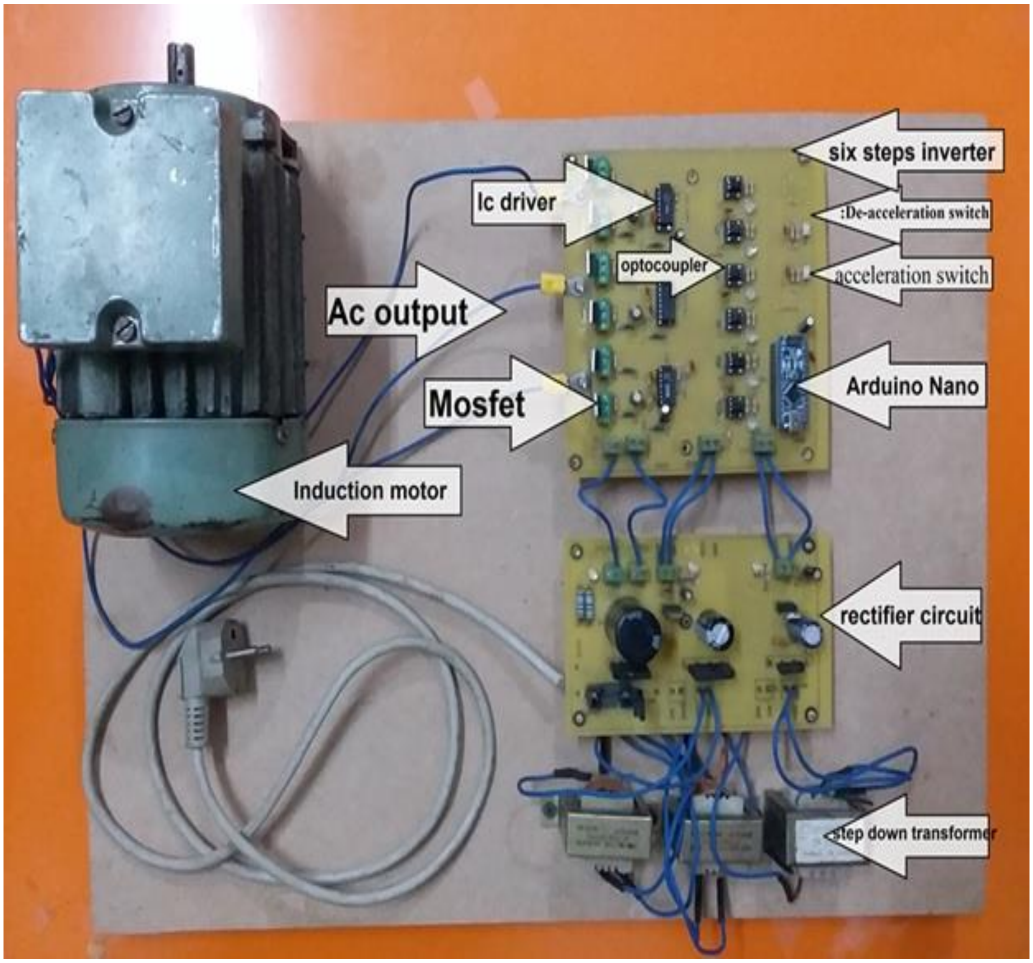
Six Step Inverter to Drive the Three Phase Induction Motor



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CHAPTER (1)

INTRODUCTION

In the present time, in the most of the applications, AC machines are useful than DC machines due to their simple and most robust construction without any mechanical commutators. The cheapest AC machines are induction motors so, the induction motors are used in this project. The induction motors are the most widely used motor drives in industry because of its simple construction and other advantages such as reliable operation, low initial cost, easy operation and simple maintenance and having good speed control. Invention of modern semiconductor switches like MOSFET and IGBT increases the freedom for controlling electric machines. Three-phase DC- AC six step inverter is one of the simplest way control the induction motor. The six step inverter and induction motor are used in various applications because they have low cost, high efficiency, wide speed range and robustness. Now thyristor, MOSFET and IGBT more commonly employed in soft starting of induction motor. These techniques are more economical, convenient and reliable.

In this project the main focus is on a six-step inverter to control the voltage level for three-phase induction motor. In this project the performance evaluation of the three-phase induction motor with six step voltage source inverter was studied at different loads. These loads are constant load and fan load.

1-1 Six Step Voltage Source Inverter:

An inverter is basically a power electronic device that converts electrical energy of DC form into that of AC. These DC-AC inverters have been widely used for industrial applications such as uninterruptible power supply, AC motor drives. Recently, the inverters are also playing an important role in various renewable energy applications as these are used for grid connection of Wind Energy System or Photovoltaic System. In addition to this, the control strategies used in the inverters are also similar to those in DC-DC converters. Both current-mode control and voltage-mode control are employed in practical applications. The DC-AC inverters usually operate on pulse width modulation, space vector pulse width modulation techniques. The pulse width modulation is a very advance and useful technique in which width of the Gate pulses are controlled by various mechanisms. pulse width modulation inverter is used to keep the output voltage of the inverter at the rated voltage (depending on the user's choice) irrespective of the output load. Many industrial processes. Industrial applications of inverters are for adjustable-speed AC drives, uninterruptible power supply (uninterruptible power supply), and etc. The DC power input to the inverter maybe battery, fuel cell, solar cell or other DC source. But in most industrial applications, it is fed by a rectifier.

There are commonly two types of inverters, voltage source inverters and current source inverters. When an inverter has a DC source with small or negligible impedance, which means the inverter has a stiff DC voltage source at its input terminal, it is called a voltage source inverters or voltage fed voltage source inverters. When the input DC source has high impedance, which means the DC source has a stiff DC current source, the inverter is called a current source inverters or current fed current source inverters. The main components of power electronics systems are power converters, which allow to produce a desired effect by controlling adequately some of the system variables (voltages and currents). To generate the six-step control signals, six simulink pulse generators were connected directly to the IGBT/MOSFET gates. The main purpose of this method is to provide a three-phase voltage source where it is easy to adjust the amplitude, phase and the output voltage frequencies. It consists of six IGBT/MOSFET switches. The conduction mode of voltage source inverter is 180 degree. The main advantages of voltage source inverter is that the output voltage of voltage source inverter can be varied by varying the DC link voltage and the output voltage waveform frequency rely on rating of the switches of semiconductor devices. Voltage source inverter is generally used for speed control by varying the frequency and voltage of the voltage source. The main application of Voltage Source Inverter is in adjusting the speed of Induction Motor or Synchronous motor. The main applications of the inverter can summarize in the following;

1) Electric Motor Speed Control.
2) Induction Heating.
a) Phase Opposition Disposition (POD)
b) Alternative Phase Opposition Disposition (APOD)
c) Phase Disposition (PD)
3) HVDC Power Transmission.
4) Portable consumer devices that allow the user to connect a battery, or set of batteries, to the device to produce AC power to
run various electrical items such as lights, televisions, kitchen appliances, and power tools.
5) Use in power generation systems such as electric utility companies or solar generating systems to convert DC power to AC
power.
6) Use within any larger electronic system where as engineering need exists for deriving an AC source from a Dc source

1-2 Three Phase Induction Motor:

An Induction or asynchronous motor is an AC electric motor in which the electric current in the rotor needed to produce torque and this torque is obtained by electromagnetic induction from the magnetic field of the stator winding. An induction motor therefore does not require mechanical commutation, separate excitation or self excited for all or part of the energy transferred from stator to rotor, as in universal, DC and large synchronous motors. An induction motors rotor can be either wound type or squirrel cage type. Three-phase squirrel-cage induction motors are widely used in industrial drives because they are rugged, reliable and economical. Single-phase induction motors are used extensively for smaller loads, such as household appliances like fans. Although traditionally used in fixed-speed service, induction motors are increasingly being used with variable-frequency drives in variable-speed service. variable-frequency drives offer especially important energy savings opportunities for existing and prospective induction motors in variable torque centrifugal fan, pump and compressor load applications. Squirrel cage induction motors are very widely used in both fixed speed and variable-frequency drives applications. A dynamic model of the machine subjected to a control must be known in order to understand and design these controlled drives. Such a model can be obtained by means of either the two-axis theory or spiral vector theory of electrical machines. Following are the assumptions made for the model.

1) Each stator winding is distributed so as to produce a sinusoidal mmf along air gap, i.e. space harmonics are negligible. (Sinusoidal induction repartition)

2) The slotting in stator and rotor produces negligible variation in respective inductances.

3) Mutual inductances are equal.

4) The harmonics in voltages and currents are neglected. Saturation, hysteresis and eddy effects negligible.

1-3 Outline of the Project:

This project is organized as eight chapters.

Chapter (1): Introduction, survey of the previous researches and outlines of this study.

Chapter (2): Displays the three-phase induction motor construction, types, how to operate, performance characteristics, equivalent circuit, starting methods, power flow and efficiency and applications.

Chapter (3): It discussed the mathematical model of the three-phase induction motor in the stationery reference frame. This is done in ABC frame and in DQ frame.

Chapter (4): Displays using the inverter as the controller to drive the three-phase induction motor, types of the inverter, mathematical model for each types and analysis during the operation.

Chapter (5): Displays the operation of the three-phase induction motor with using inverter in both of open loop and closed loop control.

Chapter (6): Displays the simulation of the six-step voltage source inverter. They are tested through the simulation. Also, it displays the simulation of the Three-phase induction motor and tested under no-load and full-load. Also, the overall system is simulated under open loop and closed loop at different loads.

