form a star connection. As its name indicates, three phase slip ring induction motor consists of slip rings connected on the same shaft as that of the rotor.

The three ends of three-phase windings are permanently connected to these slip rings. The external resistance can be easily connected through the brushes and slip rings and hence used for speed controlling and improving the starting torque of three phase induction motor. The brushes are used to carry current to and from the rotor winding. These brushes are further connected to three phase star connected resistances. An electrical diagram of a slip ring three phase induction motor is shown in Fig. 2-7.

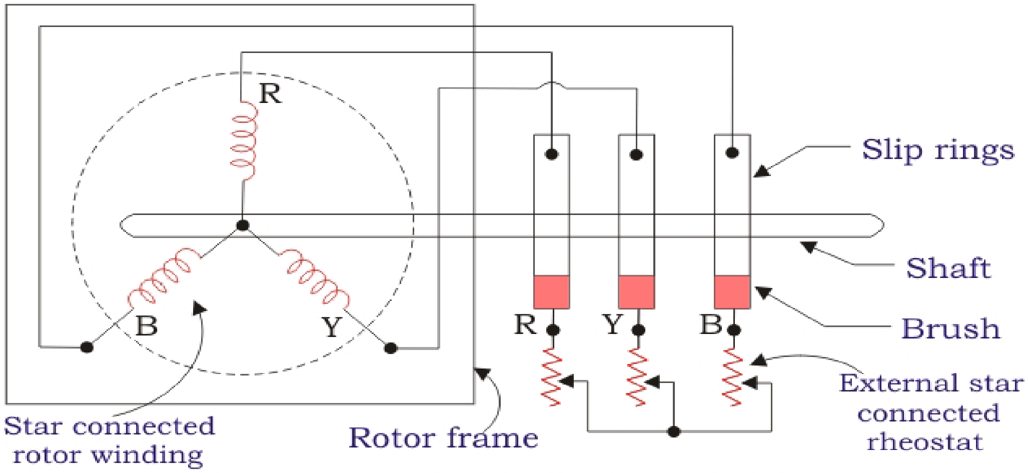


Fig. 2-7 Slipring of the three-phase induction motor

At starting, the resistance is connected to the rotor circuit and is gradually cut out as the rotor pick up its speed. When the motor is running the slip ring are shorted by connecting a metal collar, which connects all slip ring together, and the brushes are also removed. This reduces the wear and tear of the brushes. Due to the presence of slip rings and brushes the rotor construction becomes somewhat complicated therefore it is less used as compare to squirrel cage induction motor.

2-6 Advantages of Slip Ring Induction Motor:

It has high starting torque and low starting current. Possibility of adding additional resistance to control speed.

2-7 Application of Slip Ring Induction Motor:

Slip ring induction motor are used where high starting torque is required i.e. in hoists, cranes, elevator etc.

The other parts of a three-phase induction motor are:

1- Shaft for transmitting the torque to the load. This shaft is made up of steel.
2- Bearings for supporting the rotating shaft.
3- One of the problems with electrical motor is the production of heat during its rotation. To overcome this problem, we need a fan for cooling.
4- For receiving external electrical connection Terminal box is needed.
5- There is a small distance between rotor and stator which usually varies from 0.4 mm to 4 mm. Such a distance is called air gap.

2-8 Theory of operation of the three-phase induction motor:

When applying three phase supply supply on the stator winding, a magnetic flux produced in the stator due to the flow of current in the coils of the stator windings. The rotor winding is so arranged that each coil becomes short-circuited.

The flux from the stator cuts the short-circuited coil in the rotor. As the rotor coils are short-circuited, according to Faraday's law of electromagnetic induction, the current will start flowing through the coil of the rotor. When the current through the rotor coils flows, another flux generated in the rotor.

Now there are two fluxes, one is stator flux, and another is rotor flux. The rotor flux will be lagging with respect to the stator flux. Because of that, the rotor will feel a torque which will make the rotor to rotate in the direction of the rotating magnetic field.

2-9 The starting methods of the three-phase induction motor:

If an induction motor is directly switched on from the supply, it takes fifth to seventh times its full load current and develops a torque which is only one and half to two and half times the full load torque. This large starting current produces a large voltage drop in the line, which may affect the operation of other devices connected to the same line. Hence, it is not advisable to start induction motors of higher ratings directly from the mains supply. To overcome this problem, starting methods can be used. The starting methods can be classified into conventional starting methods and modern starting methods.

Firstly, the conventional starting methods:

The traditional methods can be limited to the following

1- direct on line
2- In-line resistor or inductor
3- Y start, Δ run (frequently called wye-delta starter)
4- Auto-transformer start

Direct-on-line starting

This kind of starting mode is the most basic and simplest in the motor starting. The method is characterized by less investment, simple equipment and small quantity. Although the starting time is short, the torque is smaller at starting and the current is large, which is suitable for starting small capacity motors.

ln-Line resistor or inductor starter

This method places an impedance (resistor or inductor) in series with each phase of the motor. By voltage splitting, the voltage is reduced to the motor. By using different impedances, different voltage reductions can be obtained. Like the autotransformer, this method works on a standard motor and requires controls to switch the impedances in and out. The current reduction is the same as the voltage reduction in this method, and extra energy is dissipated if a resistor starter is used. This method of starting can be seen in Fig. 2-8

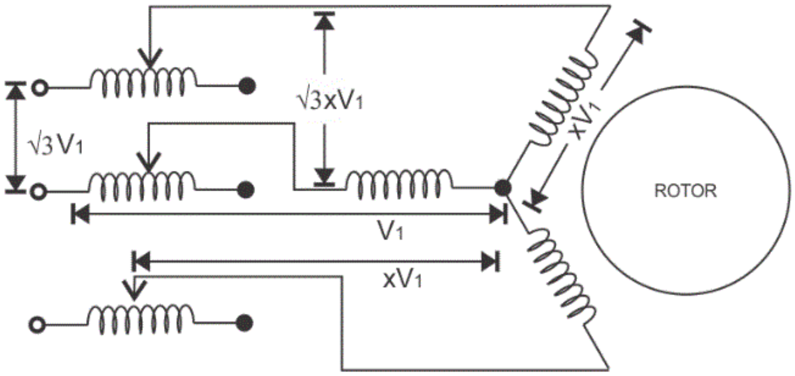


Fig. 2-8 Starting method by in line inductor starter

Star delta starter:

Fig. 2-9 shows the principle of the Y-Delta Starter. The phase coils are designed to be connected in Delta for running, but they are connected in Y to start the motor.

Each coil receives times the line voltage during starting, which means the current and torque 1/3 of what they would be during a full voltage start. When the motor nears rated speed, the coils are momentarily opened and reconnected in Delta to receive full line voltage. This type of starting requires a motor designed for Y-Delta starting (6 or 12 leads) as well as control equipment to switch the connections. When Y—Delta starting is used, a maximum of 36 seconds is allowed for the acceleration time if the motor is brought to full speed on Y. If a full voltage is applied during acceleration, the maximum allowable starting time is 15 seconds.

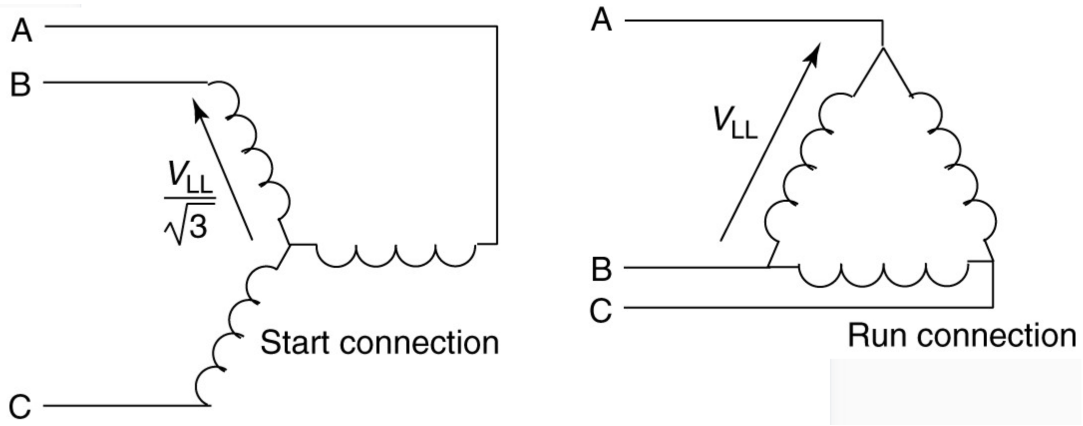


Fig. 2-9 Y-D starting of an induction motor

Autotransformer Starting

Another technique for starting large induction motors is to reduce the voltage with an autotransformer. A three-phase autotransformer is used to reduce the voltage applied to the motor during the starting period. The taps on the autotransformer can be adjusted offering the choice of several different levels of voltage reduction. This technique has the advantage of working with an induction motor. Like the Y-Delta starter, this method requires controls to do the switching. The disadvantage of the autotransformer starter is that the current level is reduced exactly the same as the voltage, while the torque reduction is still the square of the voltage reduction. In addition, there will some exciting current required for the autotransformer. The allowable starting time for an autotransformer starting depends on the voltage reduction. If the motor is brought to full speed on reduced voltage, some manufacturer recommendations are:

80% voltage during starting →19 seconds allowed for acceleration

65% voltage during starting →28 seconds allowed for acceleration

50% voltage during starting → 48 seconds allowed for acceleration

Secondly, the modern starting methods:

The modern methods can be limited to the following

1- By using soft starter
2- By using inverter

Firstly, starting by using the soft starter:

Motors can frequently require a large amount of energy when they accelerate up to full speed. A soft starter is used to reduce the inrush currents and limit torque, useful if you want to protect your equipment, extend the life of your motor and reduce motor heating with frequent starts and stops.

So, a soft starter provides a gentle acceleration up to full speed and they are used only at startup. This gradual start is achieved by ramping up the initial voltage to the motor.

We tend to utilize soft starters in applications that require speed and torque control only during startup or where there is a requirement to reduce the large startup inrush currents associated with a large motor. We can also use a soft start when a mechanical system (like conveyors, belt-driven systems, gears, and so on) needs a gentle start to relieve torque spikes and tension associated with normal startup. We can also use them in pumps to eliminate pressure surges caused in piping systems.

There can be two types of control using soft starter:

Open Control: A start voltage is applied with time, irrespective of the current drawn or the speed of the motor. For each phase, two SCRs are connected back to back and the SCRs are conducted initially at a delay of 180 degrees during the respective half-wave cycles (for which each SCR conducts). This delay is reduced gradually with time until the applied voltage ramps up to the full supply voltage. This is also known as Time Voltage Ramp System. This method is not relevant as it doesn’t control the motor acceleration.

Closed-Loop Control: Any of the motor output characteristics like the current drawn or the speed is monitored and the starting voltage is modified accordingly to get the required response. The current in each phase is monitored and if it exceeds a certain set point, the time voltage ramp is halted.

Thus, the basic principle of the soft starter is by controlling the conduction angle of the SCRs the application of supply voltage can be controlled.

Two Components of a basic soft starter:

1- Power switches like SCRs which need to be phase controlled such that they are applied for each part of the cycle. For a three-phase motor, two SCRs are connected back to back for each phase. The switching devices need to be rated at least three times more than the line voltage.
2- Control Logic using PID controllers or Microcontrollers or any other logic to control the application of gate voltage to the SCR, i.e. to control the firing angle of SCRs to make the SCR conduct at the required part of the supply voltage cycle.

Working Example of Electronic Soft Start System for three phase induction motor

The system consists of the following components as shown in Fig. 2-10.

1- Two back to back SCRs for each phase, i.e. six SCRs in total.
2- Control Logic circuitry in the form of two comparators- LM324 and LM339 to produce the level and the ramp voltage and an opto-isolator to control the application of gate voltage to each SCR in each phase.

3- A power supply circuitry to provide the required dc supply voltage.

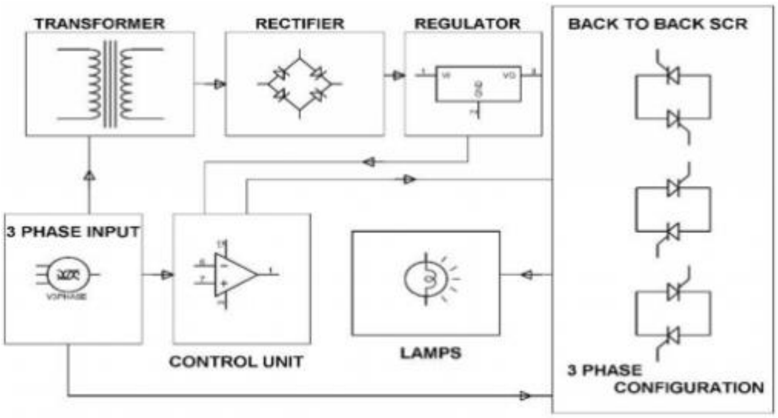


Fig. 2-10 Soft starter circuit

Technical specifications to buy the soft starter device:

1- We mention the nominal motor data, which are voltage, current, output power, efficiency and power factor at full load, and this can be obtained from the motor name plate.

2- From the factory data sheet that is requested when purchasing the motor, we extract from it the ratio of starting torque to rated load torque, the ratio of maximum torque to rated torque of load, type of mechanical load and its specifications as far as Possible, the need to save energy, whether in starting or during operation or not, and the need for a smooth stop A sudden stop, and will the device perform the start-up process for one device or a group of motors that are similar in performance or different in performance.

3- In the absence of the factory data sheet and the availability of the name plate data, you only have to contact with the company supplying of the device to send an engineer to study the load and provide the best suitable starting device.

2-10 Specifications of the voltage applied to the motor for safe operation:

1- The voltage should not be less or more than 10% of the rated value when the frequency is constant.

2- When the voltage is constant, the frequency should not be more or less than 5% of the rated value.

3- The motor should not withstand more than 150% of the rated current value for two minutes.

4- The time of the starting current of the motor should not exceed than 12 seconds

5- The value of unbalanced voltages should not exceed 1% of the rated value if they are on the motor.

2-11 NEMA and IEC Motor Classes:

Various standard classes (or designs) for motors, corresponding to the torque curves (Fig. 2-11) have been developed to better drive various type loads. The National Electrical Manufacturers Association (NEMA) has specified motor classes A, B, C, and D to meet these drive requirements. Similar, International Electrotechnical Commission (IEC) classes N and H correspond to NEMA B and C designs respectively.

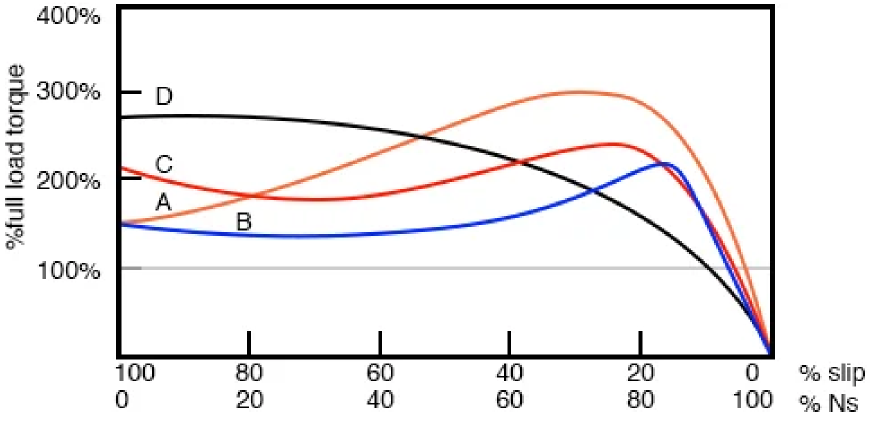


Fig. 2-11 Torque characteristic for NEMA design

All motors, except class D, operate at 5% slip or less at full load.

Class B (IEC Class N) motors are the default motor to use in most applications. With a starting torque of LRT = 150% to 170% of FLT, it can start most loads, without excessive starting current (LRT). Efficiency and power factor are high. It typically drives pumps, fans, and machine tools.

Class A starting torque is the same as class B. Drop out torque and starting current (LRT) is higher. This motor handles transient overloads as encountered in injection molding machines.

Class C (IEC Class H) has higher starting torque than class A and B at LRT = 200% of FLT. This motor is applied to hard-starting loads which need to be driven at constant speed like conveyors, crushers, and reciprocating pumps and compressors.

Class D motors have the highest starting torque (LRT) coupled with low starting current due to high slip (5% to 13% at FLT). The high slip results in lower speed. The speed regulation is poor. However, the motor excels at driving highly variable speed loads like those requiring an energy storage flywheel. Applications include punch presses, shears, and elevators.

Class E motors are a higher efficiency version of class B.

Class F motors have much lower LRC, LRT, and break down torque than class B. They drive constant, easily started loads.

CHAPTER (3)

FREQUENCY CONVERTERS FOR CONTROLLING IN THE MOTORS SPEED

The converters have many functions from these functions, the controlling in the speed of the motors, conversion the DC power into AC power in the solar system, it is used with battery as in uninterrupted power supplies and used to improve the power factor and harmonics as in the active power supply. These converters have many names as, variable frequency drive and variable speed drive. The variable speed drive can be seen in Fig. 3-1. From this Fig. can be concluded that, the converter consists of rectifier, DC link and inverter.

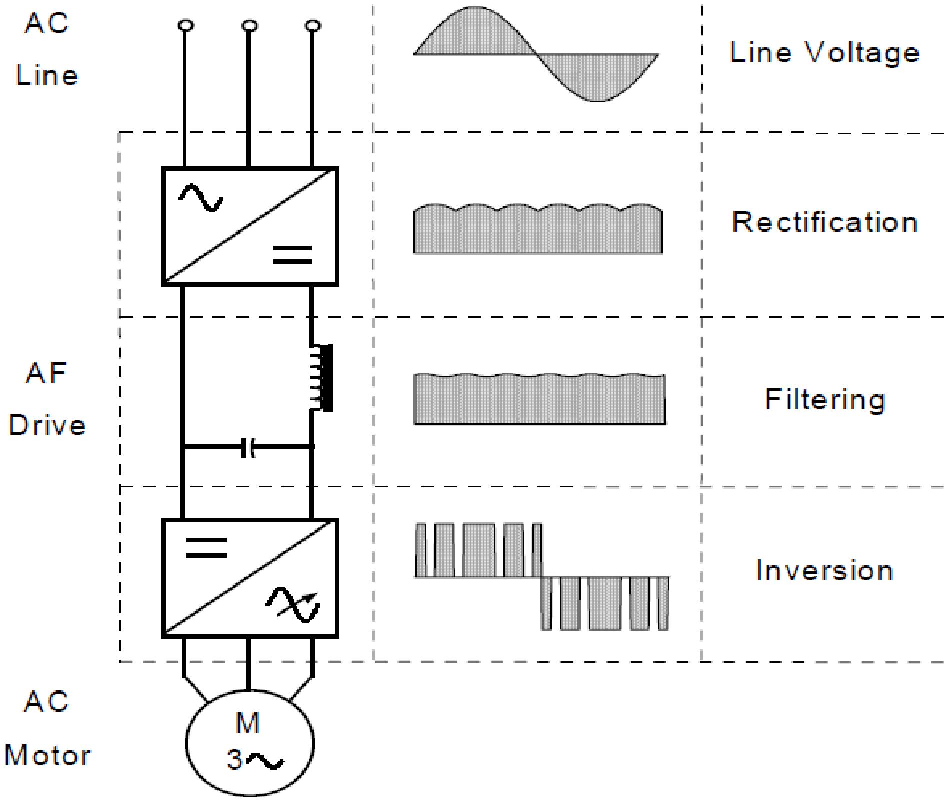


Fig. 3-1 Variable speed drive

3-1 The rectifiers and types:

The rectifier has many shapes as, uncontrolled rectifier or controlled rectifier. In the uncontrolled rectifier the power diodes are used. The power diode is an electronic device used to convert the alternating current or voltage into the direct current or voltage. The uncontrolled rectifier classifies from the power feeding into single phase uncontrolled rectifier and three phase uncontrolled rectifier.

The single-phase uncontrolled rectifier was shown in Fig. 3-2. It is called single-phase uncontrolled rectifier due to feed from single phase and due to uncontrolled the output power. It consists of four diodes. The diode is the electronic switch allow to the voltage and current will pass in certain direction and the these current and voltage prevent from passing in the other direction. From Fig. 3-2, it is found that, the input voltage is AC and the output voltage is a DC. This can be seen through Fig. 3-3.

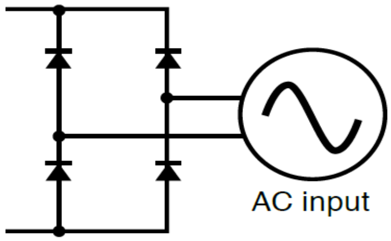


Fig. 3-2 Rectifier bridge feeds from single-phase

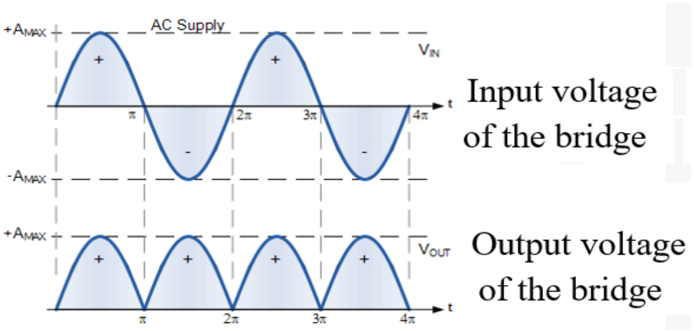


Fig. 3-3 The input and output voltages of the bridge rectifier

From this Fig. it is found that, the output voltage isn't direct voltage but this voltage is a pulsating voltage. To improve this pulsating voltage into direct voltage the capacitor is used. This capacitor connects across the bridge rectifier. This can be seen in Fig. 3-4. By measuring the output voltages before and after the filter of the capacitor it is found that, the shapes of these voltages can be seen in Fig. 3-5. This means that the parallel capacitor improves the output voltage e.g. the pulsating voltage changes into direct voltage.

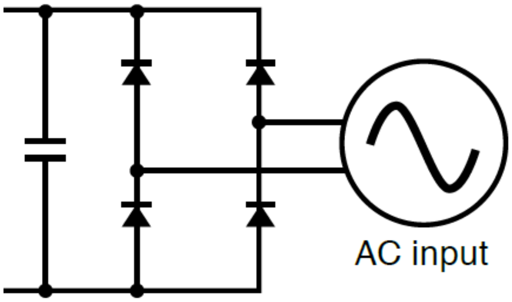


Fig. 3-4 The bridge rectifier with filter capacitor

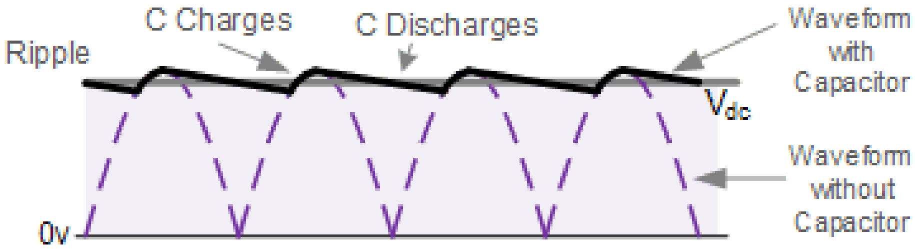


Fig. 3-5 The shapes of the voltage before and after capacitor filter

From Fig. 3-5 can be concluded that during the charging of the capacitor voltage reaches maximum voltage of the power supply. With using capacitor filter the ripples in the voltage decreases and rate of change of the voltage with respect to time improved. From important problem which arises as the side effect for using the uncontrolled rectifier the starting current. Due to the output voltage is maximum value with uncontrolled rectifier the starting value is maximum value. To decrease this current, the resistor inserted as shown in Fig. 3-6. This resistance reshaped waste energy so after certain time the contactor is energized and the inserted resistance becomes outside of the circuit by using the bypass (contact normally open from the contactor). The effect of using inserted resistance on the single-phase uncontrolled rectifier on the starting current (inrush current) can be seen in Fig. 3-7.