Chapter (7): displays the construction of the hardware, software and the result of operation.

Chapter (8): displays conclusion and future work

CHAPTER TWO

INDUCTION MOTORS

Induction motors are the electric machines that convert the electrical power into mechanical power by the interaction between the magnetic fields set up in the stator and rotor windings. Three-phase squirrel-cage induction motors are widely used in industrial applications because they are self-starting, reliable, robust in construction and can work in any dusty environment, low maintenance cost, cheaper, absence of brushes, absence of commutator, good operating characteristics, good speed regulation, high efficiency and long life time. This chapter discusses what is the meant by induction motor, construction of induction motor, operation of induction motor, equivalent circuit of induction motor, performance characteristics of induction motor, applications of induction motor.

2-1 Induction Motor Construction:

Like most motors, an AC induction motor has a fixed outer portion, called the stator and a rotor that spins inside with a carefully engineered air gap between the two. This air-gap ranges from 0.4 mm to 4 mm, depending on the power of the motor.

The main body of the induction motor comprises of two major parts as shows in Fig. 2-1. These parts 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. In order to overcome this problem, we need 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.

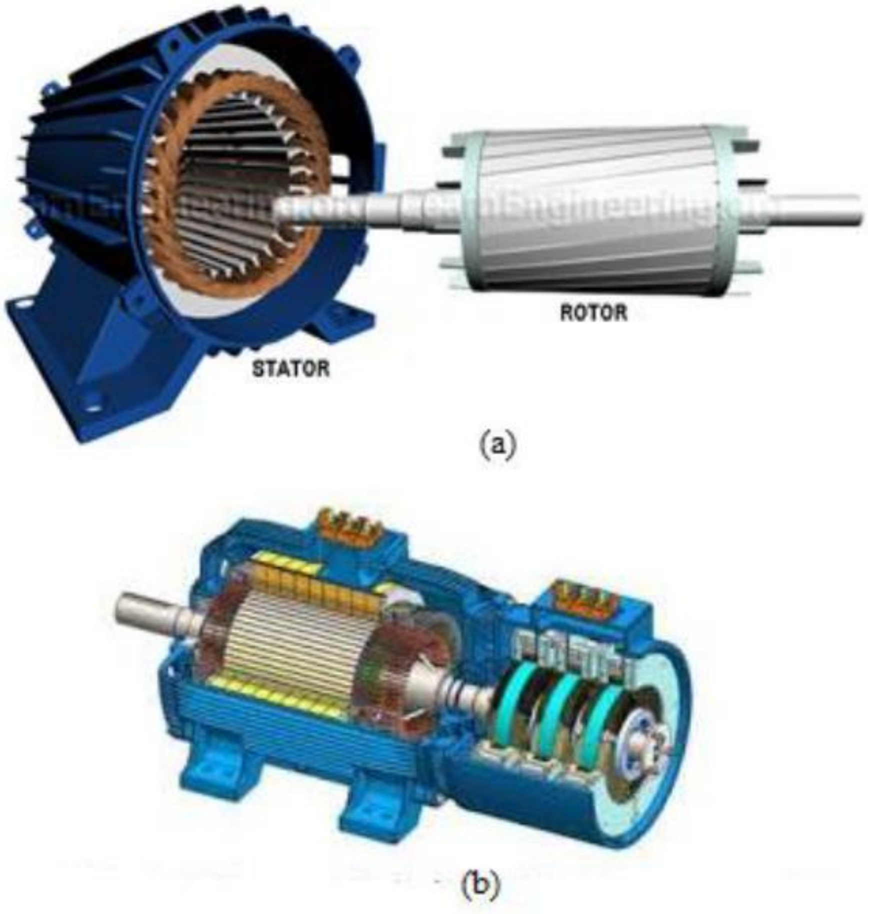


Fig. 2-1 Three phase induction motor (a) squirrel cage rotor (b) slip ring rotor.

2-1-1 The stator of induction motor:

As its name indicates, stator is a stationary part of induction motor. A stator winding is placed in the stator of induction motor and the three-phase supply is given to it. The stator is made up of several thin laminations of aluminum or cast iron. They are punched and clamped together to form a hollow cylinder (stator core) with slots as shown in Fig. 2-2. Coils of insulated wires are inserted into these slots. Each grouping of coils, together with the core it surrounds, forms an electromagnet (a pair of poles) on the application of AC supply. The number of poles of an AC induction motor depends on the internal connection of the stator windings. The stator windings are connected directly to the power source. Internally they are connected in such a way, that on applying AC supply, a rotating magnetic field is created.

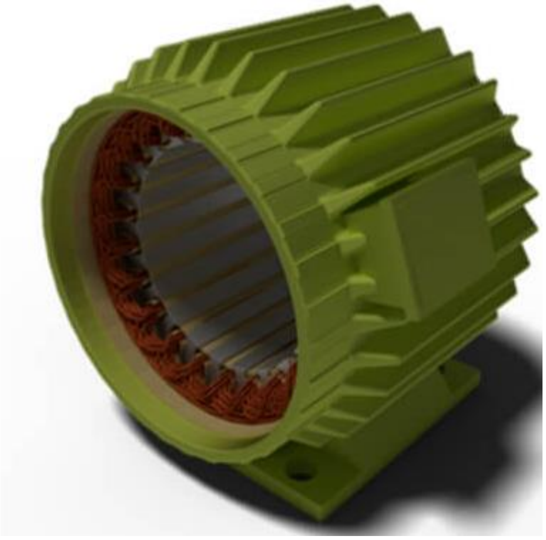


Fig. 2-2 Stator of three phase induction motor

From the above can be concluded that; the stator of the three-phase induction motor consists of three main parts. These parts are stator frame, stator core and stator winding. These parts can be explained as the follows;

1. Stator frame: it is the outer most 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 provide 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 very strong and rigid as the air gap length of motorist very small.
2. 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 are stamped together to form stator core, which is

then housed in stator frame. The stamping is generally made up of silicon steel, which helps to reduce the hysteresis loss occurring in motor.

3. Stator winding: The slots on the periphery of stator core of the motor carries three phase windings. This three-phase winding is supplied by three phase AC supply. The three phases of the winding are connected either in star or delta depending upon which type of starting method is used. The squirrel cage motor is mostly started by star – delta stator and hence the stator of squirrel cage motor is delta connected. The slip ring three phase induction motor are started by inserting resistances so, the stator winding of slip ring induction can be connected either in star or delta. 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.

2-1-2 Rotor:

The rotor is a rotating part of induction motor. The rotor is connected to the mechanical load through the shaft. Rotor consists of cylindrical laminated core with parallel slots that carry conductor bars. Conductors are heavy copper or aluminum bars which fits in each slot. These conductors are brazed to the short-circuiting end rings. The slots are not exactly made parallel to the axis of the shaft but are slotted a little skewed for the following reason, they reduce magnetic hum or noise and they avoid stalling of motor. The rotor, mounted on a shaft, is a hollow laminated core having slots on its outer periphery. The winding placed in these slots (called rotor winding) may be one of the following two types: squirrel cage type or wound type.

Squirrel cage rotor is a squirrel cage three phase induction motor. The rotor of the squirrel cage three phase induction motor is cylindrical in shape 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 cadge rotor beside) as the skewing prevents magnetic locking of stator and rotor teeth and makes the working of motor more smooth and quieter. The squirrel cage rotor consists of aluminum, brass or copper bars. 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. In order 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 the bars are permanently shorted by end rings, the rotor resistance is very small and it is not possible to add external resistance as the bars are 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. These motors have the advantage of adapting any number of pole pairs. The below diagram shows squirrel cage induction rotor having aluminum bars short circuit by aluminum end rings. It consists of a laminated cylindrical core having parallel slots on its outer periphery. One copper or aluminum bar is placed in each slot. All these bars are joined at each end by metal rings called end rings (Fig. 2-3). This forms a permanently short-circuited winding which is indestructible. The entire construction (bars and end rings) resembles a squirrel cage and hence the name. The rotor is not connected electrically to the supply but has current induced in it by transformer action from the stator. Those induction motors which employ squirrel cage rotor are called squirrel cage induction motors. Most of 3-phase induction motors use squirrel cage rotor as it has a remarkably simple and robust construction enabling it to operate in the most adverse circumstances. However, it suffers from the disadvantage of a low starting torque. It is because the rotor bars are permanently short-circuited and it is not possible to add any external resistance to the rotor circuit to have a large starting torque.

Fig. 2-3 squirrel cage rotor

Advantages of squirrel cage induction rotor

a- Its construction is very simple and rugged.
b- As there are no brushes and slip ring, these motors require less maintenance.

Applications:

Squirrel cage induction motor is used in lathes, drilling machine, fan, blower printing machines etc.

Wound rotor. Slip ring or wound 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 stator but it has less number of slots and has less turns per phase of a heavier conductor. The rotor also carries star or delta winding similar to that of 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 star connection. As its name indicates three phase slip ring induction motor consists of slip rings connected on same shaft as that of 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 control 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. At starting, the resistances are connected in 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 connect all slip ring together and the brushes are also removed. This reduces wear and tear of the brushes. Due to presence of slip rings and brushes the rotor construction becomes somewhat complicated therefore it is less used as compare to squirrel cage induction motor. It consists of a laminated cylindrical core and carries a three- phase winding, similar to the one on the stator. The rotor winding is uniformly distributed in the slots and is usually star-connected. The open ends of the rotor winding are brought out and joined to three insulated slip rings mounted on the rotor shaft with one brush resting on each slip ring. The three brushes are connected to a three-phase star-connected rheostat as shown in Fig. 2-4. At starting, the external resistances are included in the rotor circuit to give a large starting torque. These resistances are gradually reduced to zero as the motor runs up to speed. The external resistances are used during starting period only. When the motor attains normal speed, the three brushes are short-circuited so that the wound rotor runs like a squirrel cage rotor.

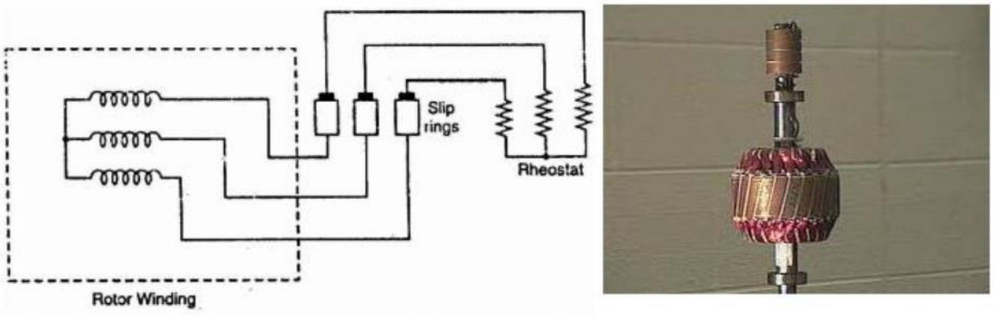


Fig. 2-4 Slip ring rotor

Advantages of slip ring induction motor

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

Applications:

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

2-2 Principle of Operation of the Three Phase Induction Motor:

When the three-phase stator winding is energized from a three-phase supply, a rotating magnetic field is produced which rotates around the stator at synchronous speed. The synchronous speed can be calculated as;

$$n_s = \frac{120f}{P} \qquad 2.1$$

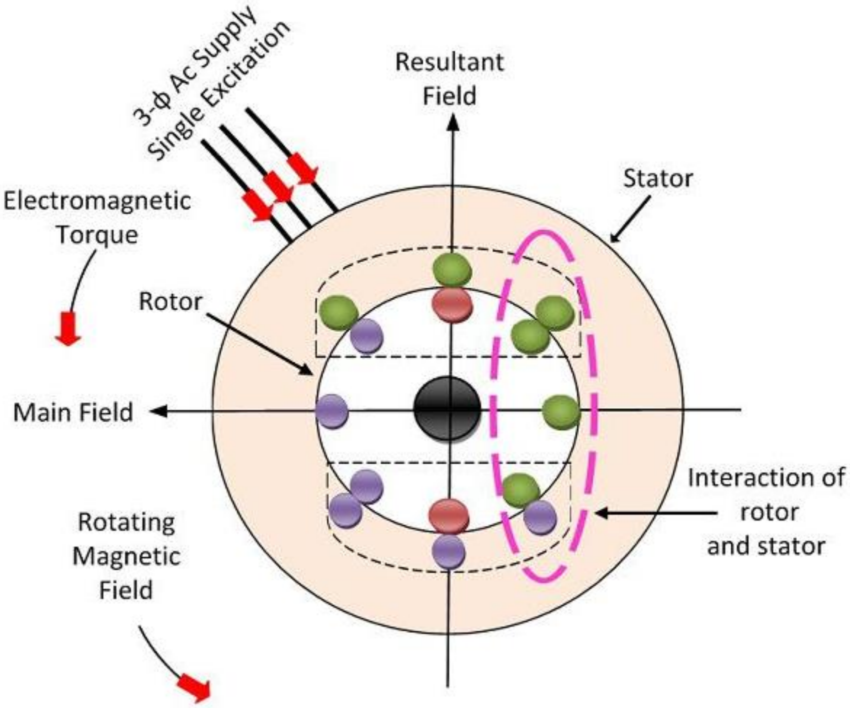
Where n_s is the synchronous speed , f is the supply frequency and P is the number of poles

The Fig. 2-5 shows how rotating magnetic field setup in the stator. Consider that the rotating magnetic field induces in the anticlockwise direction. The rotating magnetic field has the moving polarities. The polarities of the magnetic field vary by concerning the positive and negative half cycle of the supply. The change in polarities makes the magnetic field rotates.

The rotating magnetic field cuts the rotor conductors, which as yet, are stationary. Due to this flux cutting, emfs are induced in the rotor conductors. As rotor circuit is short circuited, therefore, currents start flowing in it.

Now, as per Lenz's law, "the direction of induced current will be such that it opposes the very cause that produced it ".

Here, the cause of emf induction is the relative motion between the rotating field and the stationary rotor conductors. Hence, to reduce this relative motion, the rotor starts rotating in the same direction as that of the stator field and tries to catch it but, can never catch it due to friction and windage and therefore emf induction continues and motor keeps rotating. This means that, two fluxes one because of the rotor and another because of the stator. These fluxes interact each other. On one end of the conductor the fluxes cancel each other, and on the other end, the density of the flux is very high. Thus, the high-density flux tries to push the conductor of rotor towards the low-density flux region. This phenomenon induces the torque on the conductor, and this torque is known as the electromagnetic torque. The direction of electromagnetic torque and rotating magnetic field is same. Thus, the rotor starts rotating in the same direction as that of the rotating magnetic field.



The Fig. 2-5 Setup rotating magnetic field in the stator

Thus, principle of the three-phase induction motor also explains why rotor rotates in same direction as the rotating field and why induction motor is self-starting. When rotor winding is short-circuited with no resistance in series, it is called a squirrel cage induction motor and when rotor winding is shorted through a resistance in series, it is called slip ring induction motor.

Thus, from the working principle of three phase induction motor, it may be observed that the rotor speed should not reach the synchronous speed produced by the stator. The difference between the field (synchronous speed) and rotor speed is called slip speed. This slip speed can be calculated from the following relation

$$n_{slip} = n_s - n_r \tag{2.2}$$

Where n_{slip} is the slip speed and n_r is the rotor speed

If the speeds become equal, there would be no such relative speed, so no emf induced in the rotor, and no current would be flowing, and therefore no torque would be generated. Consequently, the rotor cannot reach the synchronous speed. The difference between the stator (synchronous speed) and rotor speeds is called the slip. The rotation of the magnetic field in an induction motor has the advantage that no electrical connections need to be made to the rotor.

Thus, the three-phase induction motor is:

1. Self-starting.
2. Less armature reaction and brush sparking because of the absence of commutators and brushes that may cause sparks.
3. Robust in construction.
4. Economical.
5. Easier to maintain.

2-3 The Slip:

The slip is very important factor to determine the all performance of the three-phase induction motor. This slip arises because the friction and windage would immediately cause the rotor to slow down. Hence, the rotor speed (n_r) is always less than the suitor field speed (n_s). This difference in speed depends upon load on the motor. The difference between the synchronous speed n_s of the rotating stator field and the actual rotor speed n_r is called slip. It is usually expressed as a percentage of synchronous speed as,

$$s = \frac{n_s - n_r}{n_s} \qquad 2.3$$

Where s is the slip speed

From eq. 2.3 can be concluded that

1. When the rotor is stationary (i.e., N = 0), slip, s = 1
2. In an induction motor, the change in slip from no-load to full-load is hardly 0.1% to 3% so that it is essentially a constant-speed motor.
3. If the motor runs at synchronous speed, s =0

By comparing between the induction motor and transformer it found that; there some similarity of the operation. In transformer, when applied voltage on the primary windings produce induced voltage on the secondary winding. This voltage has the same frequency of the primary voltage and the value of this voltage depends upon the turns ratio between the primary and secondary windings. This occurs because there isn’t relative motion between the primary winding and secondary winding. In case of induction motor, this occurs at starting due to no relative motion between the stator and rotor. When the induction motor starts to run, the induced voltage and frequency of the rotor depending upon the relative motion, the direction of the rotation and the turns ratio between the rotor and the stator. And hence the magnitude of the voltage and frequency are varying.

2-4 Rotor Frequency at Operating Condition:

The frequency of a voltage or current induced due to the relative speed between a vending and a magnetic field is given by the following depends upon eq. 2.1

$$f = \frac{P n_s}{120}$$

For a rotor speed n_r, the relative speed between the rotating flux and the rotor is $n_s - n_r$. Consequently, the rotor current frequency f_2 is given by;

$$f_2 = \frac{P(n_s - n_r)}{120} \qquad 2.4$$

By substituting from eq. 2.3 into eq. 2.4 it found that;

$$f_2 = \frac{s\, n_s P}{120} \qquad 2.5$$

By substituting from eq. 2.4 into eq. 2.5 it found that;

$$f_2 = s f \qquad 2.6$$

2-5 The different methods to connecting the windings:

When connecting a motor to the electrical network, it can be done in two ways. Either use star connection or Delta connection. These connections can be seen in Fig. 2-6. The U1-U2, V1-V2 and W1-W2 that marks the coil ends of the three different phases that is present on the terminal block of the motor. The L1, L2 and L3 represent the three phases coming from the electrical network.

A Delta connection is when the phase coils are connected across with connection bars and then later connected to L1, L2 and L3 according to Figure 13. A Wye connection is when one side of all three phase coils are connected together with connection bars and the other side is connected to L1, L2 and L3 according to Fig. 2-6.