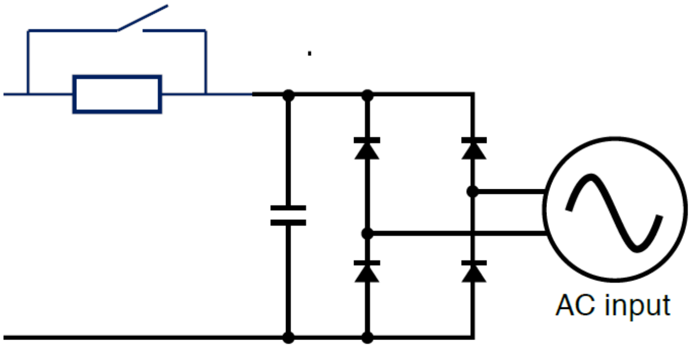


Fig. 3-6 single-phase uncontrolled rectifier with filter capacitor and protection resistance

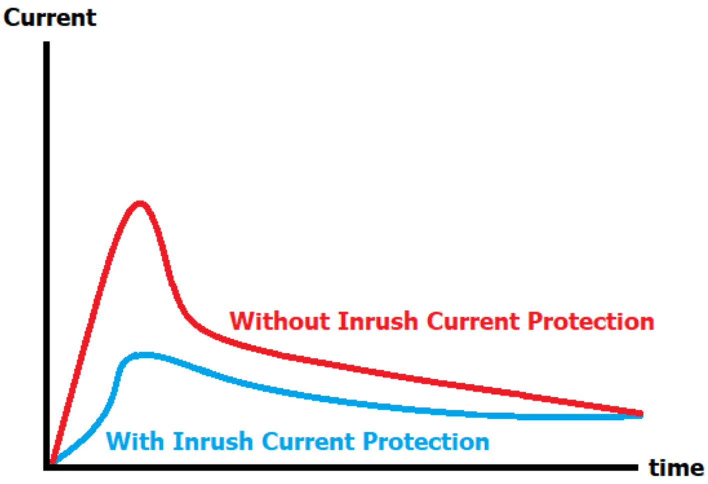


Fig. 3-7 The inrush current with and without protected resistance

When used high power motor in the drive circuit, the single-phase uncontrolled rectifier isn’t sufficient so the three-phase uncontrolled rectifier is used. To see this type of rectifier, Fig 3-8 shows that. The inductor filter is used to improve the ripples in the current by decreasing the rate of change of the current with respect to time. Also, the capacitor voltage is improved the voltage by improve the ripple voltage with respect to time. Also, it is improved the power factor by controlling in the reactive power of the motor.

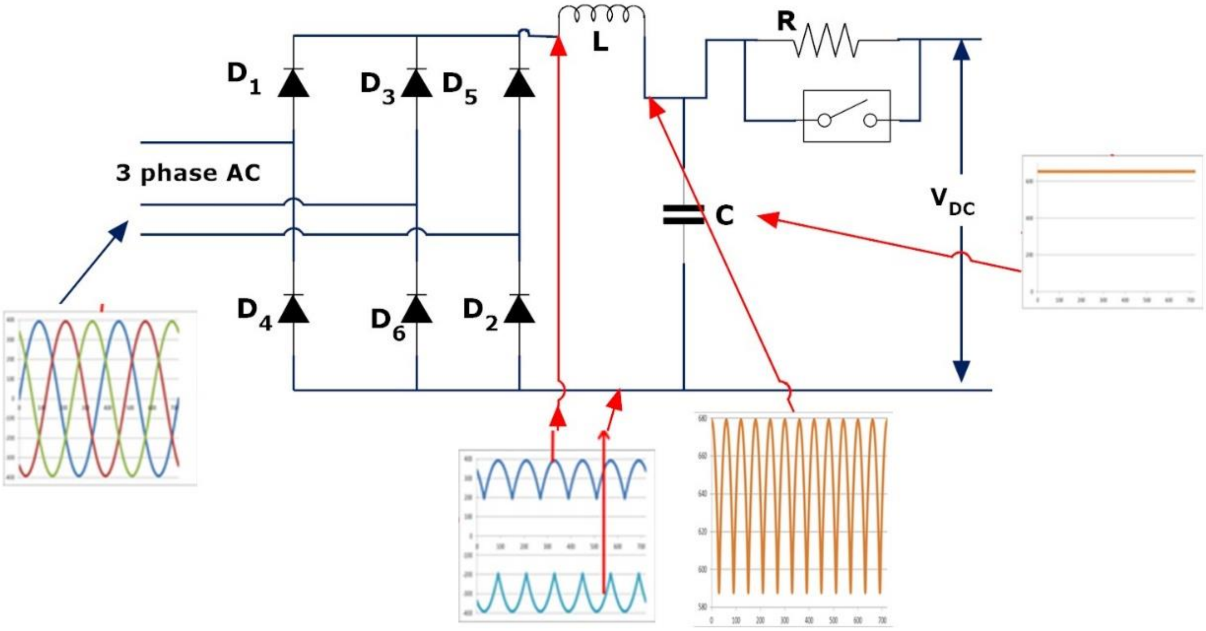


Fig 3-8 Three phase uncontrolled rectifier with LC filter and protection resistance

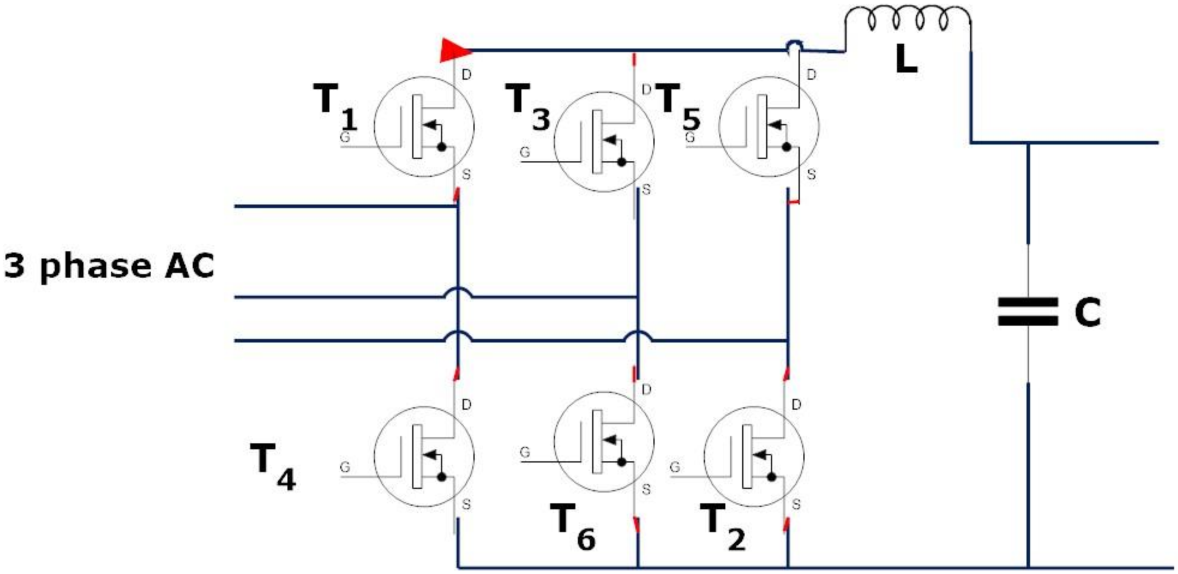


Fig. 3-9 Controlled rectifier with LC filter

In some applications, the uncontrolled rectifier is replaced by controlled rectifier with this type of the converter the output voltage can be controlled so at starting, the output voltage can be reduced and hence, the inrush current is reduced. This means that we don't need inserting resistance. With this controlled rectifier, when the converter is used in generating mode, the power can be returned to supply. Fig. 3-10 shows the controlled rectifier when using the thyristors as the electronic switch. Also, in case of using controlled rectifier with the three legs six thyristors, the output voltage at different firing angle can be seen in Fig. 3-11.

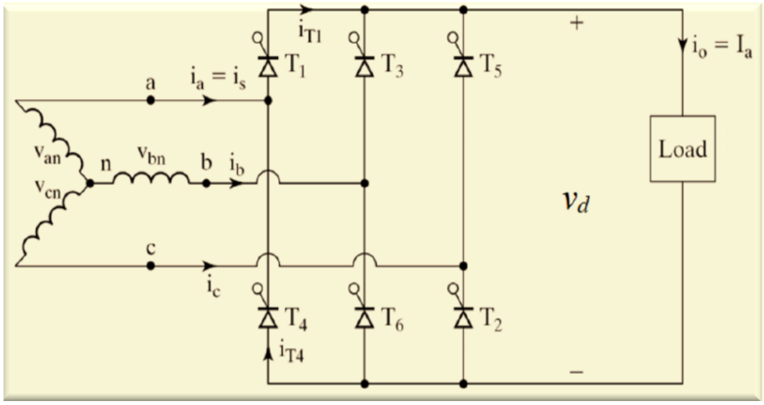


Fig. 3-10 Controlled rectifier with three legs thyristors

After discussing the rectifier and DC link (LC filter) now the inverter will discuss. The inverter can be defined as; an electronic device that converts the DC voltage or current into AC voltage or current. Inverters can be classified as the nature of the output voltage into single and three- phase, use controlled turn-on and turn–off devices (BJT's, MOSFET's, IGBT's, MCT's, GTO's, et cetra) or forced commutated thyristors. These inverters use PWM control signals for producing an ac output voltage in open loop control and closed loop control but there are another two methods of control used only in the open loop control. These methods are 120^0 conduction band and 180^0 conduction band. The output voltage or current from inverter can be controlled in the root mean square value of the voltage or can be controlled in the root mean square value of the voltage and frequency. This depends upon the type of rectifier circuit.

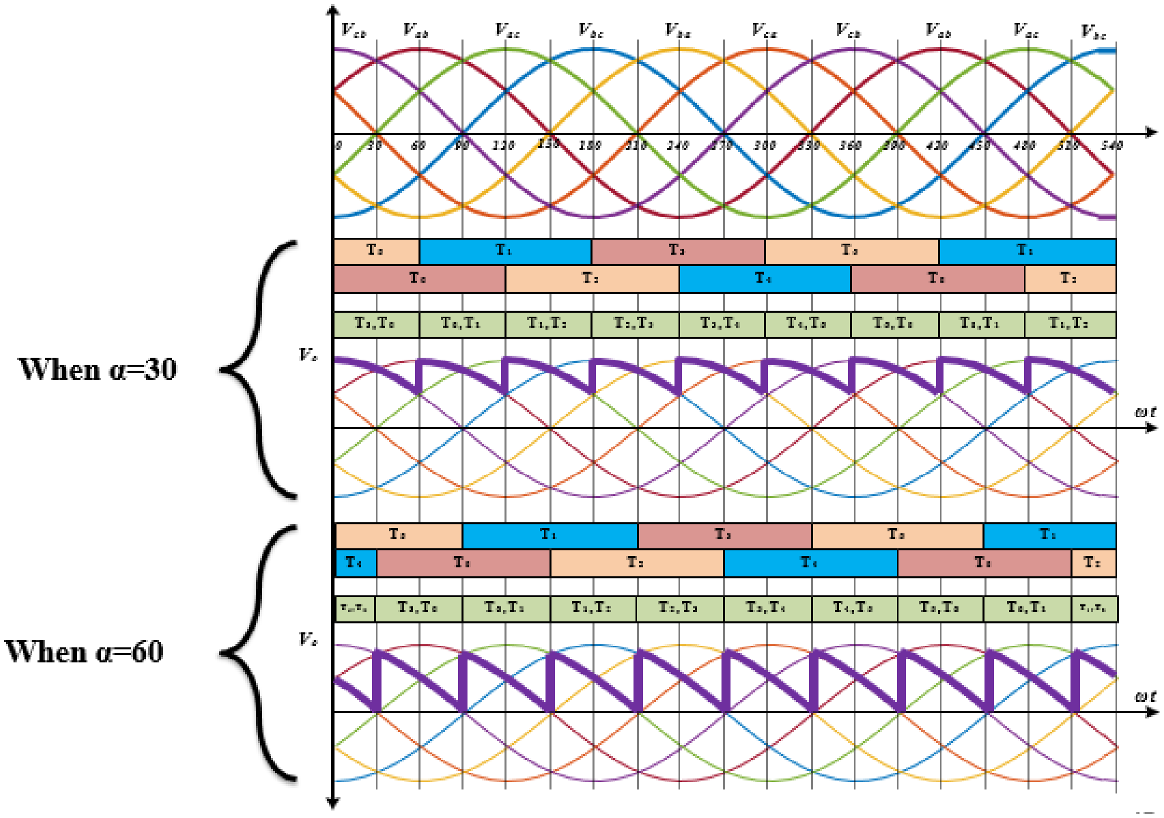
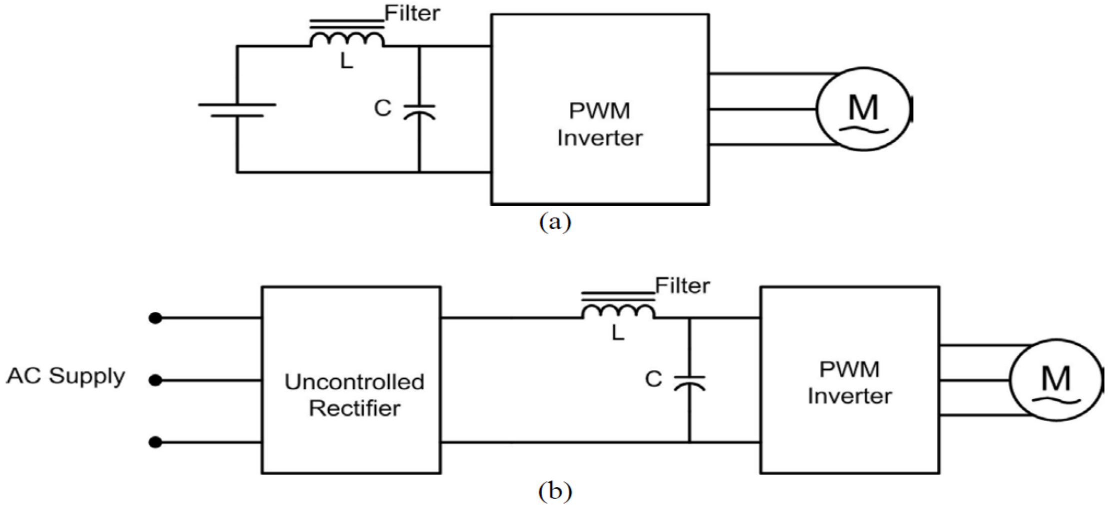


Fig. 3-11 The voltage wave form at different firing angle with three legs thyristors

This means that, if the input voltage of inverter is constant level (from battery or from uncontrolled rectifier), the inverter is used to controlling the root mean square value and wave frequency of the voltage. This can be seen in Fig. 3-12 but in case of using controlling rectifier (controlled rectifier or DC chopper), the inverter is used only to controlling the frequency of the output voltage and the level of the output voltage from inverter can be controlled depending upon the different values of the level of the input voltages of inverter (from the resulting voltage of controlled rectifier). This can be seen in Fig. 3-13, Fig. 3-14 and Fig. 3-15. Also, the inverter can be classified into voltage fed inverter and current fed inverter. A voltage fed inverter (VFI) is one with a constant input voltage, while a current fed inverter (CFI) is one with a constant input current. A variable dc linked inverter is one with controllable input voltage. The inverter used here is a voltage source inverter. It is used for low power and high-power applications and a three-phase output can be obtained from a configuration of six switching devices as shown in the Fig. 3-16.



(a)

(b)

Fig 3-12 Pulse width modulation inverter to controlling the voltage and frequency

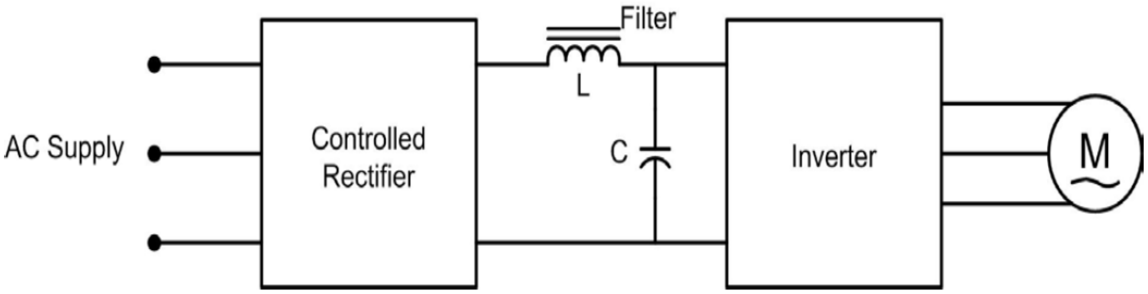


Fig 3-13 Six step inverter-controlled rectifier with inverter

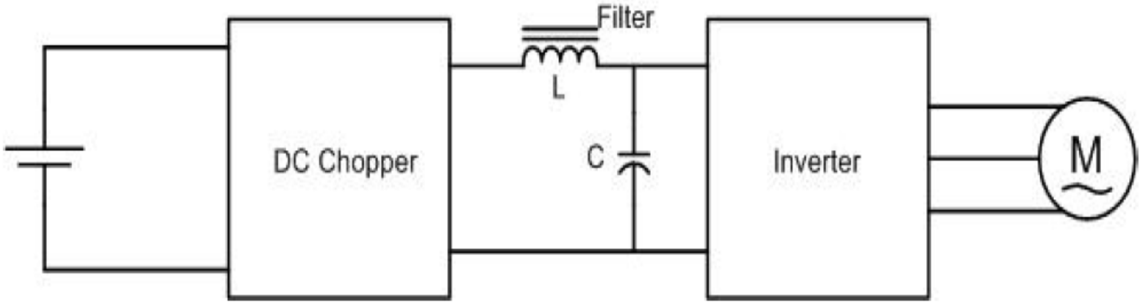


Fig 3-14 Six step inverter DC chopper with inverter

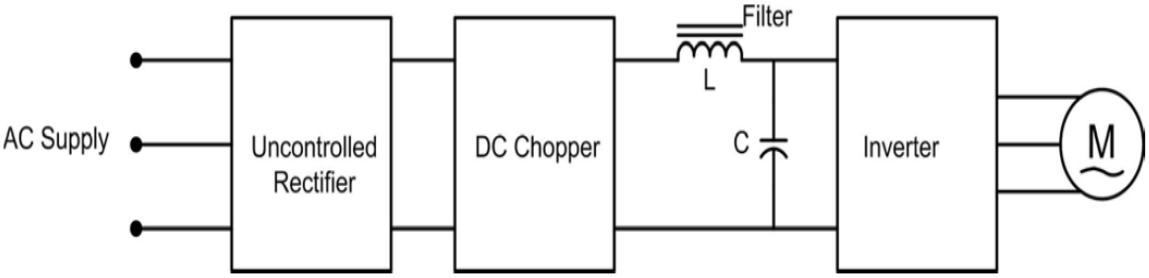


Fig 3-15 Six step inverter uncontrolled rectifier DC chopper with inverter

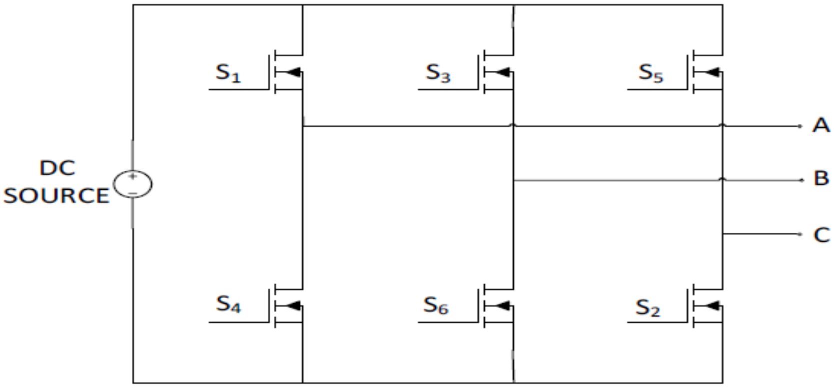


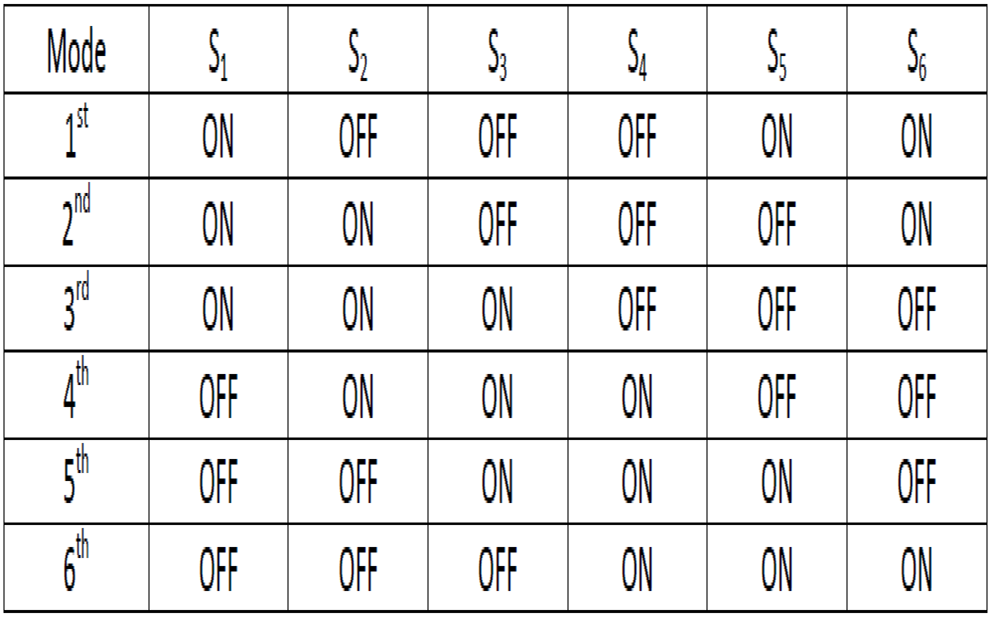
Fig. 3-16 Three phase inverter

3-2 Types of controlling in the switching device of inverter:

To controlling the switching devices of the inverter many methods are used. This depending upon the type of controlling (open loop control and closed loop control). In open loop control 120^0 conduction band can be used or 180^0 conduction band can be used also, the pulse width modulation can be used with open loop control or with closed loop control. Each switch can be operated for 120^0 only or 180^0 only. These modes of operations are called 120^0 conduction mode and 180^0 conduction mode. these methods occur in sequence. This inverter can be operated as six step inverter or pulse width modulation inverter. These methods can be explained as the follows;

3-2-1 Switching mode of operation for 180^0 conduction band:

In the three-phase inverter of each switch conduct 180° of cycle, transistor pair in each arm i.e. S1, S4; S3, S6 and S5, S2 are turned on with a time interval of 180°. It means that S1 conduct for 180° and S4 for the next 180° of a cycle. Switch in the upper group i.e. S1, S3, S5 conduct at an interval of 120°. It implies that if S1 is fired at ωt=0°, then S3 must be fired at ωt=120° and S5 at ωt=240°. Same is proved lower group of switches. On the basis of this firing scheme, a table in prepared as shown at table 3-1.

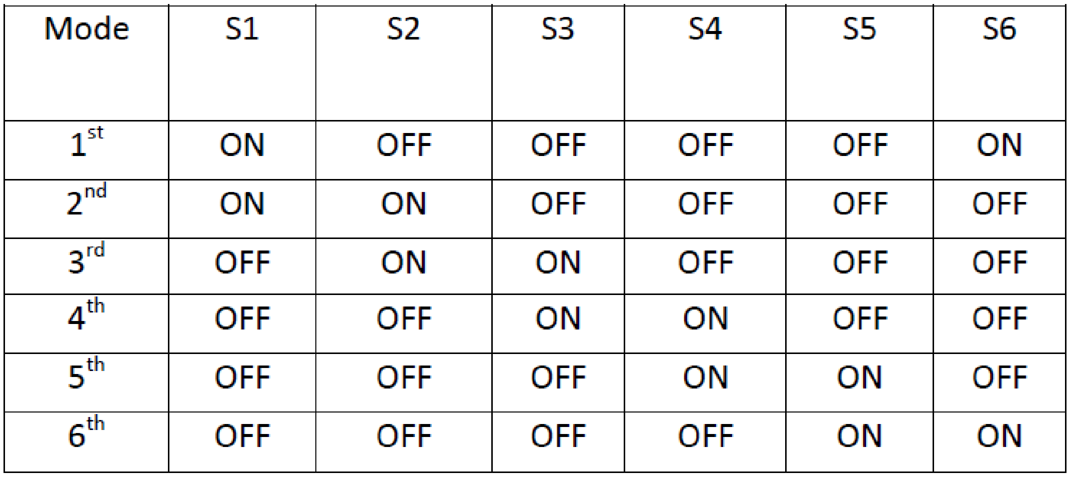


Mode	S_1	S_2	S_3	S_4	S_5	S_6
1st	ON	OFF	OFF	OFF	ON	ON
2nd	ON	ON	OFF	OFF	OFF	ON
3rd	ON	ON	ON	OFF	OFF	OFF
4th	OFF	ON	ON	ON	OFF	OFF
5th	OFF	OFF	ON	ON	ON	OFF
6th	OFF	OFF	OFF	ON	ON	ON

Table 3-1 Switching state in 180^0 conduction mode

3-2-2 Switching mode of operation for 120^0 conduction band:

For the 120° mode VSI, each thyristor conducts for 120° of a cycle. Like 180° mode, 120° mode inverter also requires six steps, each of 60° duration for completing one cycle output AC voltage. Switch in the upper group i.e. S1, S3, S5 conduct at an interval of 120°. It implies that if S1 is fired at ωt=0°, then S3 must be fired at ωt=120° and S5 at ωt=240°. Same is proved lower group of switches. For this inverter too, a table giving the sequence of firing the six thyristor is prepared as shown in the table 3-2.