The difference between star and delta connection is the difference in voltage over the phase windings. For example when a 400V network is connected to L1, L2 and L3 on the delta connected motor there is 400V over the different phases, meaning 400V between U1 and U2, 400V between V1 and V2 and also W1 and W2. But when the motor connected in star, it will still have 400V between L1 and L2 but only have 230V volts over each phase winding U1 to U2 and so on.

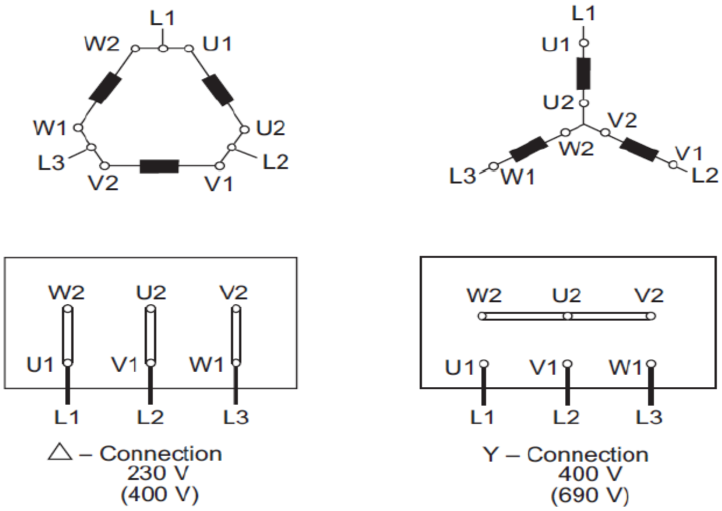


Fig. 2-6 The different connections methods of the induction motor windings

So, in the star connected motor the network voltage divided by the square root of 3 over each phase winding while the delta connection has the same voltage as the network over the phase windings.

2-6 An Equivalent Circuit of Induction Motor:

The equivalent circuit of induction motor is similar to the equivalent circuit of transformer except that the secondary windings are rotating. Any winding when expressed to AC voltage represented by resistance and leakage inductance.

Depending upon that, the equivalent circuit of induction motor can be deduced as the follows;

1. An induction motor represents the magnetic coupling between the two circuits.
2. The stator produces a rotating magnetic field that induces voltage in both windings.
3. A magnetizing reactance (X_m) and a resistance connected in parallel represent the magnetic field generation.
4. The resistance (R_c) represents the eddy current and hysteresis losses in the iron core.
5. The induced voltage is depending on the slip and the turn ratio.

From the above, the stator and rotor circuits of induction motor can be drawn as shown in Fig. 2-7.

In this circuit, the magnetizing reactance generates a flux that links with both the stator and the rotor and induces a voltage in both circuits. The magnetic flux rotates with constant amplitude and synchronous speed. This flux cuts the stationary conductors of the stator with the synchronous speed and induces a 50 Hz voltage in the stator windings. The rms value of the voltage induced in the stator is

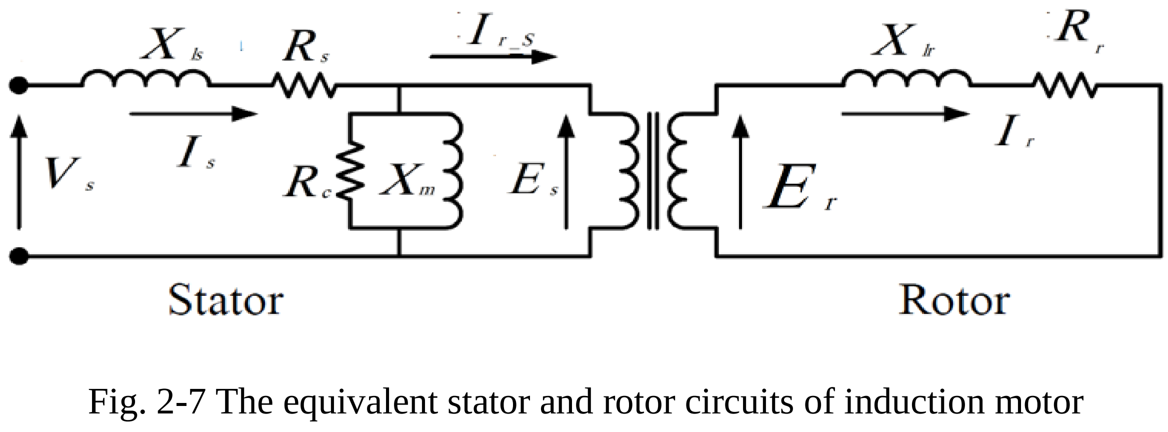


Fig. 2-7 The equivalent stator and rotor circuits of induction motor

$$E_s = \frac{N_{sta}\phi_{\max}\omega_s}{\sqrt{2}} \qquad 2.7$$

Where N_{sta} is the number of stator turns, $\phi_{\max}$ is the maximum flux linkage of stator winding and ω_s is the field speed in Rad/sec

The flux rotates with the synchronous speed and the rotor with the motor speed. Consequently, the flux cuts the rotor conductors with the speed difference between the rotating flux and the rotor. The speed difference is calculated using the slip relation as;

$$s = \frac{\omega_s - \omega_r}{\omega_s} \qquad 2.8$$

and ω_r is the rotor speed in Rad/sec

By substituting from eq. 2.8 into eq. 2.7 it is found that; The induced rotor voltage (E_r) can be calculated as;

$$E_r = \frac{N_{rot}\phi_{\max}(\omega_s - \omega_r)}{\sqrt{2}}$$

$$E_r = \frac{N_{rot}\phi_{\max} s\,\omega_s}{\sqrt{2}} \qquad 2.9$$

Where N_{rot} is the number of rotor turns, $\phi_{\max}$ is the maximum flux linkage of rotor windings

By division eq. 2.9 on eq. 2.7, the ratio between induced stator and rotor voltage can be written as;

$$\frac{E_r}{E_s} = \frac{N_{rot}}{N_{rot}} s$$

$$E_r = \frac{N_{rot}}{N_{sta}} E_s s$$

$$E_r = E_{r\_s} s \qquad 2.10$$

Where E_{r_s} is the induced rotor voltage referred to stator

The speed difference determines the frequency of the rotor current as;

$$f_r = \frac{\omega_s - \omega_r}{2\Pi} \qquad 2.11$$

But $\omega_s - \omega_r = s\omega_s$ so,

$$f_r = \frac{s\omega_s}{2\Pi} \qquad 2.12$$

But $f_s = \frac{\omega_s}{2\Pi}$ so,

$$f_r = s f_s \qquad 2.13$$

The rotor circuit leakage reactance can be calculated as;

$$X_r = \omega_r Llr$$

$$X_r = s\omega_s Llr$$

$$X_r = s X_{r\_s} \qquad 2.14$$

The relation between rotor current and the rotor-induced voltage is calculated by the loop voltage equation as;

$$V_r = sV_{r\_s} = I_r(R_r + jsX_r) \qquad 2.15$$

By division on the slip eq. 2.15 becomes

$$V_{r\_s} = I_r\left(\frac{R_r}{s} + jX_r\right) \qquad 2.16$$

The implementation of this equation simplifies the equivalent circuit

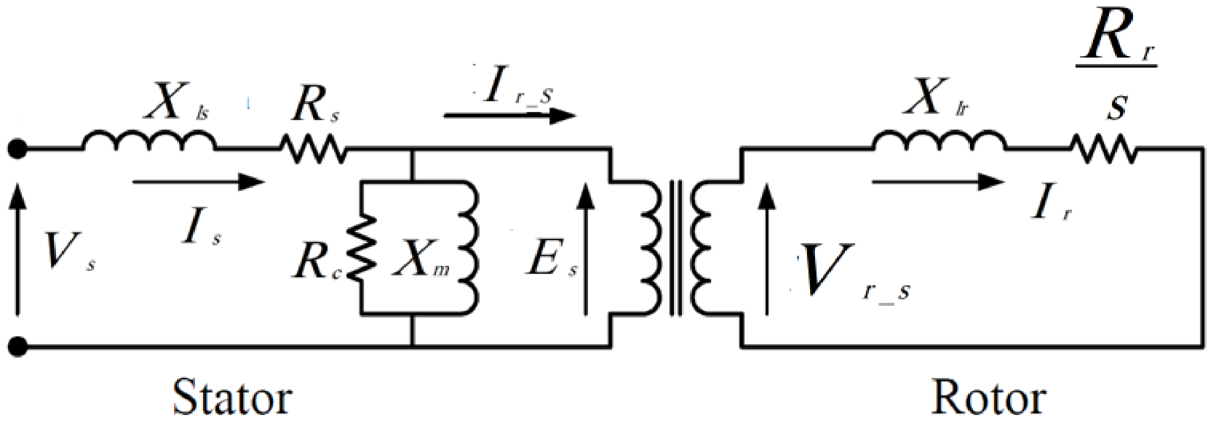


Fig. 2-8 Modified equivalent circuit of a three-phase induction motor

The rotor impedance is transferred to the stator side. This eliminates the transformer