Mode	S1	S2	S3	S4	S5	S6
1st	ON	OFF	OFF	OFF	OFF	ON
2nd	ON	ON	OFF	OFF	OFF	OFF
3rd	OFF	ON	ON	OFF	OFF	OFF
4th	OFF	OFF	ON	ON	OFF	OFF
5th	OFF	OFF	OFF	ON	ON	OFF
6th	OFF	OFF	OFF	OFF	ON	ON

Table 3-2 Switching sequence 120^0 conduction mode

3-2-3 Concept of Pulse Width Modulation:

Higher order harmonics in the load current could be easily filtered out using a series Inductor. A selected range of lower order harmonics can be reduced or eliminated by choosing the number of pulses per half cycle. When number of pulses increases then the order of harmonics is also increased and that can be easily eliminated by means of filters. In this method, a fixed AC voltage is given to the converter and controlled DC output voltage is obtained by adjusting the ON and OFF periods of the pulses. This is the most popular method of controlling the output voltage and this method is termed as pulse width modulation control.

The pulse width modulation has some advantages as

1. The output voltage control can be obtained without any additional components.
2. Lower order harmonics can be eliminated or minimized along with its output voltage control. As higher order harmonics can be filtered easily, the filtering requirements are minimized.

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.

1. Single-pulse modulation
2. Multiple-pulse modulation
3. Sinusoidal-pulse modulation

3-2-4 The sinusoidal pulse width modulation:

To produce a sinusoidal output voltage waveform at a desired frequency, a sinusoidal control signal at the desired frequency is compared with a triangular waveform. The frequency of triangular waveform, f_s, establishes the inverter switching frequency which is kept constant with its amplitude, v_{tri}.

The control signal, v_{con}, is used to modulate the switching duty ratio and has a frequency, f, which is the desired fundamental frequency of inverter output voltage.

Amplitude modulation ratio is given by, $m_a = \frac{v_{con}}{v_{tri}}$ and Frequency modulation ratio is given by, $m_f = \frac{f_s}{f}$

Thus, the peak amplitude of the fundamental frequency component is given by,

$$v_o = m_a x \frac{v_d}{2}$$

The sinusoidal AC voltage reference is compared with the high-frequency triangular carrier wave in real time to determine switching states for each pole in the inverter. After comparing, the switching states for each pole can be determined based on the following rule:

1- Voltage reference v_{con} >Triangular carrier v_{tri}: upper switch is turned on (pole voltage=V_d/2)

2- Voltage reference v_{con} <Triangular carrier v_{tri} : lower switch is turned on (pole voltage=$-V_d/2$)

This is used in each phase and hence the sequence of the electronic switch can be obtained. Fig. 3-17 shows how comparator can be obtained and Fig. 3-18 shows the pulses obtain from comparator and the fundamental component of the output voltage.

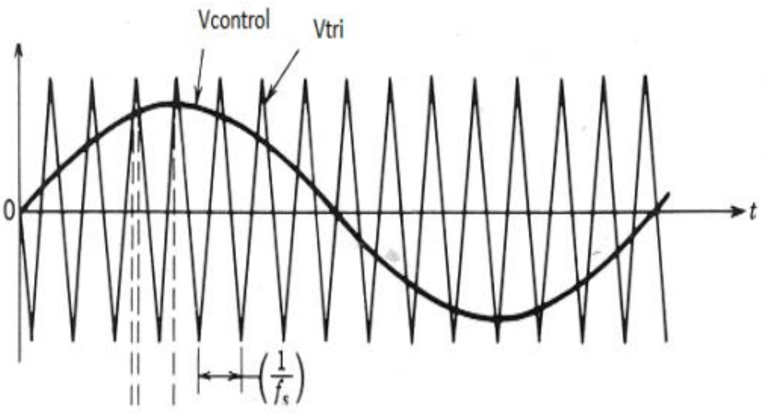


Fig. 3-17 Desired frequency is compared with a triangular waveform

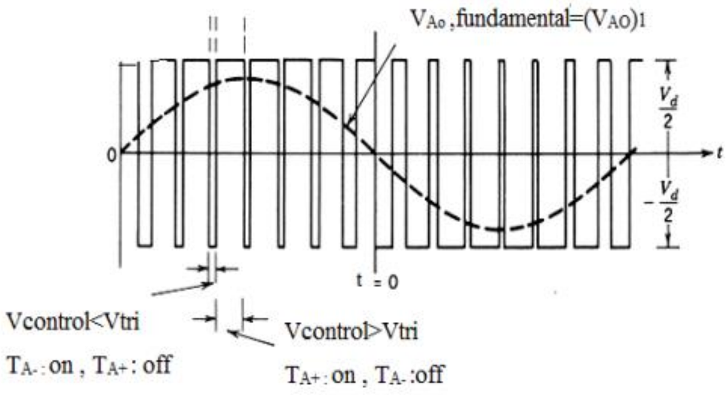


Fig. 3-18 Pulse-width Modulation (PWM)

General notes on the frequency converter:

1- In any leg of the frequency converter, there must be a time interval between operating the electronic keys on the same leg in order to don’t shortening in the modulator circuit. It was found that this time interval ranges between 2 microseconds and 4 microseconds

2- The frequency of the triangular waves (carriers) must be between 2 kilohertz and 20 kilohertz to obtain good performance for the speed control system of the electric motor

3- When choosing the carrier frequency, the chosen value must be taken into account an increase in the lost power in this frequency converter and reduce its life span. Therefore, it must management between the advantages and disadvantages choose the appropriate frequency

4- Care when using long cables between the motor and the frequency converter, because the frequency of the carrier wave, if it increases, will lead to an increase in voltage at the terminals of the motor, which exposes it to danger as the capacity of the cable increases

The voltage source inverter has some advantages and some disadvantages as

Advantages:

1.VSI drive provides good efficiency

2.Multi-motor operation is possible

3.Commutater less motor (CLM) mode is very stable

4.PWM drive has better dynamic response

5.VSI used for high and medium power applications, PWM used for low and medium power applications.

Disadvantages:

1.The converter cost is high

2.By using VSI there is instability and harmonic content in output

3.VSI is not applicable for low speed operations

4. The speed range of motor is limited to 40% due to harmonics

5. Efficiency inversely proportional to losses

6. Smooth operation is not possible, troubles occur in torque pulsations

CHAPTER (4)

MOTOR SPEED CONTROL

Many loads in the industrial applications need changing its speed so, must be changed the motor speed which rotates it. Here the motor under study is the three-phase induction motor. Before talking about how to speed control of the three-phase induction motor, firstly talking about the required conditions which must be verified through choosing the method of control. These conditions can be surmised in the following: -

1- it has wide range to control of the speed.
2- It has high sensitivity to speed control.
3- It has high accuracy to speed control.
4- It keeps the rate of variation between the motor torque and motor speed at minimum value.
5- The losses of this method is limited.
6- The method of control in the motor speed doesn’t weak performance of the motor.
7- The cost of this method is low.
8- This method has maintenance less.

4-1 The main methods to speed control of the three-phase induction motor:

Since we are dealing with squirrel cage inductions motor where the rotor is closed on itself, the control methods can only be done through the stator. Among the main methods of controlling the stator part are the following:

1- Speed control by changing the number of poles.

2- Speed control by changing the voltage exerted on the stator.

3- Speed control by changing the frequency imposed on the stator.

4- Speed control by changing the voltage with the frequency imposed on the stator.

4-1-1Speed control of induction motor through the number of poles:

The motor speed can be controlled by changing the number of poles because the motor is running near to the synchronous speed. The synchronous speed calculates from ($n_s = \frac{120f}{P}$) where P is number of poles and f is frequency. By keeping the motor frequency is constant and changing the number of poles the synchronous speed changes and motor speed changes. This occurred by design the coils of any phase of the motor to becomes three terminals. These terminals are start terminal, middle terminal and end terminal. These terminals for each phase are connected on the switch with two positions. One of these positions are to form certain number of poles the other position are to form double of the number poles. This type of this control can be seen in elevator. The low number of poles gives the ordinary speed of the elevator and the higher pole gives low speed of the elevator.

4-1-2 The speed control of the induction motor by controlling the stator voltage:

Stator Voltage Control is a method used to control the speed of an Induction Motor. The speed of a three-phase induction motor can be varied by varying the supply voltage. As we already know that the torque developed is proportional to the square of the supply voltage and the slip at the maximum torque is independent of the supply voltage. The variation in the supply voltage does not alter the synchronous speed of the motor. The Torque-Speed Characteristics of the three phase Induction motors for varying supply voltage and also for the fan load are shown in Fig. 4-1.

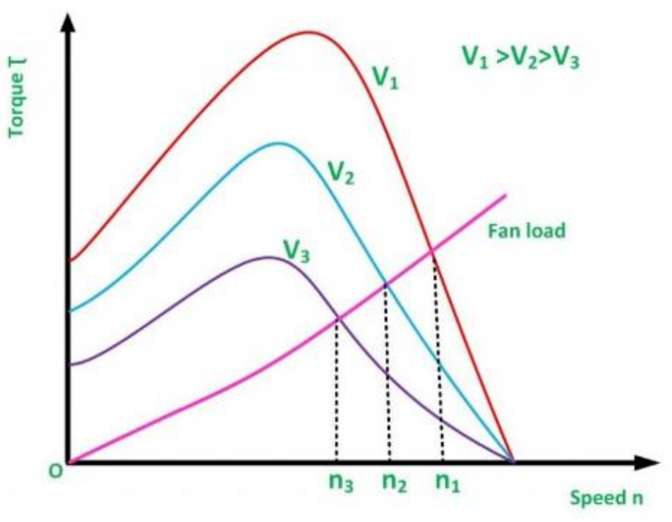


Fig. 4-1 The torque speed characteristics of three phase induction motor with stator voltage variation

By varying the supplying voltage, the speed can be controlled. to reduce the speed for the same value of the same current, the value of the voltage is reduced and as a result, the torque developed by the motor is reduced. This stator voltage control method is suitable for the applications where the load torque decreases with the speed. For example- In the fan load. This method gives a speed control only below the normal rated speed as the operation of the voltages if higher than the rated voltage is not admissible. This method is suitable where the intermittent operation of the drive is required and also for the fan and pump drives. As in fan and pump the load torque varies as the square of the speed. These types of drives required low torque at lower speeds. This condition can be obtained by applying lower voltage without exceeding the motor current. To reduce the stator voltage this can be done by two methods of control one of them called conventional speed control and the other is modern technique.

Firstly, the classical technique:

1- By connecting an external resistance in the stator circuit of the motor.

2- By connecting an external reactance in the stator circuit of the motor.
3- By using an Auto transformer.

<u>Secondly, the modern technique:</u>

1- By using a Thyristor voltage controller
2- By using a Triac Controller

Nowadays the Thyristor voltage controller method is preferred for varying the voltage. In case of a three-phase induction, motor three pairs of Thyristor are required which are connected back to back. Each pair consists of two Thyristor. Fig. 4-2 shows the Stator Voltage Control of the three phase induction motors by Thyristor Voltage Controller.

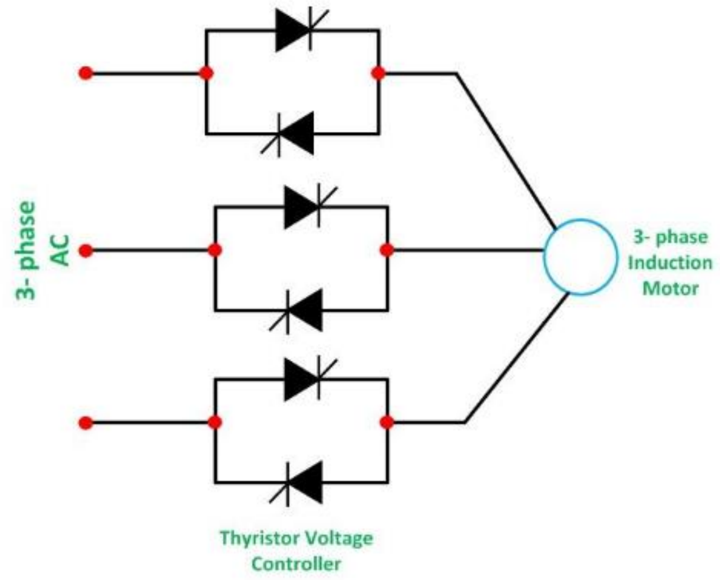


Fig. 4-2 using the thyristor to make speed control by varying the stator voltage

For lower power ratings, the back to back Thyristor pairs connected in each phase is replaced by Traic. Speed control is obtained by varying the firing angle of the Triac. These controllers are known as Solid State fan regulators. As the solid-state regulators are more compact and efficient as compared to the conventional variable regulator. Thus, they are preferred over the normal regulator.

4-1-3 Speed Control of Induction Motor by Variable Frequency Control:

Variable Frequency Control is a method which is used to control the speed of an induction motor. The synchronous speed and therefore, the speed of the motor can be controlled by varying the supply frequency. The synchronous speed of an induction motor is given by the relation $n_s = \frac{120f}{P}$. Any reduction in the supply frequency, without a change in the terminal voltage, causes an increase in the air-gap flux. Induction motors are designed to operate at the knee point of the magnetization characteristic to make full use of the magnetic material. Therefore, the increase in flux will saturate the motor. This will increase the magnetizing current, distort the line current and voltage, increase the core loss and the stator copper loss, and produce a high-pitch acoustic noise. While an increase in flux beyond the rated value is undesirable from the consideration of saturation effects, a decrease in flux is also avoided to retain the torque capability of the motor. Therefore, the Variable Frequency Control of Induction Motor Drive below the rated frequency is generally carried out at rated air-gap flux by varying terminal voltage with frequency so as to maintain (V/f) ratio constant at the rated value.

4-1-4 Variable voltage variable frequency control of induction motor:

In order to minimise the losses and to avoid the saturation as in the above method of control, the motor is operated at rated air gap flux. This condition is obtained by varying the terminal voltage with frequency so as to maintain (V/f) ratio constant at the rate value. This type of control is known as Constant Volts Per Hertz. If the ratio of voltage to frequency is kept constant, the flux remains constant. By varying the voltage and frequency the torque and speed can be varied. The torque is normally maintained constant while the speed is varied. This arrangement is widely used in the locomotives and industrial applications. The purpose of the volts hertz control scheme is to maintain the airgap flux of AC Induction motor constant in order to achieve higher run-time efficiency. The magnitude of stator flux is proportional to the ratio of stator voltage & the frequency. If ratio is kept constant the stator flux remains constant & motor torque will only depend upon slip frequency. In variable-frequency, variable-voltage operation of a drive system, the machine usually has low slip characteristics (i.e low rotor resistance), giving high efficiency. The absence of high in-rush starting current in a direct-start drive reduces stress and therefore improves the effective life of the machine. Thus, the speed control of an induction motor using variable frequency supply requires a variable voltage power source. The variable frequency supply is obtained by the following converters.

1- Voltage source inverter
2- Current source inverter
3- Cyclo converter

An inverter converts a fixed voltage DC to a fixed or variable voltage AC with variable frequency. A Cyclo converter converts a fixed voltage and fixed frequency AC to a variable voltage and variable AC frequency. The variable frequency control allows good running and transient performance to be obtained from a cage induction motor. Cyclo converter-controlled induction motor drive is suitable only for large power drives and to get lower speeds.

Variable voltage variable frequency control is a very good control if it is compared to AC voltage controller due has some advantages as constant starting torque, constant maximum torque, less harmonics, wide range of the speed control and high efficiency but it has some disadvantages as variation of the stator flux due to the variations in the supply voltage, the air-gap flux will vary according to the variation in stator resistance with temperature Torque pulsations are present at low speeds owing to presence of fifth, seventh and eleventh and higher harmonics. To improve and overcome these problems another method of control is used it is constant amplitude of air-gap flux wave form. To achieve good control in induction motor, the AC controller must be used. The AC controller wide spread under many names as adjustable speed drive, variable frequency drives, variable speed drive, frequency converter act, the AC Controller consists of three basic parts: the rectifier, inverter, and the DC link to connect the two. The rectifier converts AC input into DC (direct current), while the inverter switches the DC voltage to an adjustable frequency AC output voltage. The inverter can also be used to control output current flow if needed. Both the rectifier and inverter are directed by a set of controls to generate a specific amount of AC voltage and frequency to match the AC motor system at a given point in time. The variable speed drive has ten additional benefits users realize when operating motors with drives. These benefits are

1. Controlled Starting Current
2. Reduced Power Line Disturbances
3. Lower Power Demand on Start
4. Controlled Acceleration
5. Adjustable Operating Speed
6. Adjustable Torque Limit
7. Controlled Stopping
8. Energy Savings
9. Reverse Operation

10. Elimination of Mechanical Drive Components

At low frequencies with v/f constant, the pullout torque is reduced because of the effect of stator resistance. As the frequency approaches zero, the voltage drop due to stator resistance becomes important, and flux reduction that causes the torque reduction becomes prominent. This effect is known and easily mitigated by low-speed voltage boosting: increasing the V/f ratio at low frequencies to restore the flux. Fig. 4-3 shows a typical set of torque-speed curves for a drive with low-speed voltage boosting. Beyond rated speed, V/Hz ratio cannot be kept constant anymore because voltage cannot increase beyond rated voltage of the motor to avoid motor insulation breakdown. The increase in frequency beyond rated frequency is possible and will produce higher speed but with voltage kept at rated voltage, and consequently reducing V/Hz ratio, the flux density will reduce and the torque will reduce.

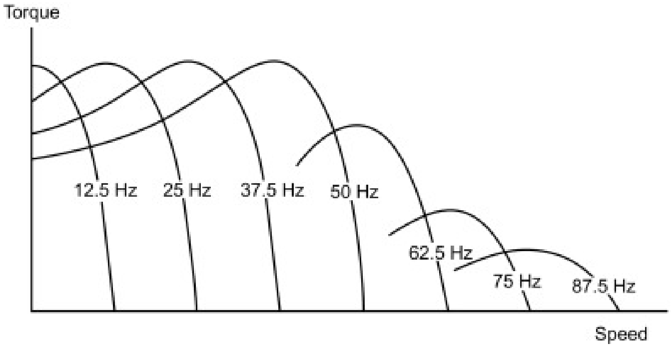


Fig. 4-3 A typical set of torque-speed curves for a drive with low-speed voltage boosting.

As mentioned previously, the VFD-driven motor can develop any torque up to rated torque at any speed up to rated speed. This area is called “constant torque” area. Above rated speed, V/Hz will reduce because voltage is kept constant at rated motor voltage, stator, and rotor current are also kept constant and speed and frequency are increasing, so the flux density will reduce and the torque will reduce inversely with the frequency. This area in the motor torque-speed characteristic is called “constant power” area. Constant power area is up to approximately twice the rated speed. Beyond constant power area is the high-speed area where current limit coincides with the pullout torque limit, which reduces inversely with the square of the frequency, so the constant power cannot be maintained any further. Constant torque, constant power, and high-speed areas are shown in Fig. 4-4.

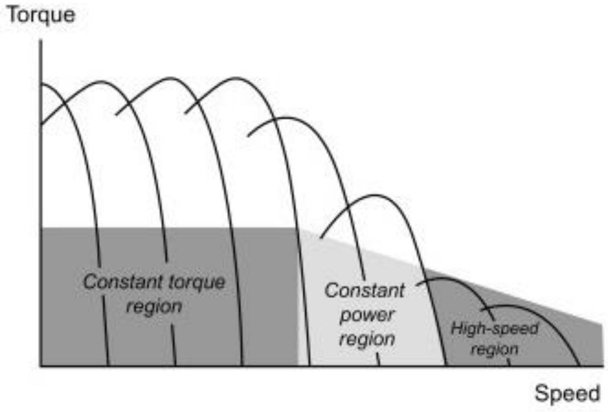


Fig. 4-4 Constant torque, constant power, and high-speed areas

To improve the torque problem at low frequency, the constant airgap flux waveform employed. This method can be explained as the follows;

4-1-5 Keeping airgap flux density constant:

Due to an accurate at low frequency and at low speed when controlling the induction motor through the variable voltage variable frequency method which is used in the last chapter, another method is used to increase the accuracy control at low frequency and at low speed. This method is called constant amplitude of airgap flux waveform. In this case the air-gap is really constant when where is an emf induced in stator winding, is electrical frequency in rad/sec and is constant value.

CHAPTER (5)

OVERVIEW OF OPEN AND CLOSED LOOPS CONTROL SYSTEMS

When a number of elements are combined together to form a system to produce desired output then the system is referred to as control system. The main feature of a control system is that there should be a clear mathematical relationship between input and output of the system. When the relation between input and output of the system can be represented by a linear proportionality, the system is called a linear control system. Again, when the relationship between input and output cannot be represented by single linear proportionality, rather the input and output are related by some non-linear relation, the system is referred to as a non-linear control system.

Requirements of a Good Control System:

Accuracy: Accuracy is the measurement tolerance of the instrument and defines the limits of the errors made when the instrument is used in normal operating conditions. Accuracy can be improved by using feedback elements. To increase the accuracy of any control system error detector should be present in the control system.

Sensitivity: The parameters of a control system are always changing with the change in surrounding conditions, internal disturbance or any other parameters. This change can be expressed in terms of sensitivity. Any control system should be insensitive to such parameters but sensitive to input signals only.

Noise: An undesired input signal is known as noise. A good control system should be able to reduce the noise effect for better performance.

Stability: It is an important characteristic of the control system. For the bounded input signal, the output must be bounded and if the input is zero then output must be zero then such a control system is said to be a stable system.

Bandwidth: An operating frequency range decides the bandwidth of the control system. Bandwidth should be as large as possible for the frequency response of good control system.

Speed: It is the time taken by the control system to achieve its stable output. A good control system possesses high speed. The transient period for such system is very small.

Oscillation: A small numbers of oscillation or constant oscillation of output tend to indicate the system to be stable.

5-1 Types of Control Systems:

There are various types of control systems, but all of them are created to control outputs. The system used for controlling the position, velocity, acceleration, temperature, pressure, voltage and current etc. are examples of control systems. Here the systems are classified into: -

1- Open loop control system
2- Closed loop control system

5-1-1 Open loop control system:

In open loop control systems, output is not fed-back to the input. So, the control action is independent of the desired output. A control system in which the control action is totally independent of output of the system then it is called open loop control system.

Fig. 1-5 shows the block diagram of the open loop control system. Here, an input is applied to a controller and it produces an actuating signal or controlling signal. This signal is given as an input to a plant or process which is to be controlled. So, the plant produces an output, which is controlled.

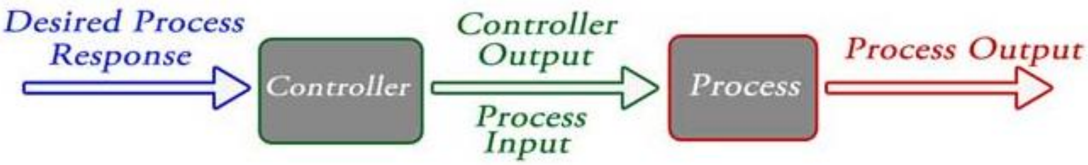


Fig. 1-5 The block diagram of the open loop control system

Practical Examples of Open Loop Control System

- Electric Hand Drier – Hot air (output) comes out as long as you keep your hand under the machine, irrespective of how much your hand is dried.
- Automatic Washing Machine – This machine runs according to the pre-set time irrespective of washing is completed or not.
- Bread Toaster – This machine runs as per adjusted time irrespective of toasting is completed or not.
- Automatic Tea/Coffee Maker – These machines also function for pre adjusted time only.
- Timer Based Clothes Drier – This machine dries wet clothes for pre-adjusted time, it does not matter how much the clothes are dried.
- Light Switch – Lamps glow whenever light switch is on irrespective of light is required or not.

Advantages of Open Loop Control System:

- Simple in construction and design.
- Economical.
- Easy to maintain.
- Generally stable.
- Convenient to use as output is difficult to measure.

Disadvantages of Open Loop Control System:

- They are inaccurate.
- They are unreliable.

- Any change in output cannot be corrected automatically.

5-1-2 Closed loop control system:

Control system in which the output has an effect on the input quantity in such a manner that the input quantity will adjust itself based on the output generated is called closed loop control system. Open loop control system can be converted in to closed loop control system by providing a feedback. This feedback automatically makes the suitable changes in the output due to external disturbance. In this way closed loop control system is called automatic control system. Fig. 5-2 below shows the block diagram of closed loop control system in which feedback is taken from output and fed in to input.

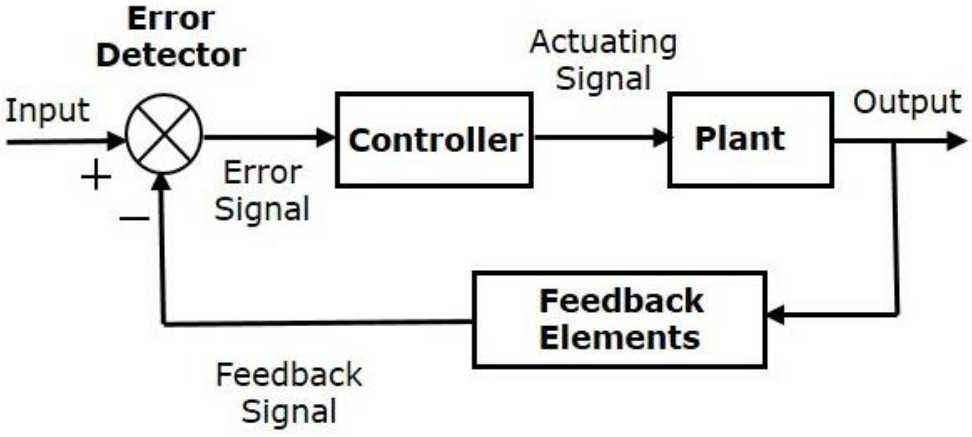


Fig. 5-2 The block diagram of closed loop control system

Practical Examples of Closed Loop Control System

- Automatic Electric Iron – Heating elements are controlled by output temperature of the iron.
- Servo Voltage Stabilizer – Voltage controller operates depending upon output voltage of the system.
- Water Level Controller – Input water is controlled by water level of the reservoir.

- Missile Launched and Auto Tracked by Radar – The direction of missile is controlled by comparing the target and position of the missile.
- An Air Conditioner – An air conditioner functions depending upon the temperature of the room.
- Cooling System in Car – It operates depending upon the temperature which it controls.

Advantages of Closed Loop Control System

- Closed loop control systems are more accurate even in the presence of non-linearity.
- Highly accurate as any error arising is corrected due to presence of feedback signal.
- Bandwidth range is large.
- Facilitates automation.
- The sensitivity of system may be made small to make system more stable.
- This system is less affected by noise.

Disadvantages of Closed Loop Control System

- They are costlier.
- They are complicated to design.
- Required more maintenance.
- Feedback leads to oscillatory response.
- Overall gain is reduced due to presence of feedback.
- Stability is the major problem and more care is needed to design a stable closed loop system.

5-3 Key Differences between Open Loop and Closed Loop System:

- The open loop system means the output of the system is free from their input. In the closed-loop system, the desired output depends on their input.
- The open loop system is called the non-feedback system while the closed loop is the feedback system.
- The control and controlled process are the two components of the open loop system. The closed loop requires some components likes an amplifier, controller, controlled process, feedback system etc.
- The construction of systems is easy because few elements are used in the system. The construction of the closed-loop system is quite difficult.
- The open loop system is not reliable whereas the closed-loop system is reliable.
- The accuracy of the system is less as compared to the closed-loop system.
- The open loop system is more stable as compared to a closed loop system. Here the word stable means the output of the system remains constant even after the disturbances.
- The open loop system is not optimized, whereas the closed-loop system is optimized.
- The open loop system gives the fast response, whereas the closed loop system gives the slow response.
- The calibration of open loop system is difficult as compared to the closed-loop system.
- In an open loop system, the disturbance affected the output, whereas in a closed loop system the output is not much affected by the disturbances.
- The output control system has a non-linear response, whereas the input control system has linear responses.

- The traffic light, automatic washing machine, etc. are the examples of the output system, whereas the temperature controller, toaster etc. are the examples of the closed-loop system.

Conclusion

The open loop and control loop are the two types of control system. The open loop system works on input, and it is simple in construction while the closed loop system is complex and their output depends on the input.

CHAPTER (6)

SCALAR CONTROL OF THE THREE PHASE INDUCTION MOTORS

To get constant motor torque the airgap flux must be constant this can be done under base speed of the motor e.g. up to rated conditions but above base speed of the motor voltage reaches maximum value so, this cannot be increased to keep the windings insulation and hence increasing the motor speed above rated speed leads to decrease the airgap flux which the torque. This type of control called scalar control or V/Hz control. This control can be divided into open loop scalar control and closed loop scalar control. Both open and closed-loop control of the speed of an AC induction motor can be implemented based on the constant V/Hz principle. Open-loop speed control is used when accuracy in speed response is not a concern such as in HVAC (heating, ventilation and air conditioning), fan or blower applications. In this case, the supply frequency is determined based on the desired speed and the assumption that the motor will roughly follow its synchronous speed. The error in speed resulted from slip of the motor is considered acceptable.

The V/Hz ratio is calculated based on the rated values (voltage and frequency) of the controlled AC motor. By keeping the value of the V/Hz ratio constant, we can maintain a relatively constant magnetic flux in the motor gap. If the V/Hz ratio increases, then the motor becomes overexcited and vice versa if the ratio decreases the motor is in an unexcited state. With applying V/Hz control the voltage increasing by increasing frequency as shown in Fig. 6-1 and Fig. 6-2. Scalar control of AC motors is a good alternative for applications where there is no variable load and no good dynamics (fans, pumps) are required. The scalar control does not require a rotor position sensor, and the rotor speed can be estimated from the frequency of the supply voltage. When scalar control is used, a high-performance digital signal processor is not required.

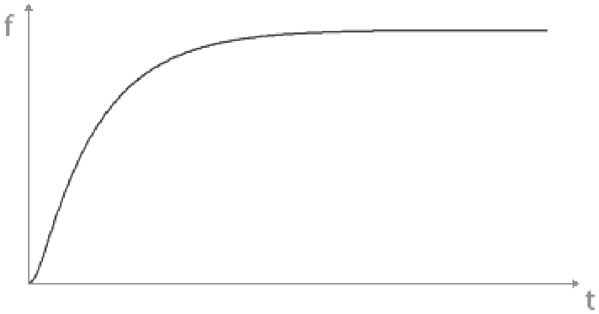


Fig. 6-1 Rate of frequency increasing

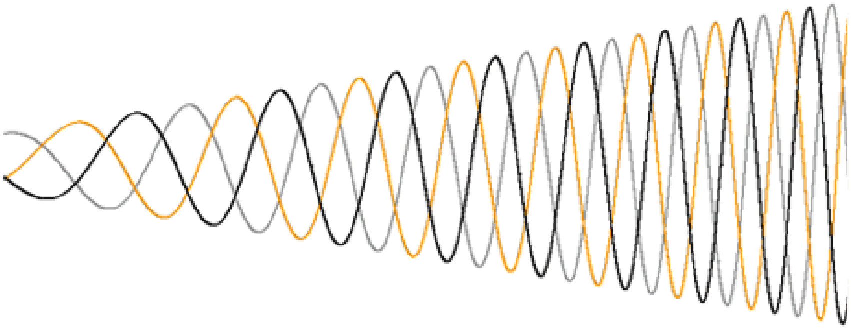


Fig. 6-2 Increasing the voltage due to increasing frequency

Constant Volts-per-Hertz (V/f) control is the most popular scalar control scheme that varies the terminal voltage in proportion to the supplied frequency in order to maintain the air-gap flux at the rated V/f ratio, especially when the machine operates below its rated frequency. However, all the non-idealities including stator resistance, leakage inductance, core losses, and rotor slip could cause the constant V/f control to exhibit deteriorated performance of speed regulation at low frequency and high load torques. Consequently, many researchers have been devoted into solving the problems. Its practical application at low frequency is still challenging due to the influence of the stator resistance and the necessary rotor slip to produce torque. In addition, the non-linear behavior of modern PWM-VSI in the low voltage range, makes it difficult to use constant V/f drives at frequencies below 3 Hz. The V/Hz operating line is ideally linear and intersects at (0,0) and (rated frequency, rated speed). At low speeds, the voltage drop caused by the stator resistance is significant. This drop has a direct effect on the motor flux or torque. There are a few adjustments you can make to fine tune your V/Hz operation. The first is called "boost". Boost adjusts the output voltage at 0Hz, and gives the motor a little voltage boost at lower speeds to compensate for the stator resistance losses. In the KEB F5 VFD, rated frequency is parameter uF.0 and boost is uF.1 which can be adjusted up to 25% of the rated voltage. This can be seen in Fig. 3-6.

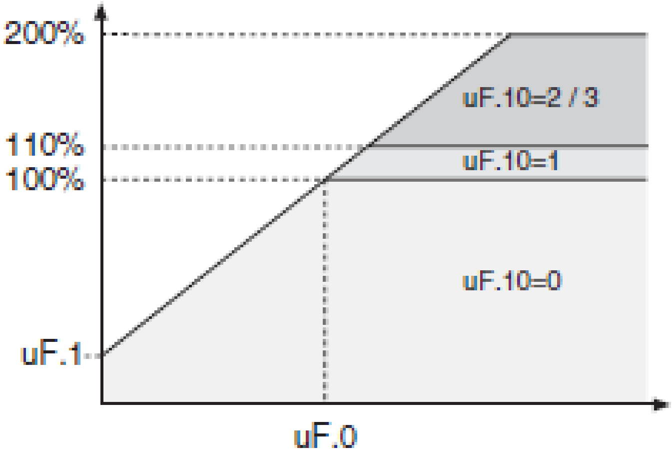


Fig. 3-6 V/Hz relationship shown with boost

There are many methods are used to compensate the voltage drop across the stator resistance at low frequency. These techniques as

1- Programable voltage frequency characteristics.
2- Formula based voltage drop compensation.
3- Current feedback-based voltage drop compensation.
4- Slip speed compensation.
5- Vectorially voltage drop compensation.

After discuss the idea of the scalar control, the application scalar control through the open loop control and closed loop control will discuss in the following;

6-1 Open loop scalar control:

The open loop V/F control of an induction motor is the most common method of speed control because of its simplicity and these types of motors are widely used in industry. Traditionally, induction motors have been used with open loop 50Hz power supplies for constant speed applications. For adjustable speed drive applications, frequency control is natural. However, voltage is required to be proportional to frequency so that the stator flux remains constant if the stator resistance is neglected. The standard control components of an open system scalar control can be seen in Fig. 4-6, where the power circuit consists of a rectifier was fed from a single or three-phase AC source, depending on the power of the motor whose speed is to be controlled, and a filter and inverter equipped with a voltage operating in a PWM method. As for the control circuit, it consists of a summer, a programmed gain unit, an integrator, and waves generator.

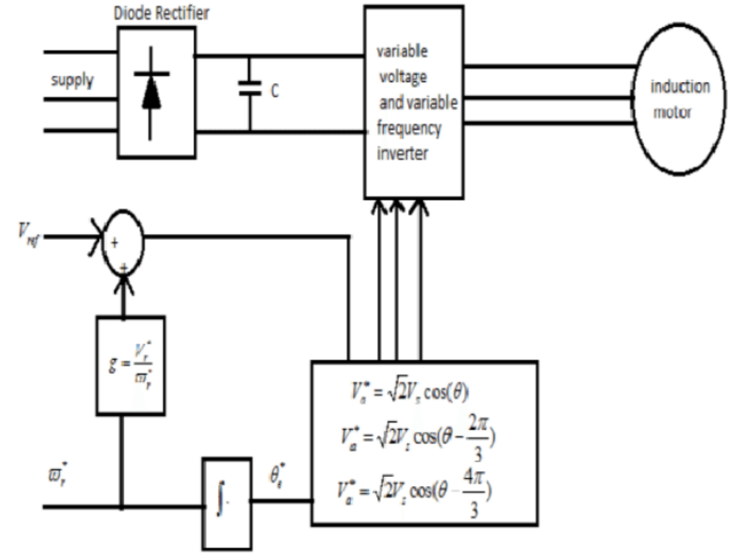


Fig. 6-4 Open loop scalar control

The idea of working for this type of control depends on setting the desired frequency or speed. This speed is multiplied by a gain coefficient according to an equation to find the appropriate voltage to be applied to the motor through the inverter, and another voltage is added to this output voltage within 10% of the rated voltage in order to manage motor at rated speed and then to obtain the variable position with respect to voltage waveform which we will deduce. The speed at which the motor is required to move is integrated through an integral unit and then the total voltage output is used with the variable position to produce the voltage and frequency that the inverter wants to output through the reference voltage generator unit and then that voltage is applied to the inverter into the modified pulse unit that is compared inside the inverter With the carriers or triangle waves to produce the pulses that operate the six electronic switches of the inverter to produce the real voltage and apply it to the motor to rotate at the required speed. Ideally no feedback signals are required for this control scheme but some problems encountered in the operation of this open loop drive are the following:

- The speed of the motor cannot be controlled precisely, because the rotor speed will be slightly less than the synchronous speed and that in this scheme the stator frequency and hence the synchronous speed is the only control variable.

- The slip speed, being the difference between the synchronous speed and the electrical rotor speed, cannot be maintained, as the rotor speed is not measured in this scheme. This can lead to operation in the unstable region of the torque-speed characteristics.

- The effect of the above can make the stator currents exceed the rated current by a large amount thus endangering the inverter-converter combination.

These problems are to be suppress by having an outer loop in the induction motor drive, in which the actual rotor speed is compared with its commanded value, and the error is processed through a controller usually a PI controller and a limiter is used to obtain the slip-speed command.

Some researchers try improve the performance of open loop scalar control through derivative relation depending upon the equivalent circuit of induction motor to get the slip speed as

$$\tilde{V}_s/\omega_e = \tilde{\lambda}_{m\_rated}[\frac{R_s}{\omega_e L_m} - \frac{\omega_e L_{ls}}{R_c} + j(1+\frac{L_{ls}}{L_m}+\frac{R_s}{R_c})]^{-1} \quad (9)$$

$$\frac{T_e}{I_s^2} = \frac{3P\omega_{sl}L_m^2 R_r}{R_r^2+\omega_{sl}^2(L_{lr}+L_m)^2} \quad (11)$$

We differentiate the right hand side of eq. (11) with respect slip frequency ω_{sl} and let it equal zero, yielding eq. (12):

$$\omega_{sl\_m} = R_r/(L_{lr}+L_m) \quad (12)$$

With help of these equations the proposed system becomes as in Fig. 6-5

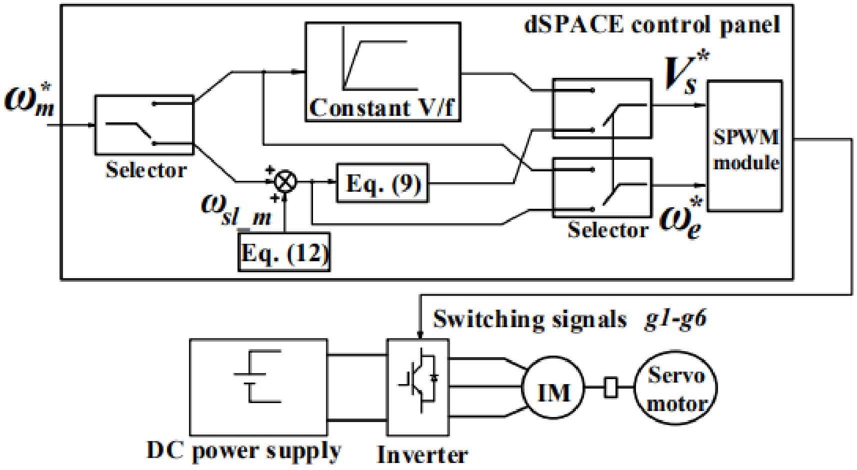


Fig. 6-5 block diagram with and without improved system

The result is as the follows;

With further testing using the proposed V/f, constant V/f control and V/f indicated by [3], the capability to maintain rated torque of V/f indicated by [3] and constant V/f control get worsened at low frequencies and the motor would just stall at a frequency of 6.67Hz. To find the controller's torque capability, rated torque is applied to see if these two V/f controls can handle it. If not, the load torque is decreased for the set V/f ratio. The comparison results are shown in Fig. 6-6.

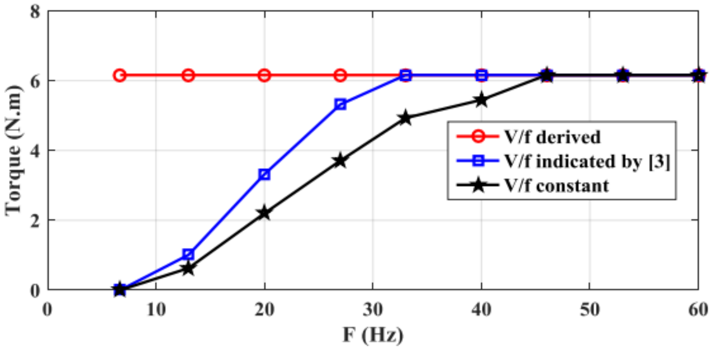


Fig. 6-6 Comparison of capability to maintain rated torque at different frequencies

The comparison results of steady-state speed performance under rated load are shown in Fig. 6-7. Note that both V/f indicated by [3] and constant V/f exhibit worse steady-state speed performance, especially when the speed command is set below 1000RPM.

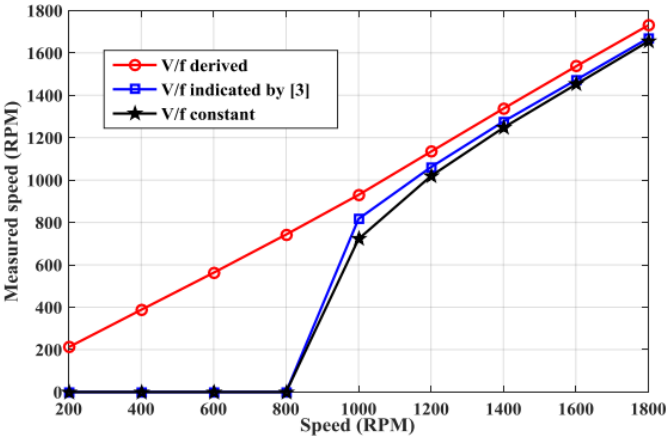


Fig. 6-7 Comparison of steady-state speed performance

Fig. 6-8 shows the % error between the command speed and measured speed under rated load for the proposed V/f control with slip compensation against the constant V/f control and V/f control indicated by [3]. It can be seen that our proposed V/f control with slip compensation maintain very good speed performance over the whole range. The steady-state speed performance of the other two controls keeps deteriorating and they can no longer provide rated torque at desired speed.

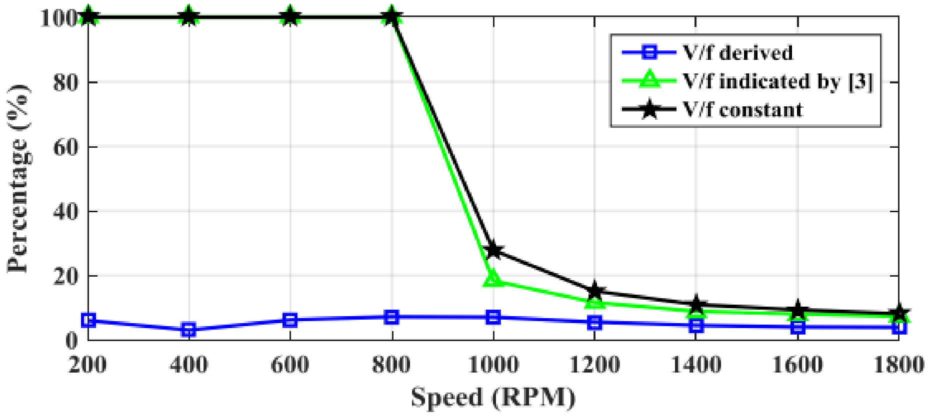


Fig. 6-8 The % error between the command speed and measured speed under rated load

In the next section of the scalar control, the closed loop scalar control will explain. With this controller, new controller element was used this controller element is the proportional integrator controller (PI controller) so firstly, this controller will explain in the following.

6-2 Proportional integrator controller (PI controller):

Conventional controllers as P, PI, PD, PID, Otto-Smith, all their different types and realizations, and other controller types. It is a characteristic of all conventional controllers that one has to know a mathematical model of the process in order to design a controller. Practical experience shows that this type of control has a lot of sense since it is simple and based on three basic behavior types: proportional (P), integrative (I) and derivative (D). Instead of using a small number of complex controllers, a larger number of simple PID controllers is used to control simpler processes in an industrial assembly in order to automates the certain more complex process.

6-2-1 Proportional controller:

Proportional controller is mostly used in first order processes with single energy storage to stabilize the unstable process. The main usage of the proportional controller is to decrease the steady state error of the system. As the proportional gain factor Kp increases, the steady state error of the system decreases. However, despite the reduction, proportional control can never manage to eliminate the steady state error of the system. As we increase the proportional gain, it provides smaller amplitude and phase margin, faster dynamics satisfying wider frequency band and larger sensitivity to the noise. We can use this controller only when our system is tolerable to a constant steady state error. In addition, it can be easily concluded that applying proportional controller decreases the rise time and after a certain value of reduction on the steady state error, increasing Kp only leads to overshoot of the system response. Proportional control also causes oscillation if sufficiently aggressive in the presence of lags and/or dead time. The more lags (higher order), the more problem it leads. Plus, it directly amplifies process noise.

The proportional controller can be written in the following form

$$p(t) = k_p e(t) \qquad 6.1$$

Where k_p is the proportional controller and $e(t)$ is the value of error

By studying the Eq. 6.1 it clears that, the controller signal is in proportional with the error and this can be drawing as showing in Fig. 6-9 where the slope of the line is proportional controller (k_p). This type of control can be represented as shown in Fig. 6-10. The transfer function for this controller can be written by taking Laplace transformation for Eq. 6.1

$$P(S) = k_p E(S) \tag{6.2}$$

And hence the transfer function for proportional controller can be written as

$$G_C(s) = \frac{P(S)}{E(S)} = k_p \tag{6.3}$$

Some electronic circuit can be used to verify the proportional controller one of them can be seen in Fig. 6-11. In this circuit (Fig. 6-11), the proportional controller can be written as

$$k_p = \frac{R2}{R1} \tag{6.4}$$

Fig. 6-9 The controller signal with error

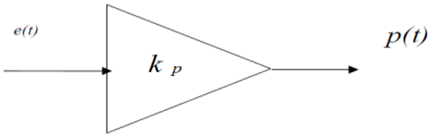


Fig. 6-10 Representation of proportional controller

This controller is highly response and simple but doesn’t cancel the error

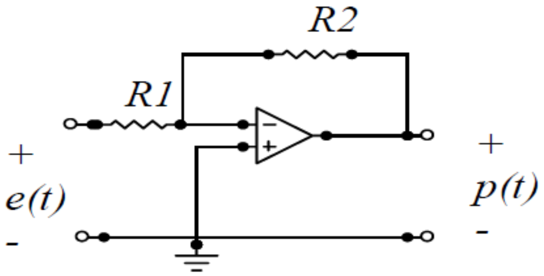


Fig. 6-11 Electronic circuit to make the function of proportional controller

6-2-1-1 Simulations and Results to Find the Constraints on Loop Tuning:

In order to observe the basic impacts, described above, of the proportional gain to the system response, see the simulations below prepared on MATLAB in continuous time with a transfer function $\frac{1}{s+1}$ and unit step input. This system is shown in Fig. 6-12 in details. The results will lead to tuning methods. Fig. 6-13 shows the response of the system with different proportional controller where it is found that;

1. By increasing the proportional controller; the steady state error is decrease and rise time decrease.

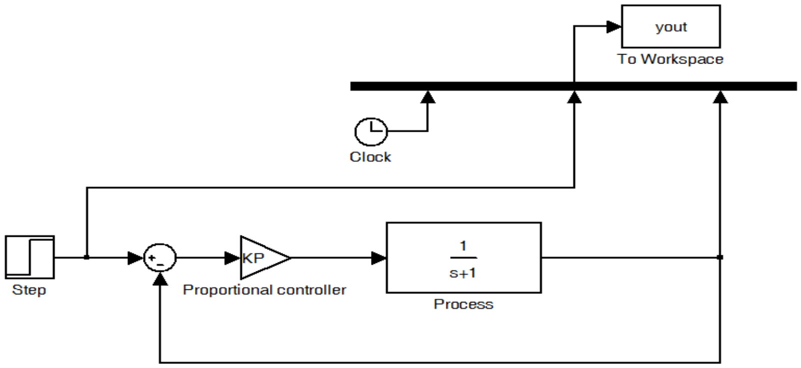


Fig. 6-12 Constructing closed loop system with proportional controller on MATLAP

6-2-2 Integral controller:

An integral controller outputs a control signal $p(t)$ that is proportional to the integral of the error signal $e(t)$. This controller can be expressed as

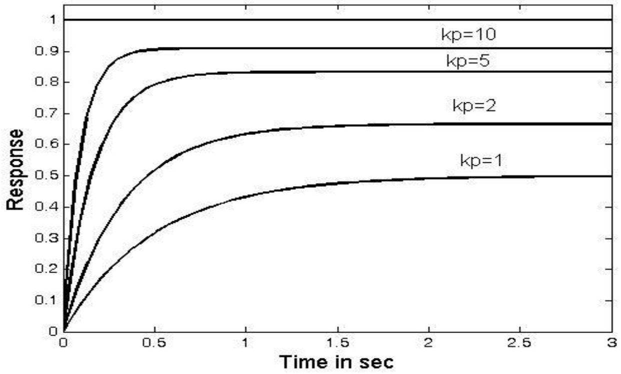


Fig. 6-13 Effect of variation proportional controller (Kp) on the response of the system

$$p(t) = k_I \int_0^t e(t)dt \qquad 6.5$$

where k_I is the integral gain.