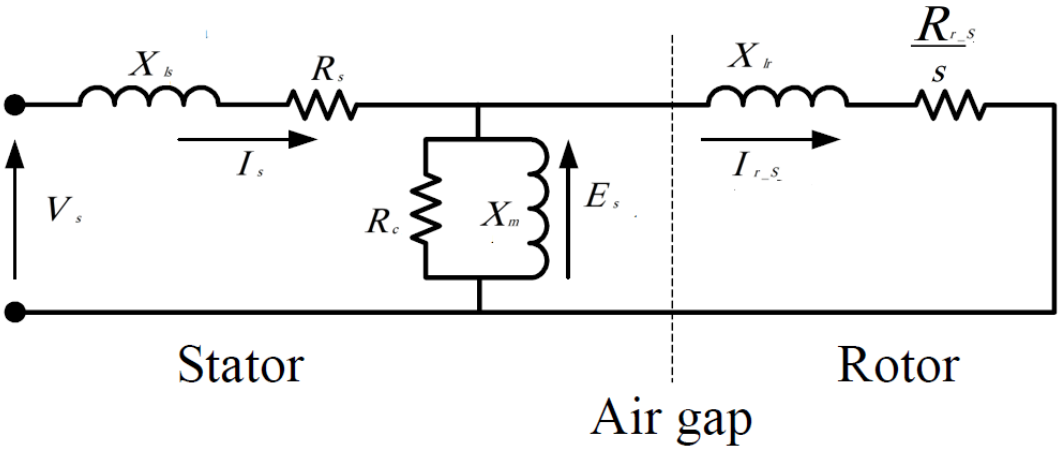


Fig. 2-9 Simplified equivalent circuit of a three-phase induction motor

The last modification of the equivalent circuit is the separation of the rotor resistance into two parts:

$$\frac{R_{r\_s}}{s} = R_{r\_s} + \frac{1-s}{s}R_{r\_s} \qquad 2.17$$

The first part in eq. 2.17 represents the rotor resistance referred to stator and the other part represents the resistance of the outgoing mechanical power. This can apply on Fig. 2-9 to becomes as Fig. 2-10.

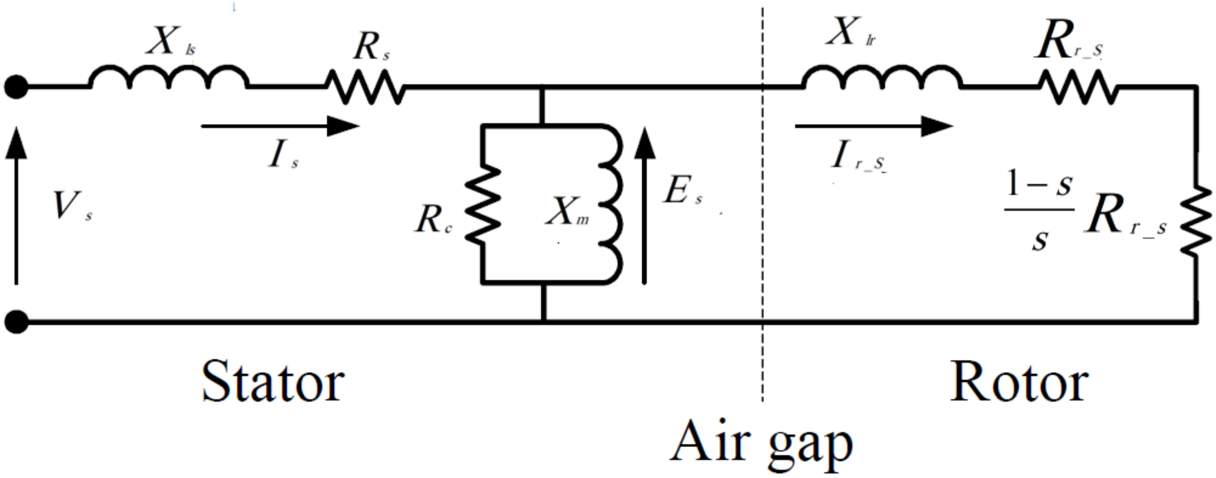


Fig. 2-10 Final single-phase equivalent circuit of a three-phase induction motor

2-7 Performance Characteristics of Induction Motor:

In this section, the performance characteristics of the three-phase induction motor are discussed. The performance characteristics here means, the power flow and torque speed characteristics of the three-phase induction motor.

2-7-1 Power flow of the three-phase induction motor:

Power Flow Diagram of Induction Motor explains the input given to the motor, the losses occurring and the output of the motor. The input power given to an Induction motor is in the form of three-phase voltage and currents. The Power Flow Diagram of an Induction Motor is shown in Fig. 2-11. From this Fig. can be concluded that,

The input power to a three-phase induction motor is given by:

$$P_{in} = \sqrt{3} V_{in} I_s \cos\theta \qquad 2.18$$

Where P_{in} is the input power, V_{in} is the supply line voltage, I_s is the stator line current and θ is the angle between supply line voltage and stator current

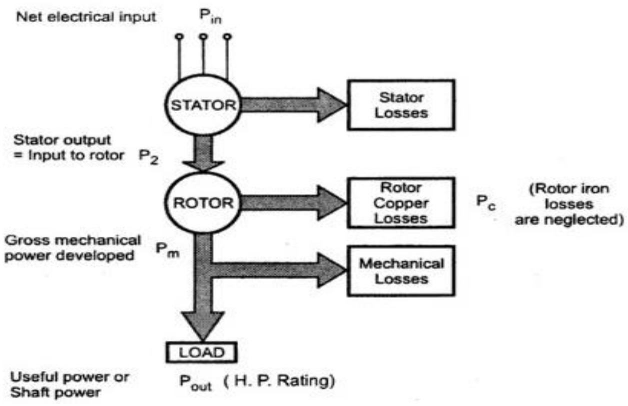


Fig. 2-11 Power flow of the three-phase induction motor

The losses in IM are the stator copper loss which is given by

$$P_{s\_loss} = 3I_s^2 R_s \tag{2.19}$$

Where P_{s_loss} is the stator copper loss and R_s is the stator resistance

The rotor copper loss is given by

$$P_{r\_loss} = 3I_{r\_s}^2 R_r \tag{2.20}$$

Where P_{r_loss} is the stator copper loss, I_{r_s} is the rotor current referred to stator and R_r is the rotor resistance

core loss or iron loss, eddy current loss and hysteresis losses in the laminations. The core loss, friction, windage and stray loss are rotational losses. These losses are subtracted from the input power to obtain the output power. The rotor input power is given by

$$P_g = 3I_{r\_s}^2 \frac{R_r}{s} \tag{2.21}$$

The power converted into mechanical system is given by

$$P_{conv} = P_g - P_{r\_loss}$$

$$P_{conv} = 3(\frac{1-s}{s})I_{r\_s}^2 R_r \qquad 2.22$$

The output power can be obtained by subtracting the rotational losses from the power converted to mechanical energy which is expressed as

$$P_{out} = P_{conv} - P_{rat\_loss} \qquad 2.23$$

The motor efficiency is given by:

$$\eta = \frac{P_{out}}{P_{in}} x\, 100 \qquad 2.24$$

2-7-2 Torque speed characteristics of the three-phase induction motor:

Typical torque-speed curve of a squirrel-cage induction motor given in Fig. 2-12. It provides information about the operation of induction motor. The induced torque of the motor is zero at synchronous speed. The curve is nearly linear in normal operating conditions which are between pullout speed and synchronous speed. Maximum possible torque the machine can induce is called the pullout torque or the breakdown torque and it limits the short-time overload capability of the motor. It is usually two or three times the rated full-load torque of the motor. The starting torque of the motor is slightly larger than its full-load torque, so this motor will start carrying any load that it can supply at full power.

2-8 Starting of the Three Phase induction Motor:

The starting of the three-phase induction motor can be done by any method from the following;

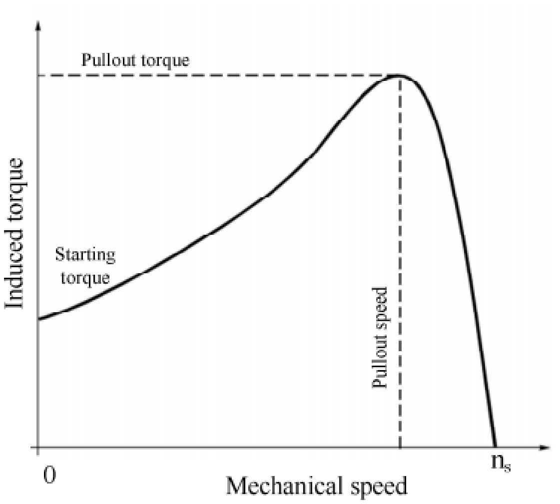


Fig. 2-12 Typical torque-speed characteristic of the three-phase induction machine

Direct on line start: When starting a motor direct on line the electrical networks voltage is directly going to the motor. It is the simplest starting method; however, the starting current can be as high as 8 times the nominal current as the motor requires additional current while the rotor needs to be magnetized while starting up.

Star delta connection start: In some scenarios one might want to have a lower starting current and that can be achieved with the use of a star delta start. The star delta starter uses the star connection of the motor windings when starting and after a while it switches to delta connection, typically when the full speed has been achieved. This can reduce the starting current so it’s only one third compared to the previous starting current. Since it gives a lower starting current it also means it gives a lower starting torque which can be useful in some applications, but just as well could it make starting impossible in others so this needs to be checked prior to using such arrangements.

Transformer start: With a transformer start, a device called a transformer is used. With the use of the transformer the voltage to the motor can be reduced and thus reducing the starting current and starting torque. It is then possible to switch back to the nominal voltage whenever it’s desired. The difference between star delta start and transformer start is that the first method is locked to give one third of the Direct on line starting current, while when using transformer start the current depends on the output voltage of the transformer.