This controller (integral controller) can be represented as shown in Fig. 6-14 where the input is the error $e(t)$ and the output is $p(t)$

To get the transfer function for this controller apply the Laplace transformation on Eq. 6.5 where it becomes

$$P(s) = \frac{k_I E(s)}{s} \qquad 6.6$$

and hence the transfer function can be written as

$$G_C(s) = \frac{P(s)}{E(s)} = \frac{k_I}{s} \qquad 6.7$$

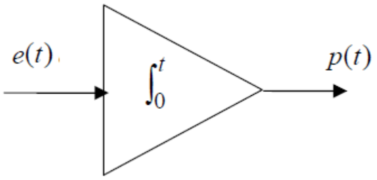


Fig. 6-14 Representation of the integral controller as a block diagram

There are some electronic circuits are used to represent the integral controller. The simplest electronic circuit is shown in Fig. 6-15.

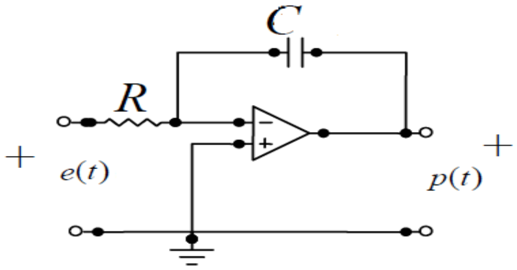


Fig. 6-15 The simplest electronic circuit to make the function of integral controller

From Fig. 6-15 the transfer function can be written as

$$G_C(s) = \frac{kI}{s} = \frac{1}{RCs} \qquad 6.8$$

The integral component of this controller provides a signal based on how long an error persists. It works to prevent this persistence of an error by increasing the control signal with time. This helps reduces the steady state error and, in some cases, depending on the type of system and the type of reference signal, eliminates it. Integral control is usually not used on its own, however it is more effective than proportional control for eliminating the step response steady state error of a first order plant. For a second order plant, using integral control leads to a third order system that, depending on the system parameters, can result in unstable oscillations.

6-2-2-1 Simulations and Results to Find the Constraints on Loop Tuning:

In order to observe the basic impacts, described above, of the integral gain to the system response, see the simulations below prepared on MATLAB in continuous time with a transfer function $\frac{1}{s+1}$ and unit step input. This system is shown in Fig. 6-16 in details.

The results will lead to tuning methods. Fig. 6-17 shows the response of the system with different integral controller where it is found that;

1. By increasing the integral controller; the steady state error is decrease and rise time decrease. With increasing the integral controller appears and the final steady state error reduce to zero.

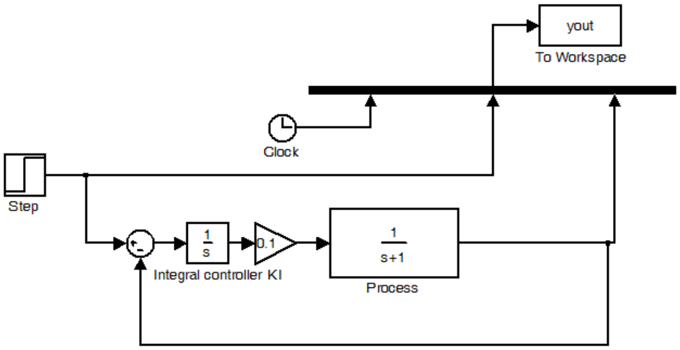


Fig. 6-16 Constructing closed loop system with integral controller on MATLAP

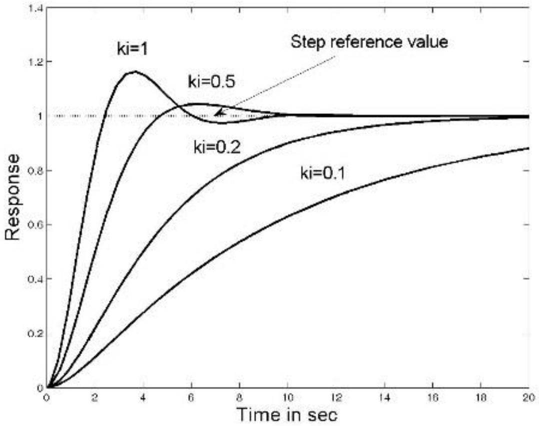


Fig. 6-17 Effect of variation integral controller (KI) on the response of the system

6-2- 3 Proportional Integrator Controller (PI):

Proportional Integrator controller is a combination of proportional and integral control. It is can be expressed as

$$p(t) = k_p \cdot e(t) + k_I \int_0^t e(t)dt \qquad 6.9$$

This type of controller can be simulated as shown in Fig. 6-18

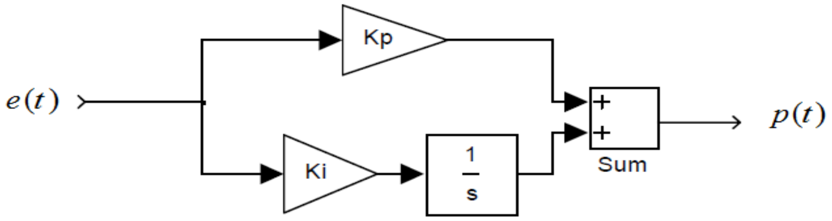


Fig. 6-18 Simulating proportional integrator controller

To get the transfer function of this controller apply Laplace transformation on Eq. 6.9 where it is found that;

$$P(s) = k_p \cdot E(s) + k_I \cdot \frac{E(s)}{s}$$

$$G_c(s) = \frac{P(s)}{E(s)} = k_p + \frac{k_I}{s} \qquad 6.10$$

This controller can be verified by using the following electronic circuit as shown in Fig. 6-19

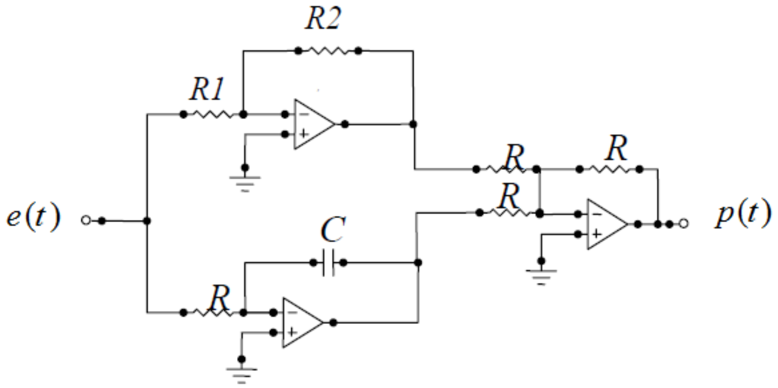


Fig. 6-19 Electronic circuit verified the proportional integral controller

As before $k_p = \frac{R2}{R1}$; $k_I = \frac{1}{RC}$

With integral control, the closed loop transfer function of a first order system is

$$G(s) = \frac{(k_p + \frac{k_I}{s})k}{\tau s + 1 + (k_p + \frac{k_I}{s})k} \qquad 6.11$$

This results in a second order system that can be written as

$$G(s) = \frac{\frac{k_p s + k_I}{\tau} \cdot k}{s^2 + \frac{1 + kk_p}{\tau} \cdot s + \frac{kk_I}{\tau}} \qquad 6.12$$

so, the equivalent natural frequency and damping ratio are

$$\omega_0^2 = \frac{kk_I}{\tau} \quad \Rightarrow \omega_0 = \sqrt{\frac{kk_I}{\tau}} \qquad 6.13$$

$$\xi = \frac{kk_p + 1}{2\sqrt{kk_I \tau}} \qquad 6.14$$

The steady state error can be calculated as

$$e_{ss} = \lim_{s \to 0} sE(S) = \lim_{s \to 0} s \bullet \frac{(\tau s + 1) \cdot R}{\tau s^2 + (1 + kk_p)s + kk_I)} = 0 \qquad 6.15$$

This shows that proportional-integral control eliminates the step response steady state error and allows for more control over the transient response (compared to only proportional or only integral control) because both the damping ratio and natural frequency can be altered using the gains. For example, it is now possible to reduce the rise time and maximum overshoot simultaneously.

6-2-3-1 Simulations and Results to Find the Constraints on Loop Tuning:

In order to observe the basic impacts, described above, of the proportional integral gain to the system response, see the simulations below prepared on MATLAB in continuous time with a transfer function $\frac{1}{s+1}$ and unit step input. This system is shown in Fig. 6-20 in details. The results will lead to tuning methods. Fig. 6-21shows the response of the system with different proportional integrator controller where it is found that;

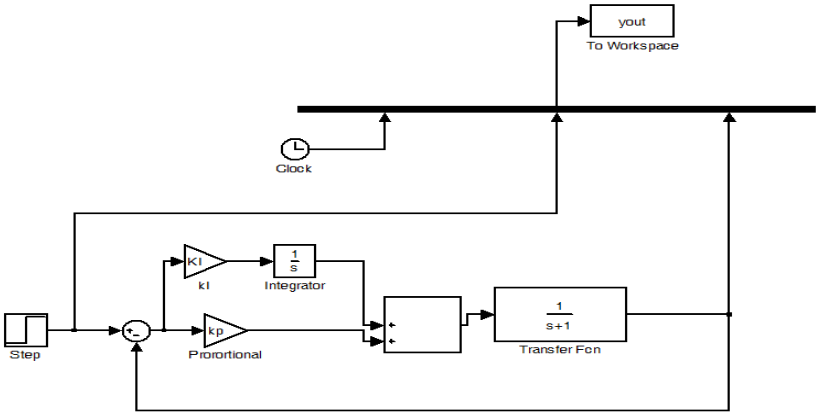


Fig. 6-20 Constructing closed loop system with proportional integral controller on MATLAP

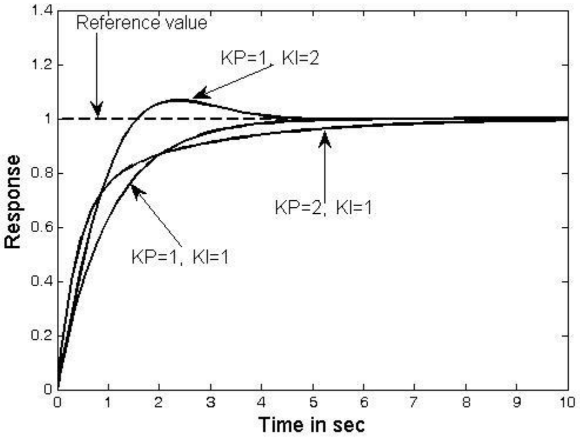


Fig. 6-21 Effect of variation proportional integral controller on the response of the system

P-I controller (proportional integrator controller) is mainly used to eliminate the steady state error resulting from P (proportional) controller. However, in terms of the speed of the response and overall stability of the system, it has a negative impact. This controller is mostly used in areas where speed of the system is not an issue. Since P-I controller has no ability to predict the future errors of the system it cannot decrease the rise time and eliminate the oscillations. If applied, any amount of I (integrator) guarantees set point overshoot.

6-3 Closed loop scalar control:

A closed loop speed control of induction motor drives is shown in Fig. 6-22. It employs inner slip-speed loop with a slip limiter and outer speed loop. The drive operation is explained as, the motor speed is measuring through speed sensor. This speed was compared to reference voltage and the speed error is processed through a PI controller and a slip regulator. PI controller is used to get good steady-state accuracy, and to attenuate noise. The slip regulator sets the slip speed command ω^*_{sl}, whose maximum value is limited to limit the inverter current to a permissible value. The synchronous speed, obtained by adding actual speed ω_r and slip speed ω^*_{sl}, determines the inverter frequency. The reference signal for the closed loop speed control of induction motor drives of the machine terminal voltage V_s^* is generated from frequency f using a function generator. It ensures nearly a constant flux operation up to base speed and the operation at a constant terminal voltage above base speed.

A step increase in speed command ω^*_r produces a positive speed error. The slip speed command ω^*_{sl} is set at the maximum value. The drive accelerates at the maximum permissible inverter current, producing the maximum available torque, until the speed error is reduced to a small value. The drive finally settles at a slip speed for which the motor torque balances the load torque.

For operation beyond the base speed, the slip speed limit of the slip regulator must be increased linearly with the frequency until the breakdown value is reached. This is achieved by adding to the slip regulator output an additional slip speed signal, proportional to frequency and of appropriate sign. For frequencies higher than the frequency for which the breakdown torque is reached, the slip speed limit is kept fixed near the breakdown value.

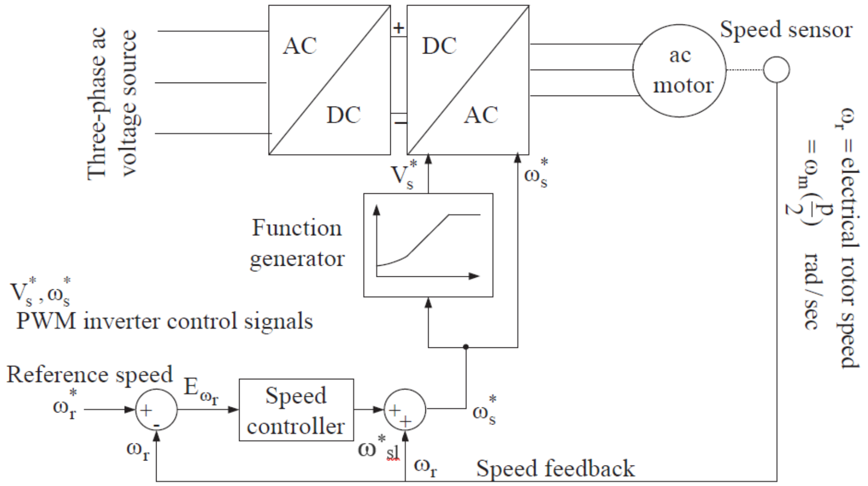


Fig. 6-22 Block diagram of closed loop speed control with slip frequency control and V/f constant

To improve the performance of the drive system at low frequency the boost voltage is added also, the slip speed can be controlled the speed limiter. The boost can be calculated as, $V_s = V_O + K\omega_s$ this modified block diagram can be seen in Fig. 6-23.

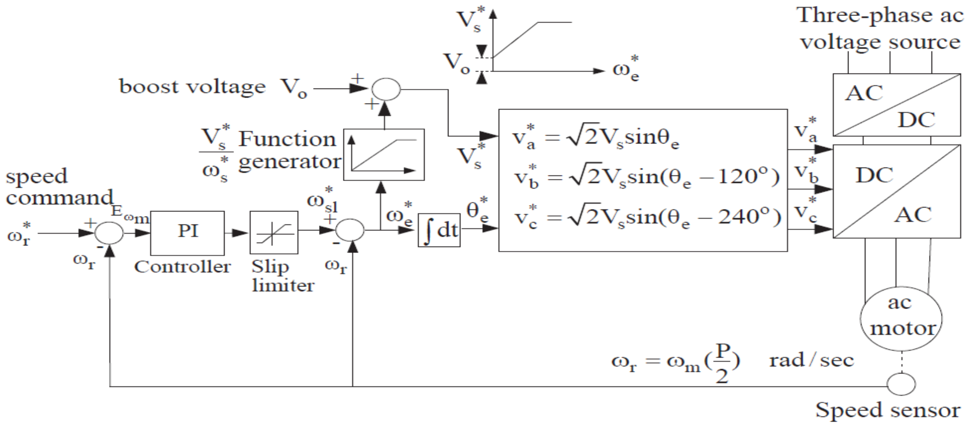


Fig. 6-23 Operation diagram of the scalar control when V/f is constant (the V_a^*, V_b^*, V_c^* reference of the PWM)

6-4 Sinusoidal PWM to drive the induction motor with reducing the torque ripple and THD:

Here sinusoidal PWM with PI current controllers are used to improve the performance of the closed loop scalar control and reduce the torque ripples and total harmonic distortion. To show these three systems are compered these systems are

1- Open loop scalar control with boost voltage.
2- Closed loop scalar control with boost voltage.
3- Closed loop scalar control with boost voltage and PI current controller.

Fig. 6-24 shows the open loop scalar control with boost voltage, Fig. 6-25 shows the closed loop scalar control with boost voltage and Fig. 6-26 shows the closed loop scalar control with boost voltage and PI current controller.

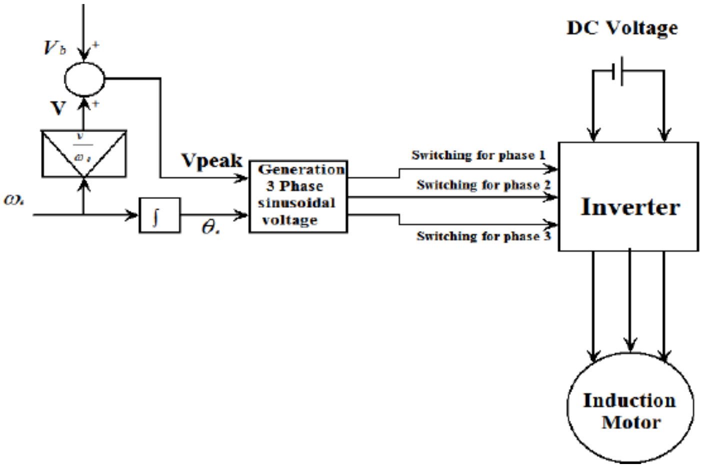


Fig. 6-24 Open loop scalar control with boost voltage

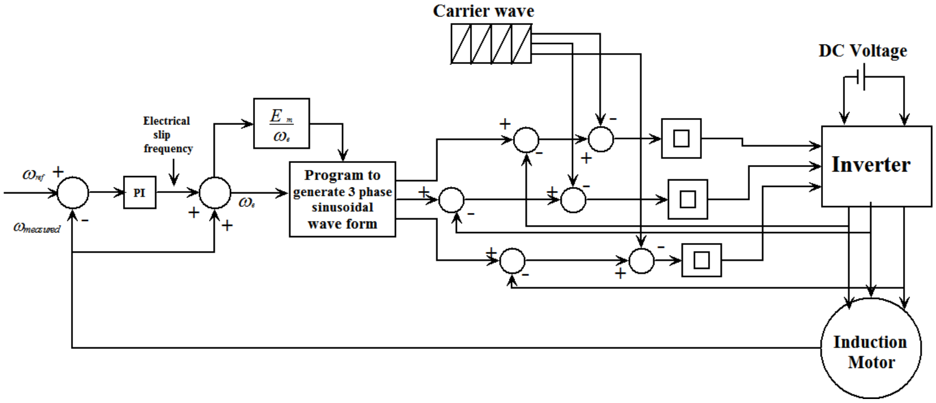


Fig. 6-25 Closed loop scalar control with boost voltage

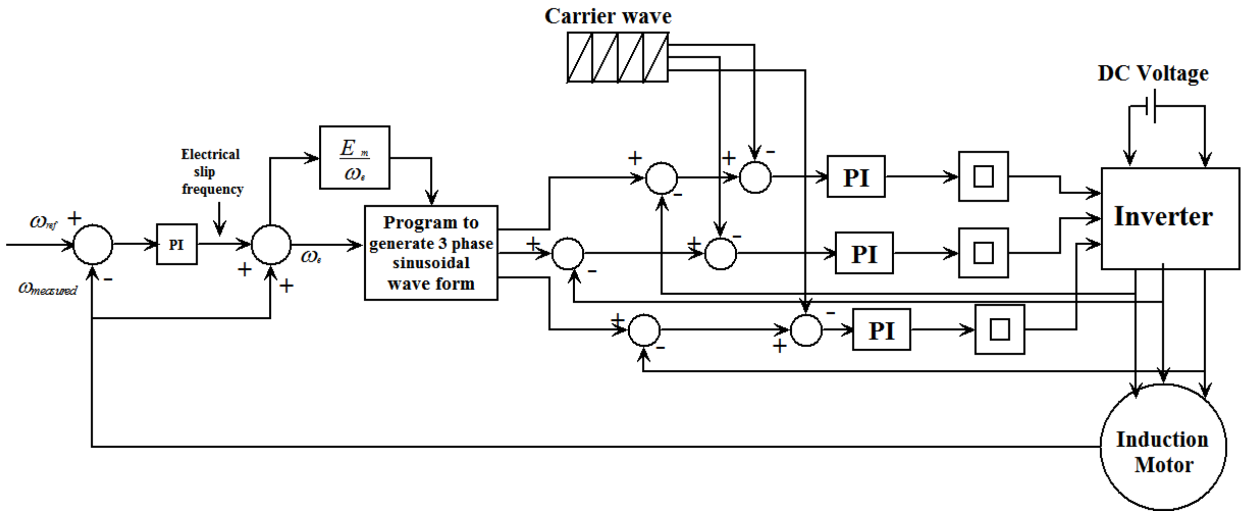


Fig. 6-26 Closed loop scalar control with boost voltage and PI current controller

By studying the performance characteristics of the three-phase induction motor under different control methods (open loop control, closed loop control, closed loop control with PI current controller). It is found that; with open loop control system, the motor torque has highly distortion and has highly distortion ripples. This can be seen in Fig.6-27. With closed loop control, the motor torque has low distortion and low ripples if it is compared to the same motor for open loop scalar control (Fig.6-27) and this can be seen in Fig.6-28. The motor torque has low distortion and ripples with closed loop scalar control with PI current controller if it is compared to the previous cases and this can be seen in Fig.6-29.