Soft starter: A soft starter is a device that can adjust the voltage to the motor to achieve the wanted starting behavior. So, if the motor have a low load, the soft starter can feed low voltage to the motor, if the motor have a higher load, the soft starter simply feed more voltage to the motor. With the soft starter, the motor can run with lower the voltage at the start and steadily increase the voltage over time. The difference between a transformer start and a soft starter is that the transformer switches the voltage between two values while the soft starter goes from zero to nominal voltage over a span time that can be adjusted.

Variable speed drive start: A Variable speed drive is a device that can change both frequency and voltage used by the motor. So, like a soft starter but instead of adjusting the voltage only, it also has the possibility to adjust the frequency of the current at the start. As the variable speed drive can adjust both voltage and frequency it means that it can keep the electromagnet flux inside the motor constant, so it does not lose any of the motor torque during the start. This means that it can use the nominal torque of the motor already from zero speed and at the same time it can limit the starting current of the motor to its nominal value. This makes the variable speed drive the most versatile of all the starting methods. It also gives an additional feature to control the rotation speed of the motor.

2-9 Classification and Applications of the Three Phase Induction Motor:

Generally, the three phase induction motors are classified into four classes: -

Class A: - Normal Starting torque, High starting current with Low Slip is the required operating criteria of this type of motor with High full load efficiency.

Examples: - Fan, Blowers, Machine tools etc.

Class B: - Normal Staring torque, Low Starting current and low operational slip are the required operational criteria of this type of motor. Application is same as class A Motor.

Class C: - High Starting torque, low Starting current and applicable for constant speed-load condition is the required operational criteria for this type of motor.

Examples: - Compressor, Crushers, Conveyors etc.

Class D: - Highest Starting torque of all the class motor, low starting current and high operating slip. This type of motors has low efficiency suitable for intermediate loads.

Examples: - Bulldozers, Die stamping etc.

CHAPTER THREE

MATHEMATICAL MODEL OF THE THREE PHASE INDUCTION MOTOR

The mathematical model for any device is very important to predict the behavior of this device at any operating point, at transient and at any fault conditions. This is useful to improve the performance of this device. Due to these reasons and due to treatment the three-phase induction motor, this chapter discussed the mathematical model of the three-phase induction motor.

3-1 The mathematical model of the three-phase induction motor:

The mathematical model of the three-phase induction motor is discussed here. This simulation is built in the stationery reference frame. This simulation is constructed for symmetrical winding arrangement of the three-phase induction motor. it has two poles, and wye-connected. It can be seen in Fig. 3-1. when constructed this model, the following assumption are made

1. The stator windings are identical,
2. Each stator winding is distributed and displaced by 120 degree so as to produce a sinusoidal mmf along air gap, i.e. space harmonics are negligible. (Sinusoidal induction repartition)
3. The slotting in stator and rotor produces negligible variation in respective inductances.
4. Mutual inductances are equal
5. The harmonics in voltages and currents are neglected.
6. Saturation, hysteresis and eddy effects negligible.

The corresponding voltage equation for the stator and rotor may be expressed as,

$$v_{abcs} = r_{abcs} i_{abcs} + p\lambda_{abcs} \qquad 3.1$$

$$v_{abcr} = r_{abcr} i_{abcr} + p\lambda_{abcr} \qquad 3.2$$

Both the stator and rotor are parameters represented by matrices which can be written as;

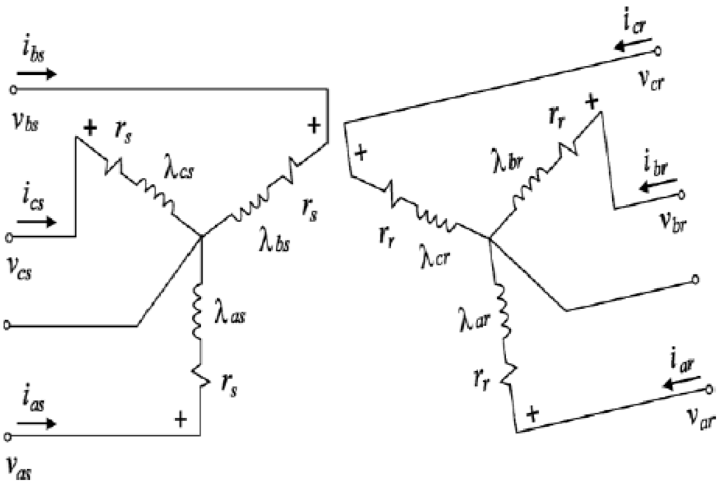


Fig. 3-1 Three phase model of induction motor

The stator and rotor voltages can be represented by the following matrices;

$$v_{abcs} = \begin{pmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{pmatrix}, \qquad v_{abcr} = \begin{pmatrix} v_{ar} \\ v_{br} \\ v_{cr} \end{pmatrix}$$

The stator and rotor currents can be represented by the following matrices;

$$i_{abcs} = \begin{pmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{pmatrix}, \qquad i_{abcr} = \begin{pmatrix} i_{ar} \\ i_{br} \\ i_{cr} \end{pmatrix}$$

The stator and rotor fluxes linkage can be represented by the following matrices;

$$\lambda_{abcs} = \begin{pmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \end{pmatrix}, \qquad \lambda_{abcr} = \begin{pmatrix} \lambda_{ar} \\ \lambda_{br} \\ \lambda_{cr} \end{pmatrix}$$

The stator and rotor diagonal resistance matrices are 3×3 can be represented by the following matrices;

$$r_{abcs} = \begin{pmatrix} r_{as} & 0 & 0 \\ 0 & r_{bs} & 0 \\ 0 & 0 & r_{cs} \end{pmatrix}, \qquad r_{abcr} = \begin{pmatrix} r_{ar} & 0 & 0 \\ 0 & r_{br} & 0 \\ 0 & 0 & r_{cr} \end{pmatrix}$$

Because the three-phase stator winding are identical so, $r_{as} = r_{bs} = r_{cs} = r_s$

Also, the three-phase rotor winding are identical so, $r_{ar} = r_{br} = r_{cr} = r_r$

The operator p denotes d/dt.

Also, the corresponding flux linkage can be written as,

$$\lambda_{abcs} = L_{abcs} i_{abcs} + L_{abcsr} i_{abcr} \qquad 3.3$$

$$\lambda_{abcr} = L_{abcr} i_{abcr} + L_{abcrs} i_{abcs} \qquad 3.4$$

The stator, rotor and mutual inductance diagonal matrices are 3×3 can be represented by the following matrices;

$$L_{abcs} = \begin{pmatrix} L_{as} & L_{abs} & L_{acs} \\ L_{abs} & L_{bs} & L_{bcs} \\ L_{acs} & L_{bcs} & L_{cs} \end{pmatrix}, \qquad L_{abcr} = \begin{pmatrix} L_{ar} & L_{abr} & L_{acr} \\ L_{abr} & L_{br} & L_{bcr} \\ L_{acr} & L_{bcr} & L_{cr} \end{pmatrix}$$

$$L_{abcsr} = L_{abcsr}^{T} = \begin{pmatrix} L_{aasr} & L_{absr} & L_{acsr} \\ L_{basr} & L_{bbsr} & L_{bcsr} \\ L_{casr} & L_{cbsr} & L_{ccsr} \end{pmatrix}$$

Because the three-phase stator winding are identical so, $L_{as} = L_{bs} = L_{cs} = L_s$

Where L_s is the stator self inductance

Also, the three-phase rotor winding are identical so, $L_{ar} = L_{br} = L_{cr} = L_r$

Where L_r is the stator rotor inductance

Also, the three-phase stator winding are identical so,

$$L_{abs} = L_{bas} = L_{acs} = L_{cas} = L_{bcs} = L_{cbs} = -\frac{1}{2} L_{ms}$$

Where L_{ms} is the mutual inductance between stator phases

Also, the three-phase rotor winding are identical so,

$$L_{abr} = L_{bar} = L_{acr} = L_{car} = L_{bcr} = L_{cbr} = -\frac{1}{2} L_{mr}$$

Where L_{mr} is the mutual inductance between rotor phases

From that;

$$L_{abcs} = \begin{pmatrix} L_s & -\frac{1}{2} L_{ms} & -\frac{1}{2} L_{ms} \\ -\frac{1}{2} L_{ms} & L_s & -\frac{1}{2} L_{ms} \\ -\frac{1}{2} L_{ms} & -\frac{1}{2} L_{ms} & L_s \end{pmatrix} , \ L_{abcs} = \begin{pmatrix} L_r & -\frac{1}{2} L_{mr} & -\frac{1}{2} L_{mr} \\ -\frac{1}{2} L_{mr} & L_r & -\frac{1}{2} L_{mr} \\ -\frac{1}{2} L_{mr} & -\frac{1}{2} L_{mr} & L_r \end{pmatrix}$$

Because the mutual inductance between the stator and the rotor effected by the angle between them so,

$$L_{abcsr} = L_{abcsr}^{T} = L_{sr} \begin{pmatrix} \cos\theta_r & \cos(\theta_r + \frac{2\Pi}{3}) & \cos(\theta_r - \frac{2\Pi}{3}) \\ \cos(\theta_r - \frac{2\Pi}{3}) & \cos\theta_r & \cos(\theta_r + \frac{2\Pi}{3}) \\ \cos(\theta_r + \frac{2\Pi}{3}) & \cos(\theta_r - \frac{2\Pi}{3}) & \cos\theta_r \end{pmatrix}$$

Where L_{sr} is the mutual inductance between rotor and stator, θ_r is the angle between stator and rotor winding

The motor torque can be written as;

$$T_e = 3\frac{P}{2} L_{sr} i_{abcs}^{T} i_{abcr} p(\theta_r) \qquad 3.5$$

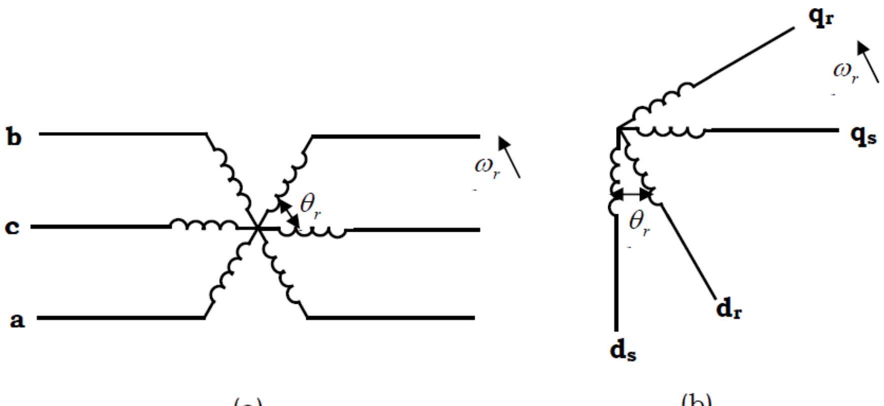
3-2 Two-axis Theory:

The motor model can be represented by an equivalent two-phase machine as shown in Fig. 3-2b. Though it is somewhat simple, the problem of time varying parameters still remains. To overcome this problem, the reference frame theory was introduced. Such a model can be described uniquely in rotor reference frame or stationary reference frame or synchronously rotating reference frame. As the stationary reference frame is simple, it is used in variable speed drives to study the transient and steady state performance of the drive. The symmetrical three phase induction motor has a three-phase system of coils on the stator and a cage on the rotor which can be considered to be an equivalent to a three-phase winding as shown in Fig. 3-2a.

To apply this theory let start by;

A symmetrical three phase windings on the stator are represented by three coils a, b, c and three phase currents are

$i_a = I_m \sin(\omega_e t)$ $i_b = I_m \sin(\omega_e t - 120)$ $i_c = I_m \sin(\omega_e t - 240)$



(a) (b)

Fig. 3-2 Coupling effect in three-phase stator and rotor windings of motor and equivalent two-phase motor

These will produce a MMF of constant magnitude (3/2) N I_m rotating with respect to windings at time frequency.

To transform from three phase into two phase, two conditions must be fulfilled,

1. The input power of the three phase machine is equal to the input power of the two phase machine.
2. The MMF of the three phase machine is equal to the MMF of the two phase machine.

This could be occurred by any method from the following:-

a- Changing the magnitude of two phase currents.
b- Changing the number of turns of two phase winding.
c- Changing magnitude both of currents and number of turns of two phase.

The last method has the advantage of the transformation for current and voltage, which has the same coefficient. Hence the impedance per phase of the three phase is equal to the impedance per phase of the two phase.

Let the number of the per phase turns in the two phase windings are equal $\frac{3}{2}$ times of the per phase turns of the three phase windings. From equal MMF wave it found that:

$$N(i_a + i_b COS(120) + i_c COS(240)) = N i_{ds} \frac{3}{2} \qquad 3.6$$

$$i_a - \frac{1}{2} i_b - \frac{1}{2} i_c = \frac{3}{2} i_{ds} \qquad 3.7$$

But

$$i_a + i_b + i_c = 0$$

Then

$$i_{xs} = \sqrt{\frac{3}{2}}\, i_a \qquad 3.8$$

$$N(i_b SIN(120) + i_c SIN(240)) = \frac{3}{2} i_{ys} N \qquad 3.9$$

$$\frac{\sqrt{3}}{2} i_b - \frac{\sqrt{3}}{2} i_c = \frac{3}{2} \quad i_{ys}$$

Then

$$i_{ys} = \frac{1}{\sqrt{2}} (i_b - i_c) \qquad 3.10$$

eq. 3.8 and eq. 3.10 can be put in matrix as the follow,

$$\begin{pmatrix} i_{xs} \\ i_{ys} \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \qquad 3.11$$

Form the above can be concluded that,

The transformation from three phase into two phase occurs by the following matrix

$$\frac{3}{2}\begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix}$$

By applying this transformation in the mathematical model of three-phase induction motor it is found that;

The dynamic model of induction motor in the stationery reference frame can be written as it is

$$v_{ds} = r_s i_{ds} + p\lambda_{ds} \tag{3.12}$$

$$v_{qs} = r_s i_{qs} + p\lambda_{qs} \tag{3.13}$$

Where v_{ds}, v_{qs} are d q axes stator voltages, i_{ds}, i_{qs} are d q axes stator currents and λ_{ds}, λ_{qs} are d q axes stator flux linkages

$$v_{dr} = r_s i_{dr} + p\lambda_{dr} + \omega_r \lambda_{qr} \tag{3.14}$$

$$v_{qr} = r_r i_{qr} + p\lambda_{qr} - \omega_r \lambda_{dr} \tag{3.15}$$

Where v_{dr}, v_{qr} are d q axes rotor voltages, i_{dr}, i_{qr} are d q axes rotor currents and λ_{dr}, λ_{qr} are d q axes rotor flux linkages

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \tag{3.16}$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \tag{3.17}$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \tag{3.18}$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \tag{3.19}$$

$$T_e = \frac{3P}{4}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \tag{3.20}$$

$$Jp\omega_m = T_e - T_L - B\omega_m \qquad 3.21$$

Where T_e is the electromagnetic motor torque, T_L is the load torque, ω_m is mechanical speed of the motor, B is the fractional coefficient and J is the moment of inertia.

The rotor position can be expressed as

$$\theta_r = \int \omega_r \, dt \qquad 3.22$$

From this mathematical model to simulate the three-phase induction motor use the eqs. 3.12 – 3.22

CHAPTER FOUR

THREE PHASE VOLTAGE SOURCE INVERTER

Inverters are used to create single or polyphase AC voltages from a DC supply. In the class of polyphase inverters, three-phase inverters are by far the largest group. A very large number of inverters are used for adjustable speed motor drives. The typical inverter for this application is a "hard-switched" voltage source inverter producing pulse-width modulated (PWM) signals with a sinusoidal fundamental. Modern inverters use insulated gate bipolar transistors (IGBTs) as the main power control devices. Besides IGBTs, power MOSFETs are also used especially for lower voltages, power ratings, and applications that require high efficiency and high switching frequency. In recent years, IGBTs, MOSFETs, and their control and protection circuitry have made remarkable progress. IGBTs are now available with voltage ratings of up to 3300 V and current ratings up to 1200 A. MOSFETs have achieved on-state resistances approaching a few milliohms. In addition to the devices, manufacturers today offer customized control circuitry that provides for electrical isolation, proper operation of the devices under normal operating conditions and protection from a variety of fault conditions.

Inverters are classified into two main categories −

1. Voltage Source Inverter (VSI) − The voltage source inverter has stiff DC source voltage that is the DC voltage has limited or zero impedance at the inverter input terminals.
2. Current Source Inverter (CSI) − A current source inverter is supplied with a variable current from a DC source that has high impedance. The resulting current waves are not influenced by the load.

4-1 The Three Phase Voltage Source Inverter:

A three-phase inverter converts a DC input into a three-phase AC output. Its three arms are normally delayed by an angle of 120° so as to generate a three-phase AC supply. The inverter switches each has a ratio of 50% and switching occurs after every $\frac{T}{6}$ of the time T (60° angle interval). The standard three-phase inverter can be seen in Fig. 4-1. It has six switches. The switches S_{11} and S_{12}, the switches S_{21} and S_{22} and switches S_{31} and S_{32} complement each other. The Fig. 4-1shows a circuit for a three-phase inverter. It is nothing but three single phase inverters put across the same DC source. The pole voltages in a three-phase inverter are equal to the pole voltages in single phase half bridge inverter. The input DC voltage is usually obtained from a single-phase or three phase utility power supply through a diode-bridge rectifier and LC or C filter. The inverter has eight switch states given in Table 4.1. Both of the switches in the same leg cannot be turned ON at the same time, as it would short the input voltage violating the KVL. Thus, the nature of the two switches in the same leg is complementary.