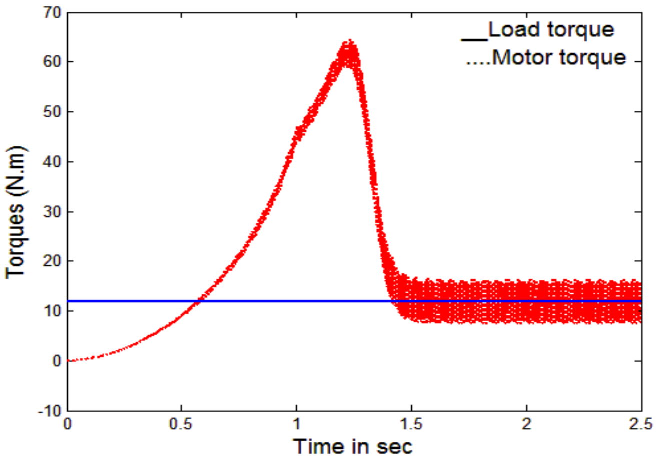


Fig.6-27 motor torque versus load torque with using open loop scalar control

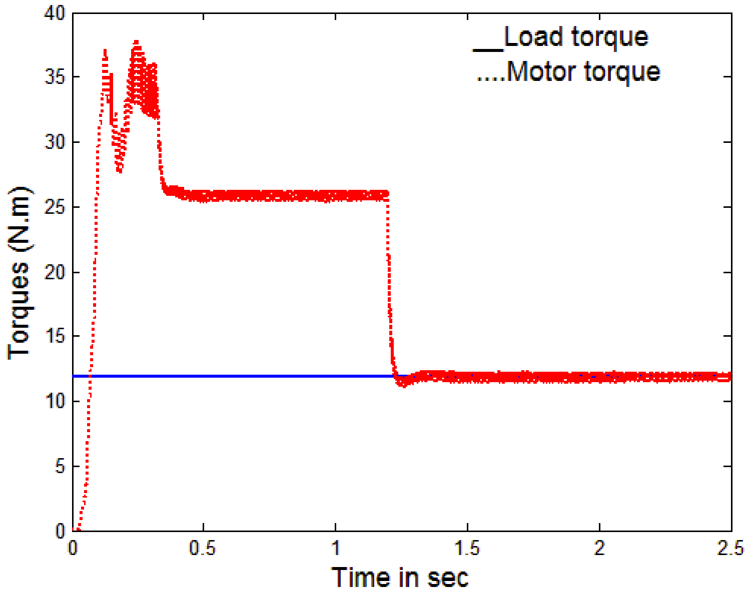


Fig.6-28 motor torque versus load torque with using closed loop scalar control

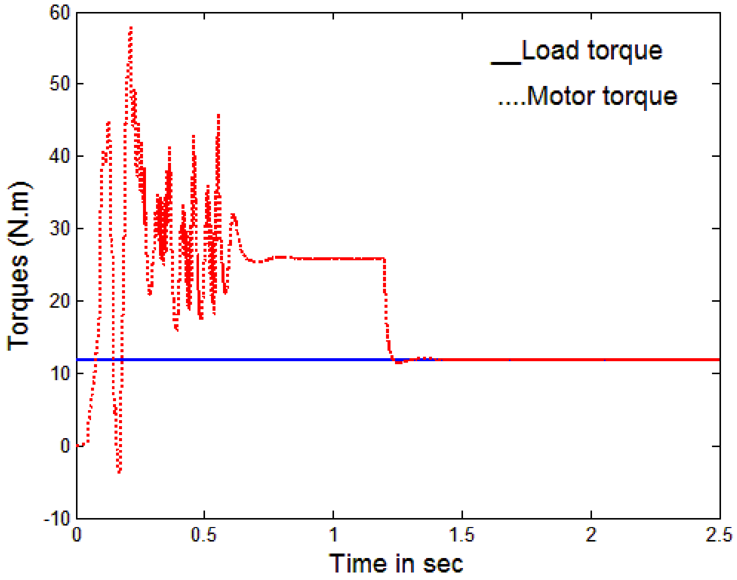


Fig.6-29 motor torque versus load torque with using closed loop PI current controller scalar control

with open loop control system, the motor current is shown in Fig. 6-30. It is increasing gradually and reach to the rated value when the motor torque and motor speed reach the motor load torque and motor speed. also, the stator current has highly distortion. Fig.6-31 shows the motor current when the motor starting with load with closed loop scalar control, this stator current has low distortion if it is compared to the same stator current for open loop scalar control (Fig.6-30). The stator current has low distortion and ripples with closed loop scalar control with PI current controller if it is compared to the previous cases and this can be seen in Fig.6-32.

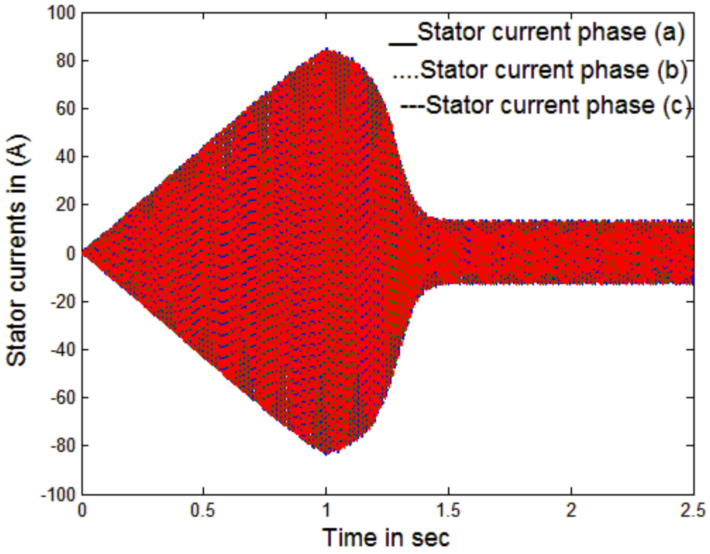


Fig.6-30 Stator current with using open loop scalar control

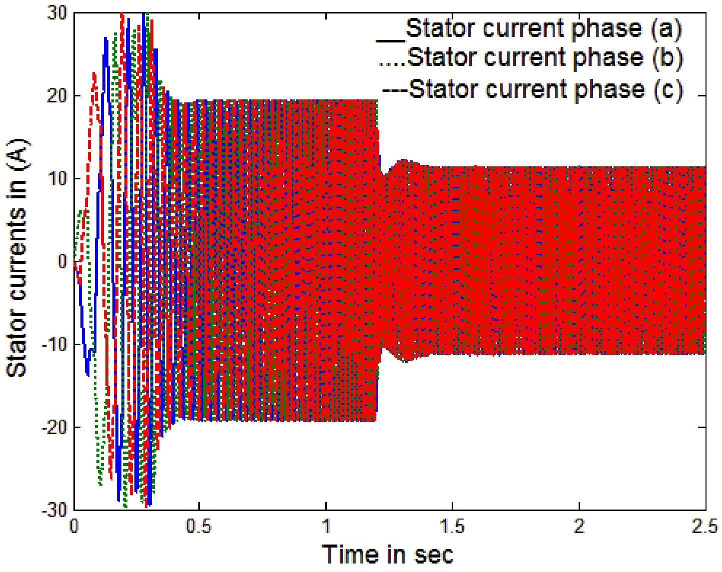


Fig.6-31 Stator current with using closed loop scalar control

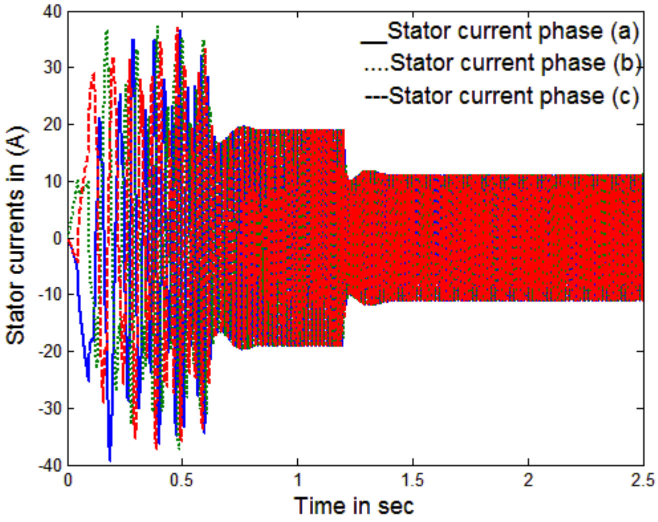


Fig.6-32 Stator current with using closed loop PI current controller scalar control

Due to apply voltage starting from zero and increasing gradually it found that, the motor speed starting in the negative direction after that speed is increasing in the positive direction and reaches to the rated value at 1.5 sec as shown in Fig. 6-33. Fig. 6-34 shows the motor speed versus the reference speed with closed loop scalar control. When comparing between motor speed in this case with the same case of motor speed in the open loop scalar control it is found that; the negative speed at starting is very low if it is compared to Fig.6-33 in case of open loop scalar control also the motor speed reaches the rated load faster than that the open loop scalar control.

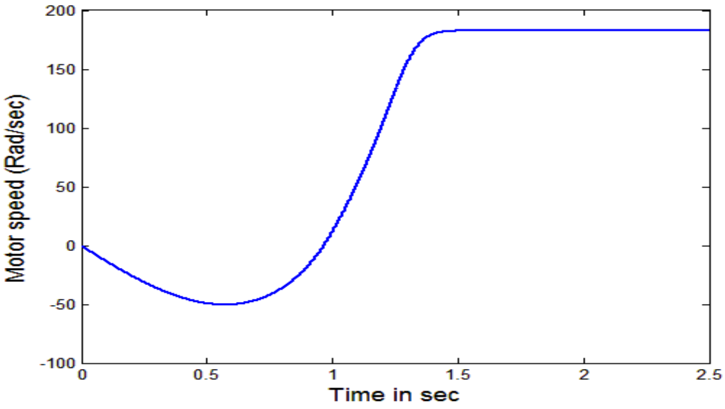


Fig.6-33 Motor speed with using open loop scalar control

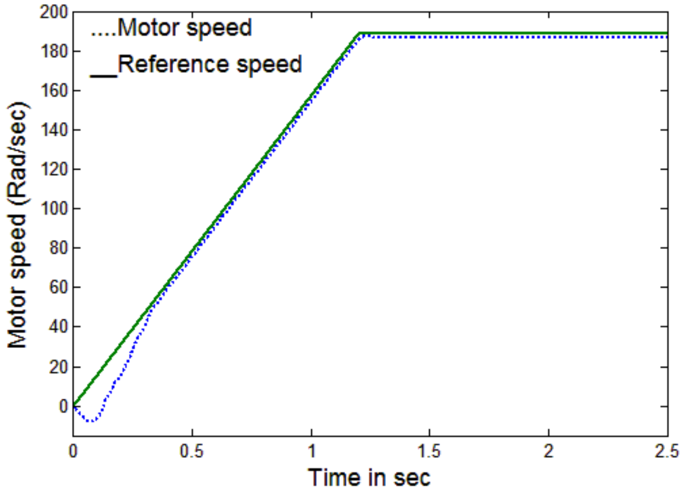


Fig.6-34 Motor speed with using closed loop scalar control

Fig. 6-35 shows the motor speed versus the reference speed with closed loop scalar control and PI current controller. This case is similar to the last case (closed loop scalar control).

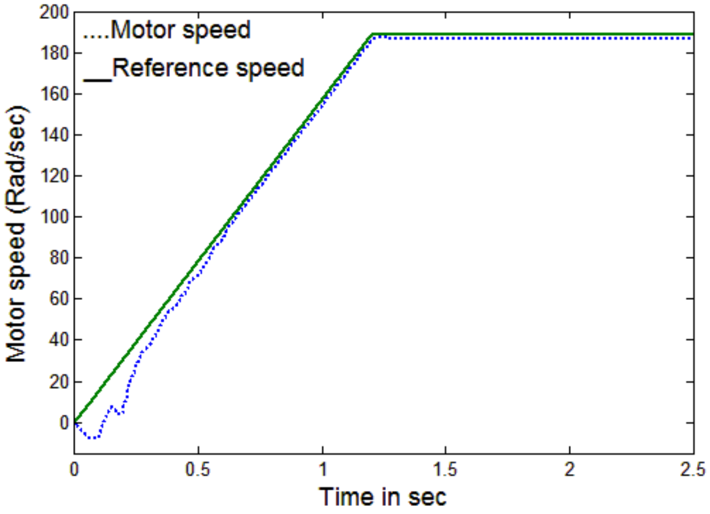


Fig.6-35 Motor speed with using closed loop PI current controller scalar control

CHAPTER (7)

DESIGN OPEN LOOP SCALAR CONTROL OF THE THREE PHASE INDUCTION MOTORS

This chapter discusses the hardware configuration, software program and experimental results. The hardware overall can be seen in Fig. 7-1.

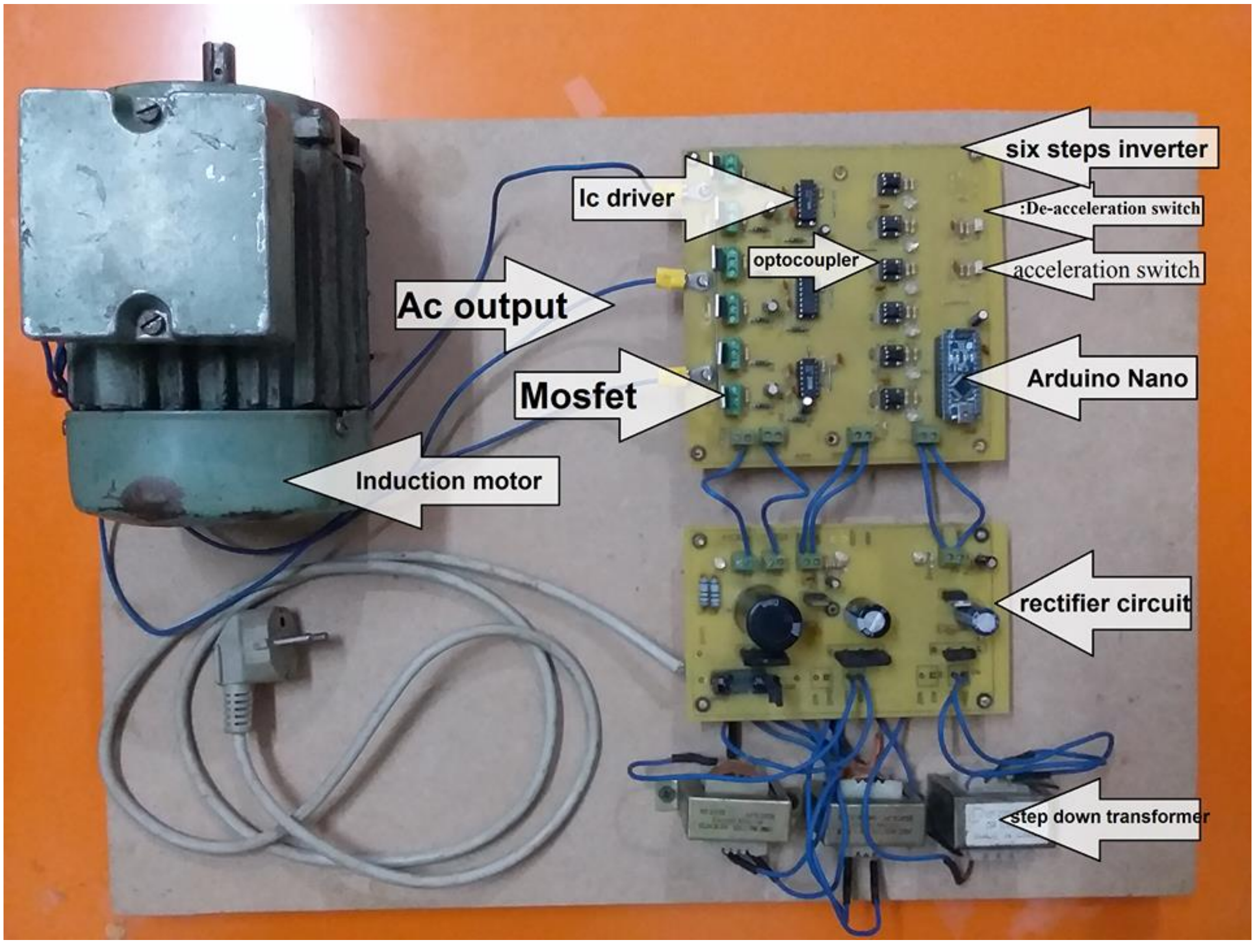


Fig. 7-1The hardware overall

The overall electronic circuits for this project can be seen in Fig. 7-2. The hardware components used in this project can be classified into three main units. These units are

1. Three-phase induction motor. This motor can be seen in Fig. 7-3.

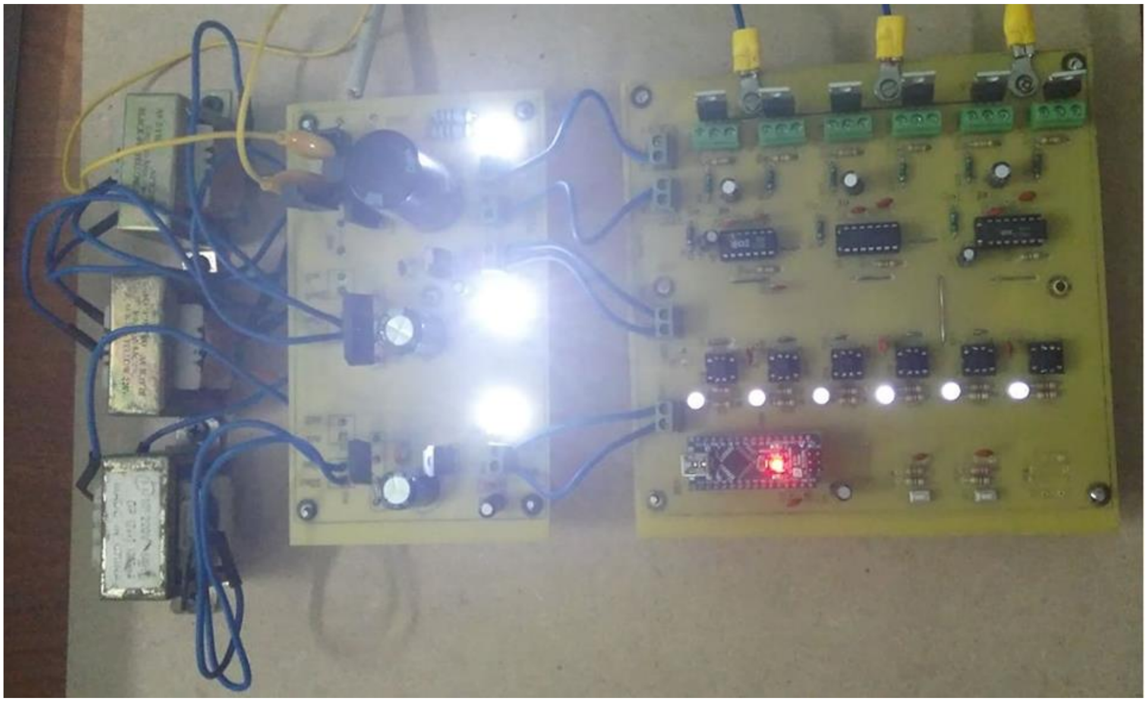


Fig. 7-2 The overall electronic circuits of the project

Fig. 7-3 Three-phase induction motor

2. The first PCB which includes rectifier bridges. It used as power circuit and control circuit for six step power inverter. The control circuit is used to control the drive of the inverter circuit, the optocoupler circuit, the Arduino circuit and for sum of the power supplies with different ratings. This PCB can be seen in Fig. 7-4.

3. The second PCB which includes Arduino to generate the pulses which is used to drive the six-step power inverter. The output of this inverter is used to drive the three-phase induction motor. These pulses are magnifying through optocoupler. The output of these optocouplers are sent to drive circuit to operate the inverter. This circuit (the second PCB) can be seen in Fig. 7-5.

Fig. 7-4 The first PCB

The details of the components which used in this project will discuss in the following sections.

7-1 The Rectifier Circuits and Power Supplies (the first PCB):

From Fig. 7-4 can be concluded that, the first PCB is the main power supply and is the main control circuit for all controller in this project. It has some of transformers (two transformers), some of bridges (three bridges), some of power supplies (two power supplies), some of chemical capacitors (three chemical capacitor), some of resistors (five resistances), some of LEDs (four LEDs) and fuse. This PCB is used to converting the AC power supply into some of DC supplies each of them has own function. The dilates of them can be explained as the follows;

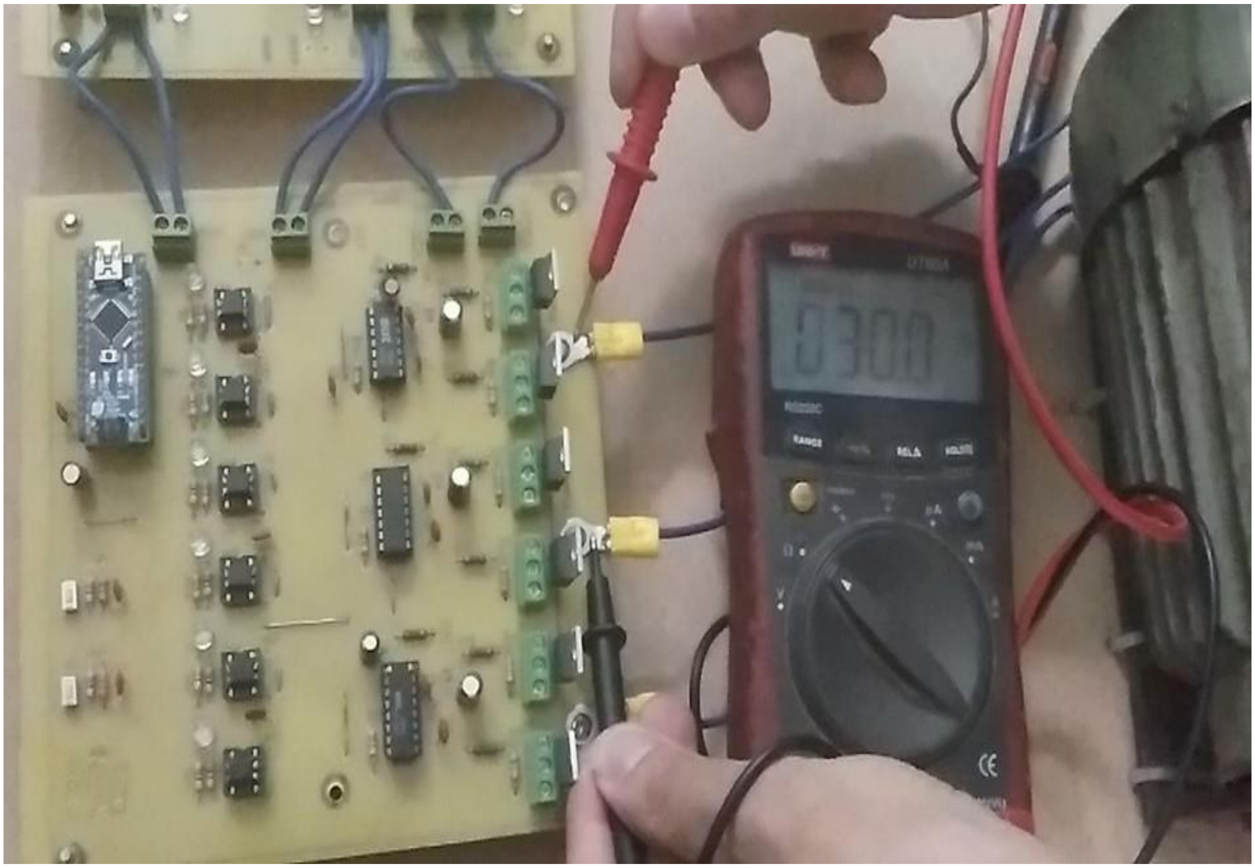


Fig. 7-5 The inverter circuit

7-1-1 The main rectifier circuit:

The main rectifier circuit is used to save the main power supply for the six-step inverter in the second PCB. This inverter is used to save the suitable power to the Three-phase induction motor. This circuit (main rectifier circuit) composed of bridge, chemical capacitor and power supply. The bridge is used to converting the AC voltage into DC voltage. The chemical capacitor is used to smoothing the output DC voltage resulting from the bridge. The power supply is used as stabilizer of the DC voltage coming from the chemical capacitor. This main rectifier circuit and output power from this circuit can be seen in Fig. 7-6. The stigmatic of this circuit through the Altium program can be seen in Fig. 7-7. In this stigmatic, there are two terminals block one is for the input (AC terminals) and the other is for the output terminals (DC terminals). To protected this circuit a fuse is used as shown. The output terminals of the DC are connected through chemical capacitor 220 microfarad. There is a led in this circuit to indicate the output in on. To protect this led, the resistance is connected in series with led to limiting the current of the led.

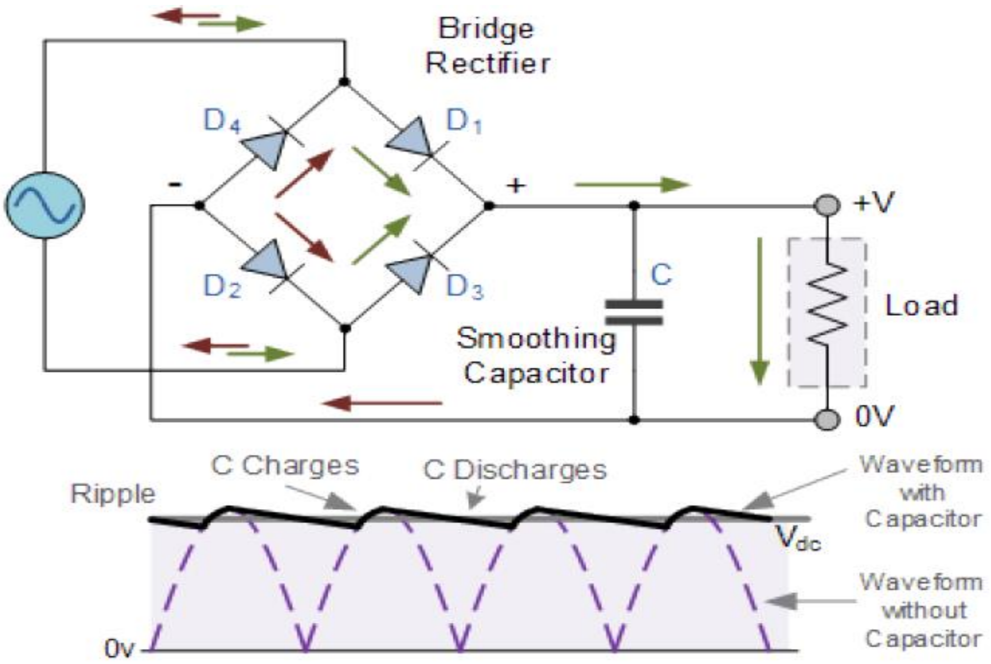


Fig. 7-6 The main rectifier circuit in the first PCB

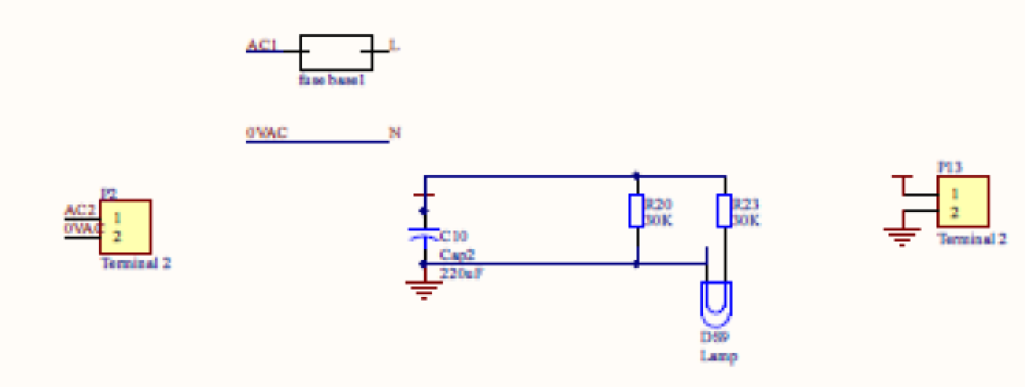


Fig. 7-7. The stigmatic of the main rectifier circuit in the first PCB

7-1-2 The controller rectifier circuits:

There are two controller rectifier circuits one of them is used save the power for Arduino and input of the optocoupler. Also, the other controller rectifier is used to save the power for the other component as the optocoupler and the IC driver.

The first controller rectifier is composed of the following component;

1. One transformer which convert 220volt AC into 5volt AC.
2. Bridge rectifier which convert the AC voltage into DC voltage which reaches 8volt.
3. To smoothing the output voltage of the above rectifier, the chemical capacitor is used.
4. Due to the Arduino which generates the pulses to drive circuit is working on 5volt so, the power supply is used to adjust this voltage.
5. Also, to indicate the operation of this circuit a led is used to indicate that. To protect this led, there series resistance connected with it.

This circuit can be drawn as shown in Fig. 7-8. Also, the layout of this circuit can be seen in Fig. 7-9 through the Altium program.

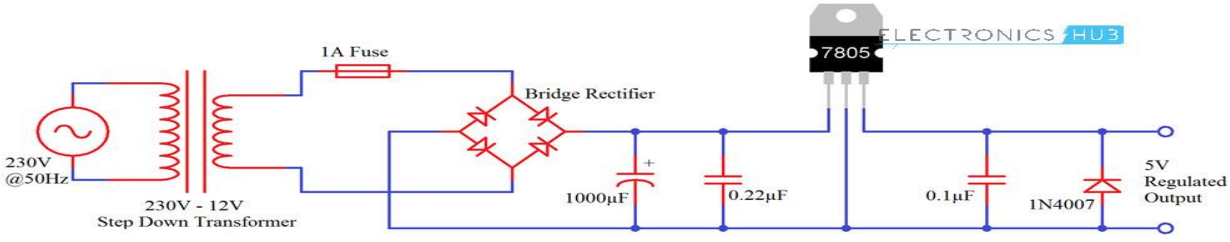


Fig. 7-8 The rectifier circuit to drive the microcontroller

The other controller circuit is similar to that the above controller circuit but it different above in the number of transformers. Because the other circuit is used with different voltage so, we use two transformers which connected in series to get the demand voltages which is used to drive four optocouplers and three IC driver. The details of this circuit can be seen through Fig. 7-10 and the stigmatic can be seen through Fig. 7-11.

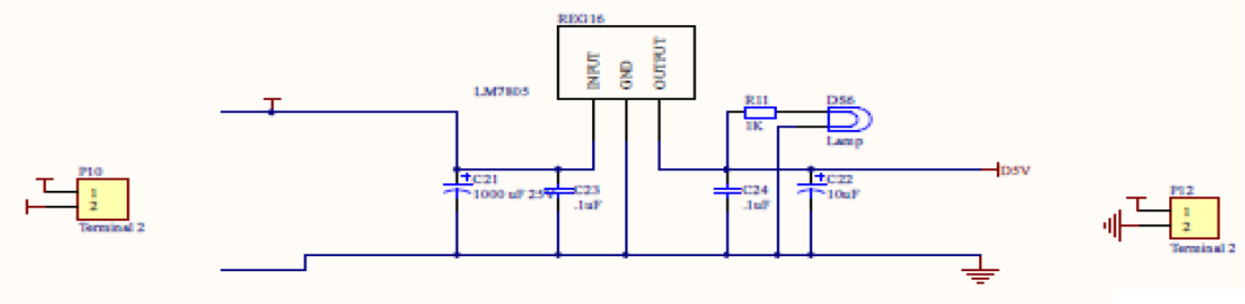


Fig. 7-9 The stigmatic from Altium program of the rectifier circuit that drive the Arduino

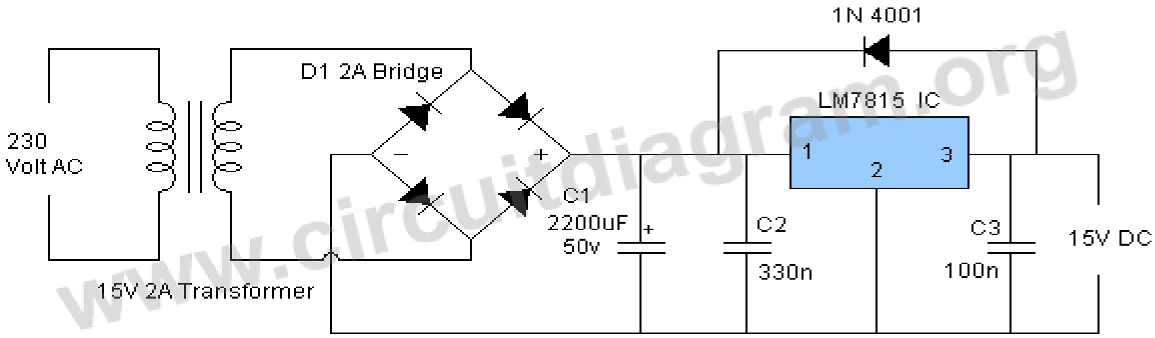


Fig. 7-10 The rectifier circuit to drive the other component in the second PCB

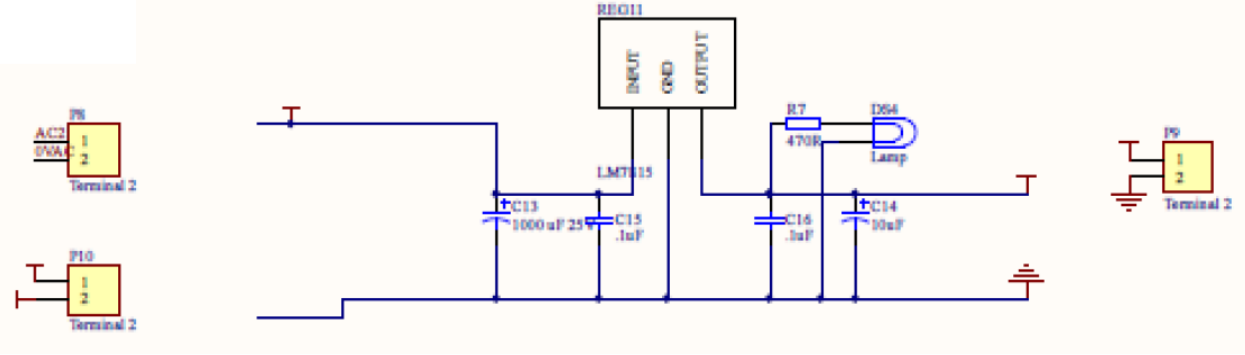


Fig. 7-11 The stigmatic from Altium program of the rectifier circuit that drive the other component in the second PCB

7-2 The Six Step Inverter (the second PCB):

The second PCB (six step inverter) contain four main components. It is Arduino circuit, optocouplers, driver circuits and power switches of inverter. Also, contains some leads used as the indicator to the power. This PCB can be represented as the block diagram as shown in Fig. 7-12. The layout of the second PCP through the Altium program can be seen in Fig. 7-12. Also, the layout of this PCB through the Altium program can be seen in Fig. 7-13. The dilates of them can be explained as the follows;

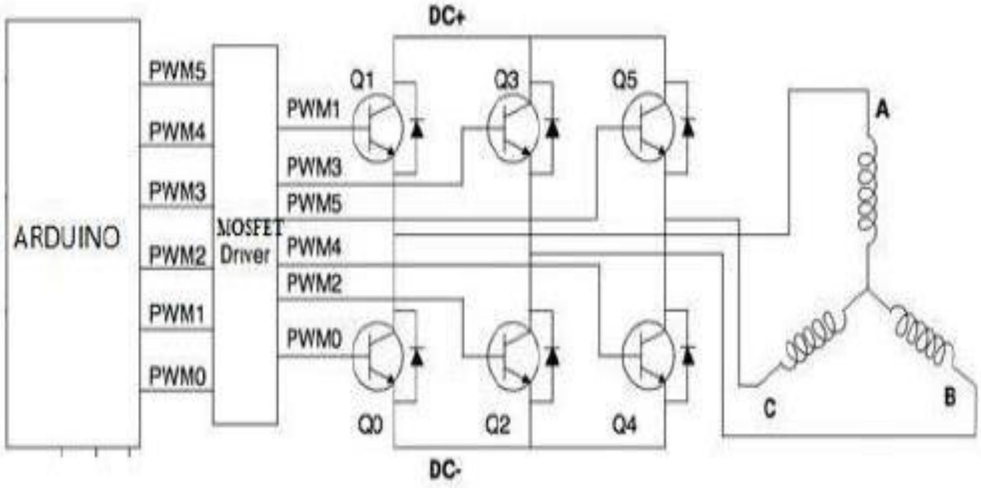


Fig. 7-12 Block diagram of the PCB two

7-2-1 The Arduino Nano:

The Arduino Nano, It is a Microcontroller board developed by Arduino.cc and based on Atmega328p / Atmega168. Arduino boards are widely used in robotics, embedded systems, and electronic projects where automation is an essential part of the system. These boards were introduced for the students and people who come with no technical background. The pinout of the Arduino Nano can be seen in Fig. 7-14. The details of connections for legs used through the Altium program can be seen through Fig. 7-15.

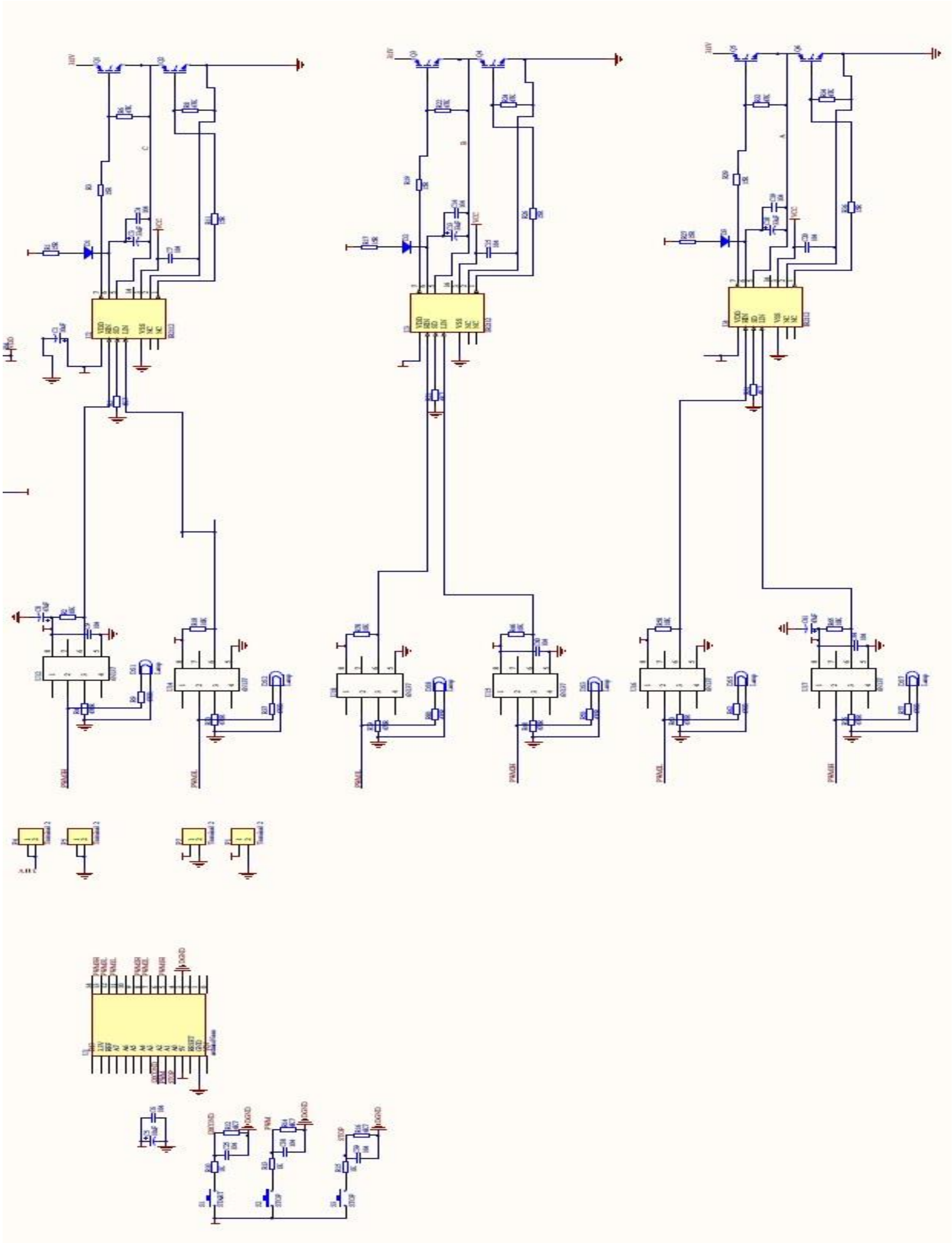


Fig. 7-13 The stigmatic of the second PCP through the Altium program

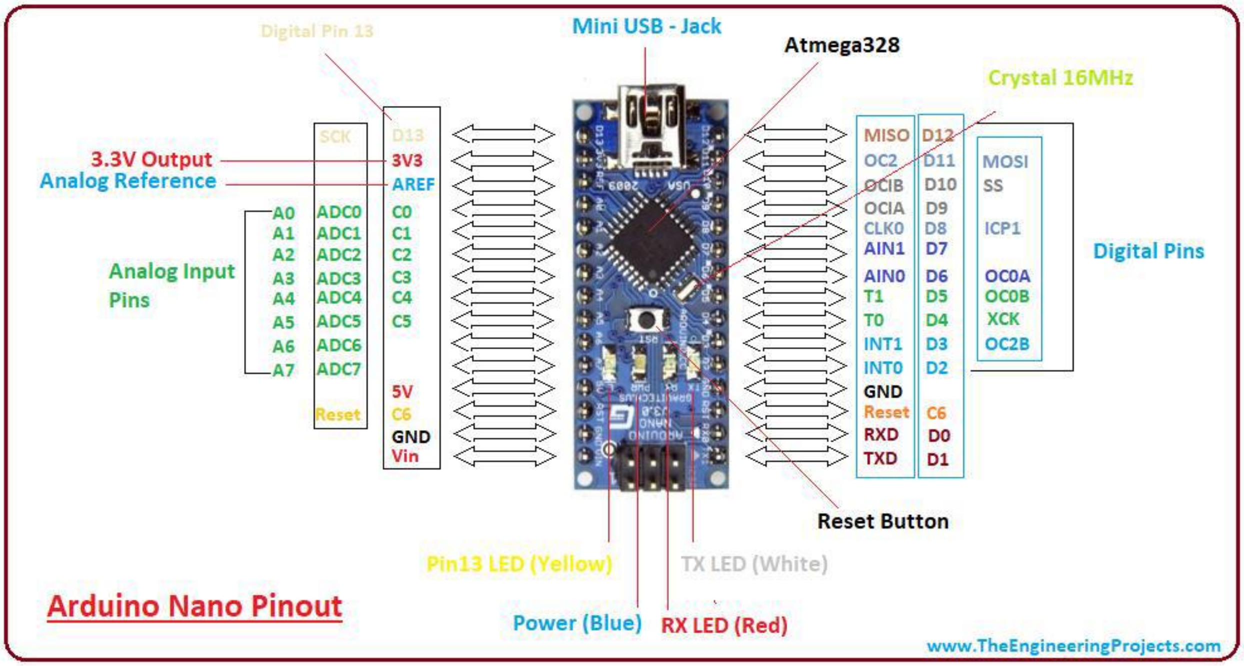


Fig. 7-14 The pinout of Arduino Nano

Here are few of its basic features which you must know if you are thinking to work on this great microcontroller board:

1. It has 22 input/output pins in total.
2. 14 of these pins are digital pins.
3. Arduino Nano has 8 analogue pins.
4. It has 6 PWM pins among the digital pins.
5. It has a crystal oscillator of 16MHz.
6. It's operating voltage varies from 5V to 12V.
7. It also supports different ways of communication, which are:

a. Serial Protocol.
b. I2C Protocol.
c. SPI Protocol.

8. It also has a mini USB Pin which is used to upload code.
9. It also has a Reset button on it.

It has below memories embedded in it which are used for different purposes and are as follows:

1. Flash memory of Arduino Nano is 32Kb.
2. It has preinstalled bootloader on it, which takes a flash memory of 2kb.
3. SRAM memory of this Microcontroller board is 8kb.
4. It has an EEPROM memory of 1kb.

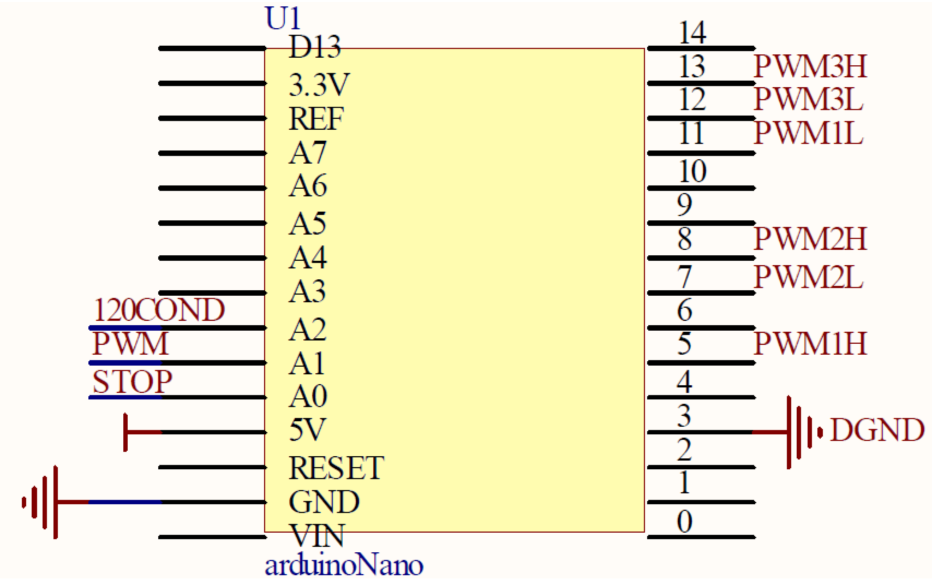


Fig. 7-15 Legs used through the Altium program

The following algorithm explain how we use this microcontroller. It is composed of define the input, define the output, define the variable, checked the type operation acceleration or deceleration, the duty variation. This algorithm can be written as the follows;

a- Wait until DC voltages stable

b- Define inputs

1. Input 1 : acceleration switch …. SW1

2. Input2 :De-acceleration switch...SW2

c- Define output

1. PWM output for MOSFET 1…..PWM1
2. PWM output for MOSFET 2…..PWM2
3. PWM output for MOSFET 3…..PWM3
4. PWM output for MOSFET 4…..PWM4
5. PWM output for MOSFET 5…..PWM5
6. PWM output for MOSFET 6…..PWM6

d- Define variables

1. Ton …….. PWM on time
2. Toff……..PWM off time
3. T = Ton + Toff
4. D= Ton/T……..Duty cycle

e- Clear all outputs

f- For six mode of 180 conduction each switch is ON every 3 ms in order manner

g- Duty (D) = 0 …all PWMs = 0 and motor off

h- Check switches SW1 and SW2

i- If SW1 is ON

1. increase duty

j- If SW2 is OFF

1. Decrease duty

This algorithm can be written in C code inside the microcontroller as the follows;

```
const int led=13;
const int s1=5;
const int s4=3;
const int s3=9;
const int s6=6;
const int s2=10;
const int s5=11;
const int on=A6;//START SWITCH
const int off=A5;//STOP SWITCH
void setup() {
pinMode (s1,OUTPUT);
pinMode (s2,OUTPUT);
pinMode (s3,OUTPUT);
pinMode (s4,OUTPUT);
pinMode (s5,OUTPUT);
pinMode (s6,OUTPUT);
digitalWrite(s1,LOW);
digitalWrite(s2,LOW);
digitalWrite(s3,LOW);
```

```
digitalWrite(s4,LOW);

digitalWrite(s5,LOW);

digitalWrite(s6,LOW);

for (int ledc=0;ledc<=5;ledc++)

{

digitalWrite(led,HIGH);

delay(1000);

digitalWrite(led,LOW);

delay(1000);

}

digitalWrite(led,LOW);

}

void wait()

{

digitalWrite(s1,LOW);

digitalWrite(s2,LOW);

digitalWrite(s3,LOW);

digitalWrite(s4,LOW);

digitalWrite(s5,LOW);

digitalWrite(s6,LOW);
```

```
delayMicroseconds(d);

}

void wait1()

{

delayMicroseconds(3300-d);

}

void loop()

{

digitalWrite(s2,LOW);

digitalWrite(s3,LOW);

digitalWrite(s4,LOW);

wait();

digitalWrite(s5,HIGH);

digitalWrite(s6,HIGH);

digitalWrite(s1,HIGH);

wait1();

/////////////////////

digitalWrite(s3,LOW);

digitalWrite(s4,LOW);

digitalWrite(s5,LOW);
```

```
wait();

digitalWrite(s1,HIGH);

digitalWrite(s6,HIGH);

digitalWrite(s2,HIGH);

wait1();

///////////////////////////

digitalWrite(s4,LOW);

digitalWrite(s5,LOW);

digitalWrite(s6,LOW);

wait();

digitalWrite(s1,HIGH);

digitalWrite(s2,HIGH);

digitalWrite(s3,HIGH);

wait1();

/////////////////////////

digitalWrite(s1,LOW);

digitalWrite(s5,LOW);

digitalWrite(s6,LOW);

wait();

digitalWrite(s2,HIGH);
```

```
digitalWrite(s3,HIGH);

digitalWrite(s4,HIGH);

wait1();

//////////////////////

digitalWrite(s1,LOW);

digitalWrite(s2,LOW);

digitalWrite(s6,LOW);

wait();

digitalWrite(s3,HIGH);

digitalWrite(s4,HIGH);

digitalWrite(s5,HIGH);

wait1();

/////////////////////////

digitalWrite(s1,LOW);

digitalWrite(s2,LOW);

digitalWrite(s3,LOW);

wait();

digitalWrite(s4,HIGH);

digitalWrite(s5,HIGH);

digitalWrite(s6,HIGH);
```

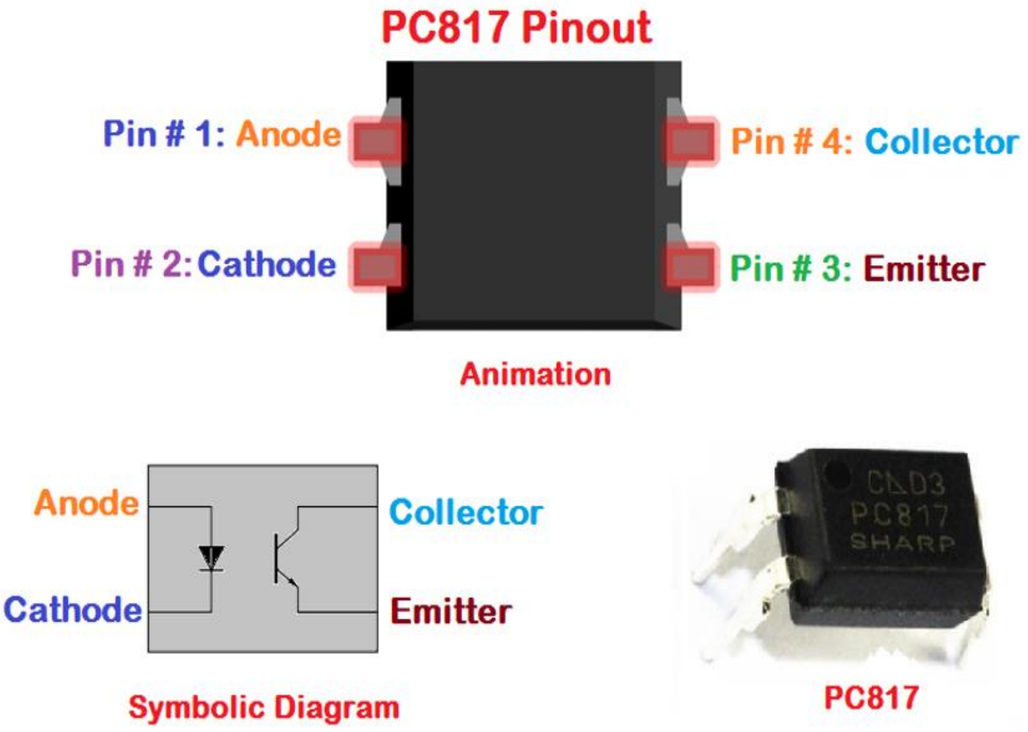
```
wait1();

if (analogRead(off)>255)

{

d=d+25 ;

if (d>=3300)

{d=3300;

digitalWrite(s1,LOW);

digitalWrite(s2,LOW);

digitalWrite(s3,LOW);

digitalWrite(s4,LOW);

digitalWrite(s5,LOW);

digitalWrite(s6,LOW);

}

}

if (analogRead(on)>255)

{

d=d-25;

if (d<25)d=25;

}

}
```

7-2-2 The optocoupler:

The device which isolates the electrical signal between an input source and an output load using just light by using a very common and valuable electronic component called an optocoupler. An optocoupler or opto-isolator consists of a light emitter, the LED and a light sensitive receiver which can be a single photo-diode, photo-transistor, photo-resistor, photo-SCR, or a photo-TRIAC with the basic operation of an optocoupler being very simple to understand. Let there be light! This device allows you to transmit an electrical signal between two isolated circuits with two parts: an LED that emits infrared light and a photosensitive device which detects light from the LED. Both of these parts are contained within a traditional black box with a pair of pins for connectivity. A current is first applied to the Optocoupler, which makes the infrared LED emit a light that’s proportional to the current. When the light hits the photosensitive device, it switches on and starts to conduct a current as any ordinary transistor might. if you’re designing an electronic device that will be susceptible to voltage surges, lightning strikes, power supply spikes, etc. then you’ll need a way to protect low-voltage devices. When used correctly, an Optocoupler can effectively:

1. Remove electrical noise from signals
2. Isolate low-voltage devices from high-voltage circuits
3. Allow you to use small digital signals to control larger AC voltages

The optocoupler in this project is used as the protection and allows by biasing of the MOSFET this is because the gate of the MOSFET which control operation of its doesn’t work under fifteen voltages so, it must be saved this voltage which generates by the optocoupler. Fig. 7-16 shows the animation of the optocoupler.



Animation

Symbolic Diagram

PC817

Fig. 7-16 The optocoupler and the animation of the optocoupler

<u>7-2-3 The driver circuit and six step inverter:</u>

Six step inverter is used to delivering power to the motor. Six step inverter circuit consists of power circuit and drive circuit. Schematic diagram of Six step inverter power circuit is shown in Fig. 7-17. It consists of six power switches (MOSFETS’). MOSFETS’ switches are chosen due to have many advantages. The advantages of this switch are fast switching, gate voltage control, small on state voltage drop and high rating. The type of MOSFET used in this thesis is TO-220AB. The package of this MOSFET is shown in Fig. 7-18. The driver circuit used in this project is IR2112. The IR2112 is a high voltage, high speed power MOSFET and IGBT driver with independent high and low side referenced output channels. Drive circuit is used to driving the power H-bridge. The overall drive circuit is shown in Fig. 7-19. This circuit consists of four stages. The first stage is amplification stage. The second stage is isolation stage. It is optocoupler circuit. The third stage is driving stage. The fourth stage is to protect and improve the performance of this circuit.

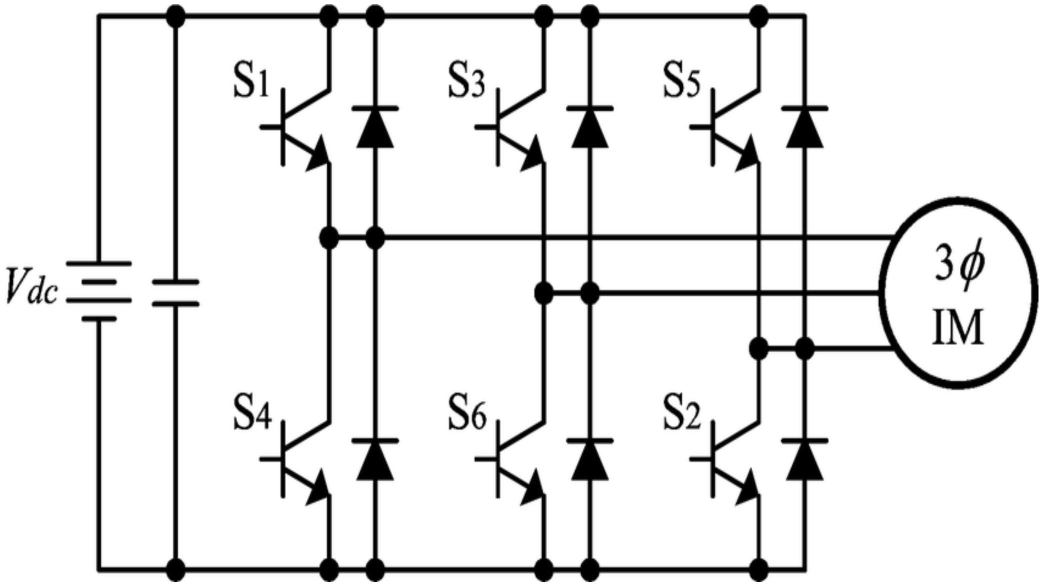


Fig. 7-17 Six step power circuit of inverter

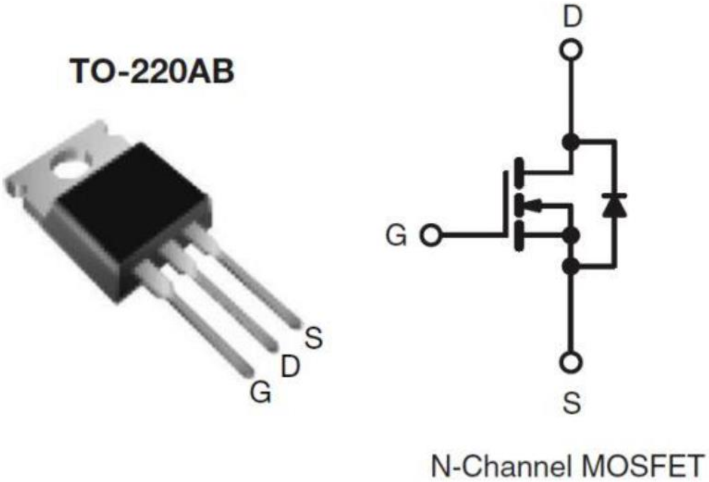


Fig. 7-18 The package of this MOSFET

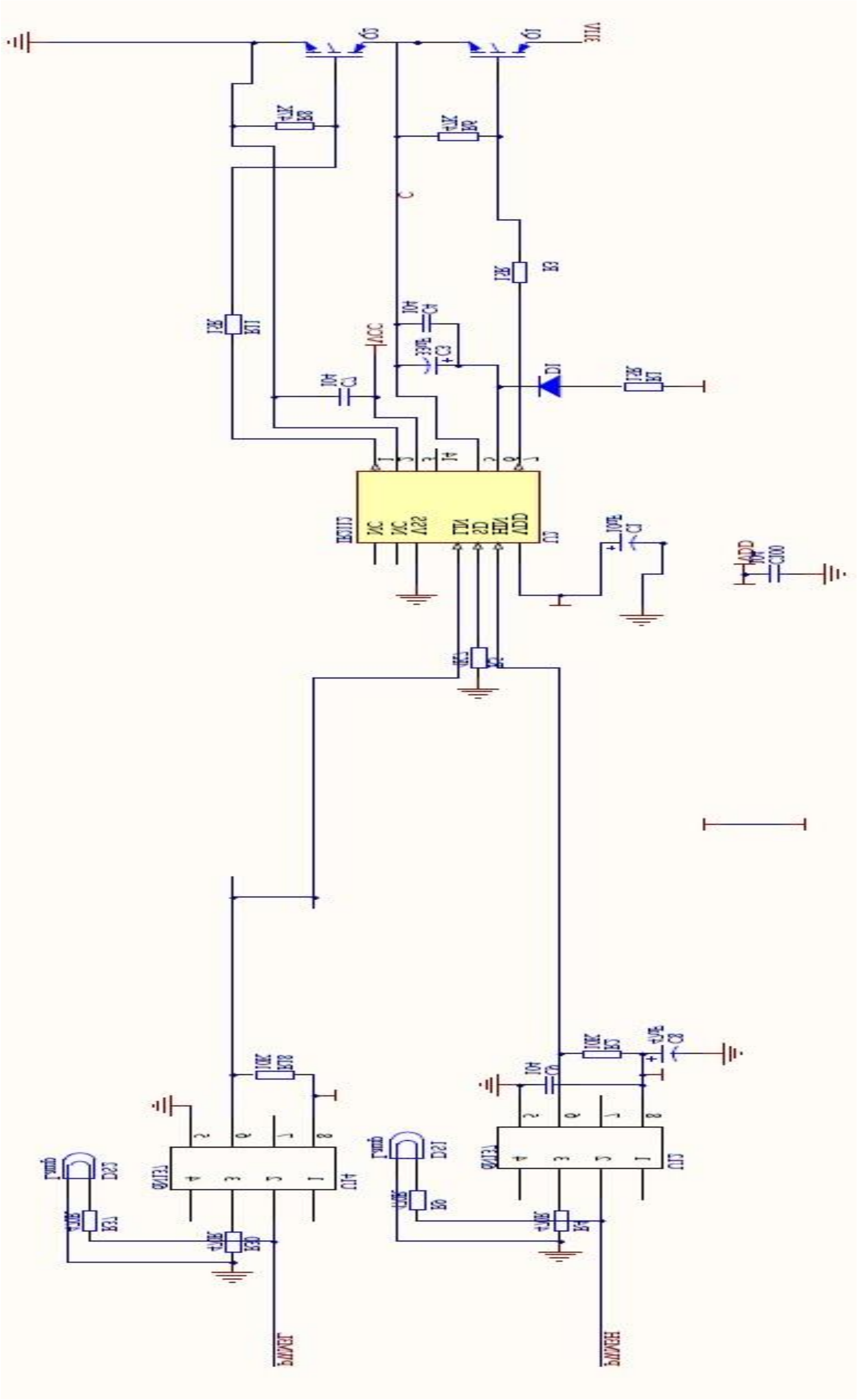


Fig. 7-19 The overall drive circuit including the optocoupler

7-3 Experimental Results:

The experimental results are discussed here. When the system is running and continuity press on the acceleration switch the duty cycle increase which means that, the output voltage of the six-step inverter increased which leads to increase the motor speed this can be seen by oscilloscope and reading the voltage of Avometer. Fig. 7-20 shows the shape of the pulse width modulation for one switch through the Adriano Nano.

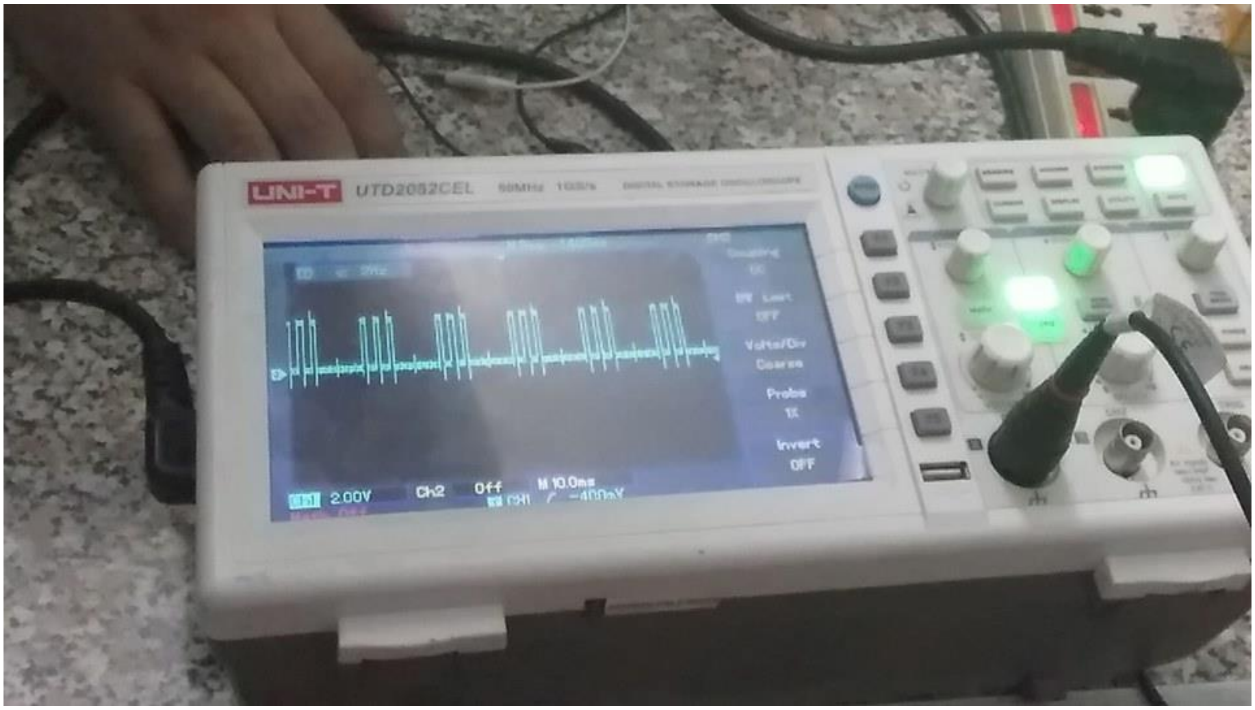


Fig. 7-20 The pulse width modulation for one switch at Arduino

By increasing the pressing in the button, the duty cycle of the pulse width modulation increased which leads to increasing the voltage and hence the motor speed increase. Fig. 7-21 duty cycle for two different switches in the different legs.

The output line to line voltage between phase a and phase b can be seen in Fig. 7-22. Where this voltage exists for 120^0 at each half cycle.

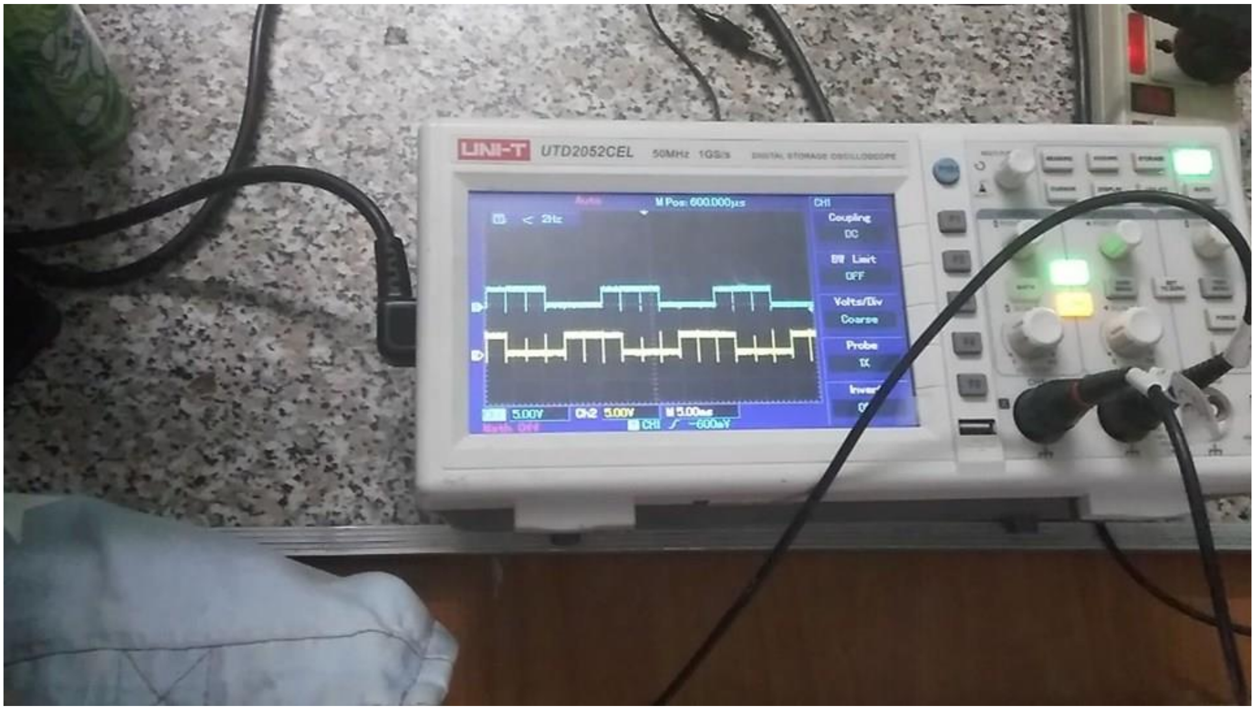


Fig. 7-21 Duty cycle for two different switches in the different legs

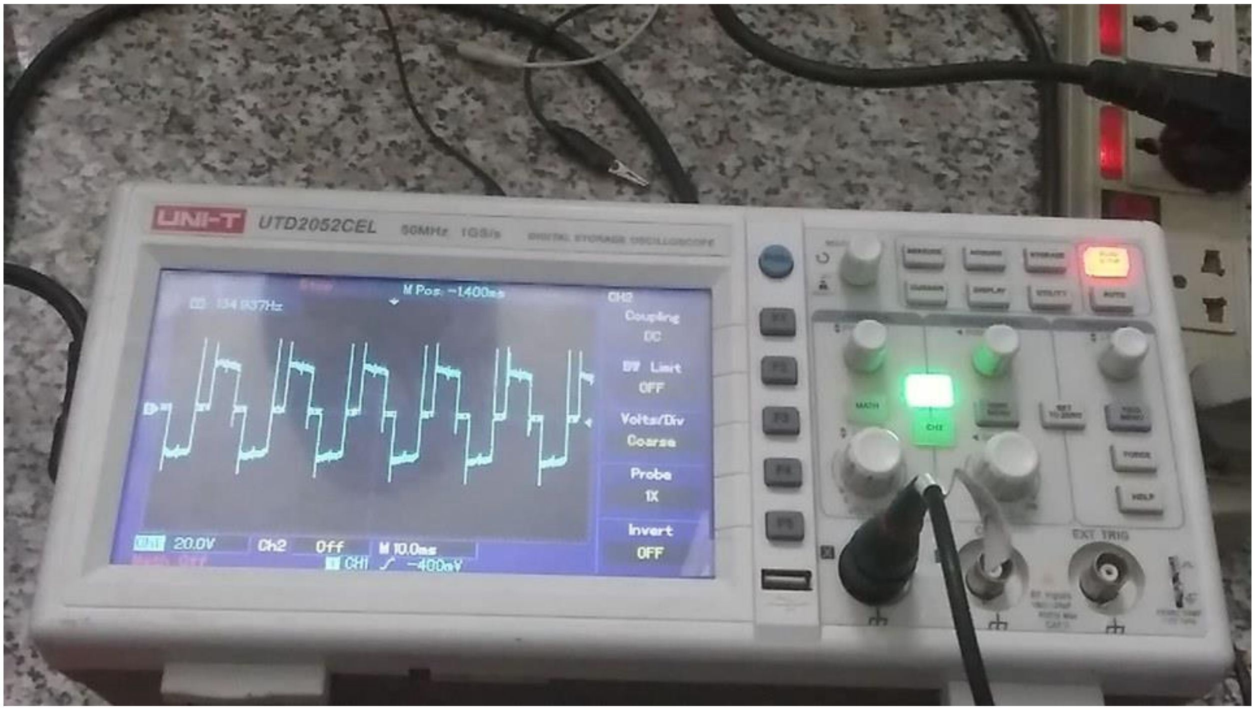


Fig. 7-22 The output line to line voltage between phase a and phase b

The pulse width modulation for two complementary switches can be seen in Fig. 7-23 where the pulse of upper switch exists the of the lower switch doesn't exist and Vaus versa.

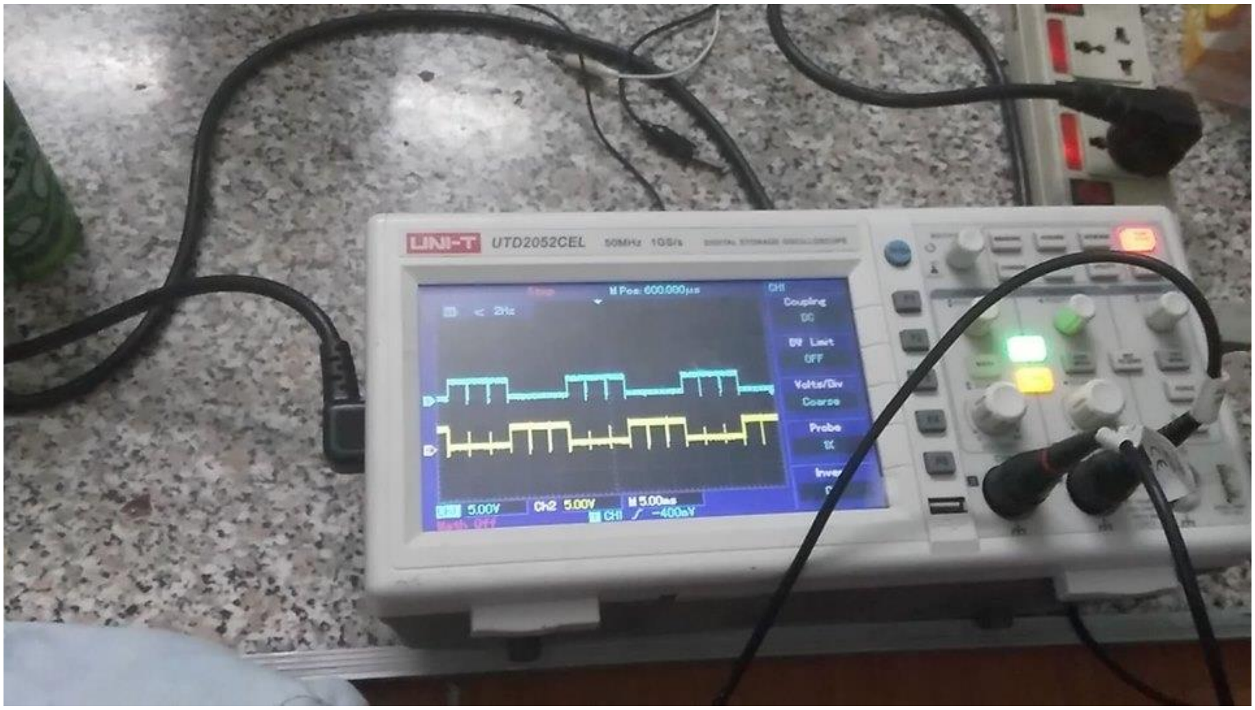


Fig. 7-23 The pulse width modulation for two complementary switches

To decrease the motor speed by pressing another switch the duty cycle decreases so the voltage decreases and the motor speed decrease by continuity pressing in this switch the motor will stopping.

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