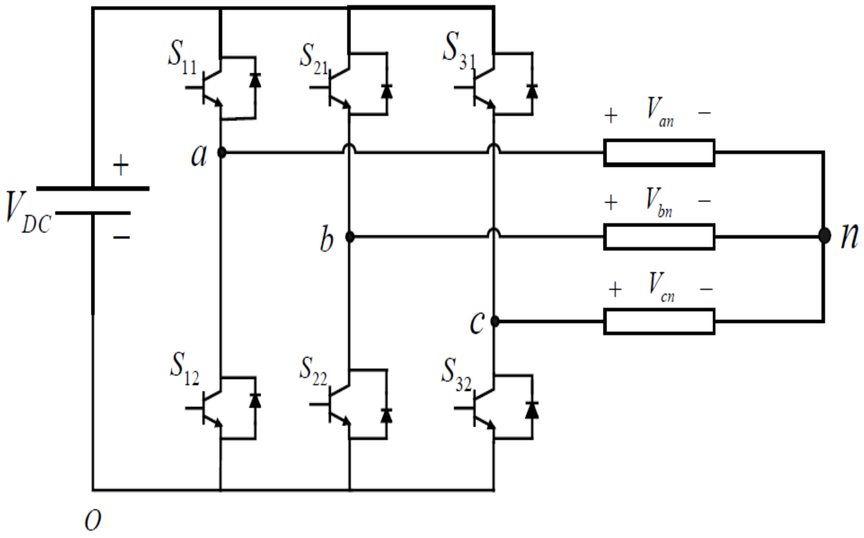
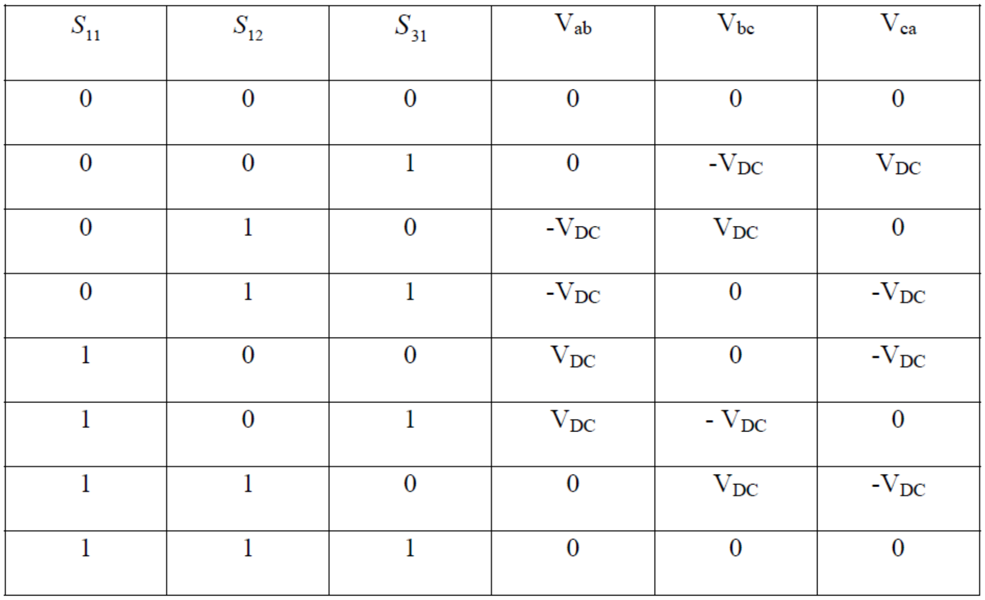


Fig. 4-1 The standard three phase inverter



S_{11}	S_{12}	S_{31}	V_{ab}	V_{bc}	V_{ca}
0	0	0	0	0	0
0	0	1	0	$-V_{DC}$	V_{DC}
0	1	0	$-V_{DC}$	V_{DC}	0
0	1	1	$-V_{DC}$	0	$-V_{DC}$
1	0	0	V_{DC}	0	$-V_{DC}$
1	0	1	V_{DC}	$- V_{DC}$	0
1	1	0	0	V_{DC}	$-V_{DC}$
1	1	1	0	0	0

Table 4.1 The switching states in a three-phase inverter

$$S_{11}+S_{12}=1 \qquad 4.1$$

$$S_{21}+S_{22}=1 \qquad 4.2$$

$$S_{31}+S_{32}=1 \qquad 4.3$$

Of the eight switching states as shown in Table 4.1 two of them produce zero ac line voltage at the output. In this case, the ac line currents freewheel through either the upper or lower components. The remaining states produce no zero ac output line voltages. In order to generate a given voltage waveform, the inverter switches from one state to another. Thus, the resulting ac output line voltages consist of discrete values of voltages, which are $-V_{DC}$, 0, and V_{DC}. The selection of the states in order to generate the given waveform is done by the modulating technique that ensures the use of only the valid states.

$$\frac{V_{DC}}{2}(S_{11}-S_{12})=V_{an}+V_{no} \qquad 4.4$$

$$\frac{v_{DC}}{2}(s_{21}-s_{22})=v_{bn}+v_{no} \tag{4.5}$$

$$\frac{v_{DC}}{2}(s_{31}-s_{32})=v_{cn}+v_{no} \tag{4.6}$$

By substituting from eq. 4.4 to eq. 4.6 in terms of modulation signals and making use of conditions from eq. 4.1 to eq. 4. 3 gives

$$\frac{v_{DC}}{2}M_{11}=v_{an}+v_{no} \tag{4.7}$$

$$\frac{v_{DC}}{2}M_{12}=v_{bn}+v_{no} \tag{4.8}$$

$$\frac{v_{DC}}{2}M_{13}=v_{cn}+v_{no} \tag{4.9}$$

By adding the eqs. from 4.7 to 4.9 it is found that,

$$\frac{v_{DC}}{2}(s_{11}+s_{21}+s_{31}-s_{12}-s_{22}-s_{23})=3v_{no} \tag{4.10}$$

Depending up on Fourier series eq. 4.10 becomes

$$\frac{v_{DC}}{6}(2s_{11}+2s_{21}+2s_{31}-3)=v_{no} \tag{4.11}$$

By substituting for v_{no} in Eqs. 4.13 to 4.15, it gives

$$\frac{v_{DC}}{3}(2s_{11}-s_{21}-s_{31})=v_{an} \tag{4.12}$$

$$\frac{v_{DC}}{3}(2s_{21}-s_{11}-s_{31})=v_{bn} \tag{4.13}$$

$$\frac{v_{DC}}{3}(2s_{31}-s_{11}-s_{21})=v_{cn} \tag{4.14}$$

4-2 Block Diagram of Voltage Source Inverter:

Fig. 4-2 shows the most block diagram of voltage source inverter. These blocks diagram are AC source, rectifier, power circuit and Driver Circuit.

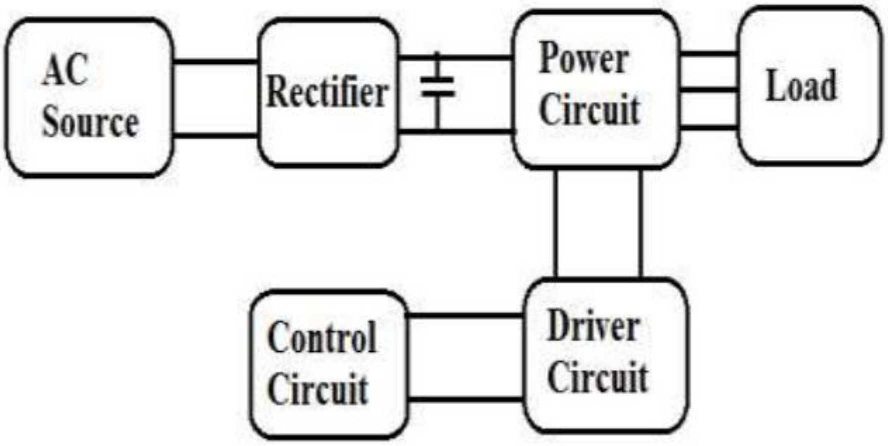


Fig. 4-2 The most block diagram of voltage source inverter

AC source:

An ac source is ordinary supply of rectifier, which has any frequency and voltage rating. Which is practically constant supply of 3 phase or 1 phase. Before this block there is switch to operate supply and protection system by fuse.

Rectifier:

A rectifier is converts alternating current (AC) to direct current (DC). A diode is like a one-way valve that allows an electrical current to flow in only one direction. This process is called rectification.

Power circuit:

Power circuit consists of bridge of six switches. For 3 phases it has 3 legs. In each leg it has two switches. Basically, the switch is IGBT or MOSFET.

Driver Circuit:

In contrast to bipolar transistors, MOSFETs do not require constant power input, as long as they are not being switched on or off. The isolated gate-electrode of the MOSFET forms a capacitor (gate capacitor), which must be charged or discharged each time the MOSFET is switched on or off. As a transistor requires a particular gate voltage in order to switch on, the gate capacitor must be charged to at least the required gate voltage for the transistor to be switched on. Similarly, to switch the transistor off, this charge must be dissipated, i.e. the gate capacitor must be discharged.

4-3 Six Step Voltage Source Inverter:

The two types of inverters above have two modes of conduction − 180° mode of conduction and 120° mode of conduction. Three-phase bridge inverters are most commonly used in ac motor drives and general-purpose ac supplied. Fig. 4-3 and Fig. 4-3 explain the generation of the output voltages in six-step mode of operation. The circuit for the six-step VSI is as shown in Fig. 4-3, which consists of three half-bridges, which are mutually phase-shifted by 120^0 to generate the three phase voltages.

The square wave phase voltages with respect to the fictitious dc center tap can be expressed using Fourier series as,

$$V_{ao} = \frac{2V_{DC}}{\Pi}[\cos\omega t - \frac{1}{3}\cos 3\omega t + \frac{1}{5}\cos 5\omega t - ....] \qquad 4.15$$

$$V_{bo} = \frac{2V_{DC}}{\Pi}[\cos(\omega t - 120^0) - \frac{1}{3}\cos 3(\omega t - 120^0) + \frac{1}{5}\cos 5(\omega t - 120^0) - ....] \qquad 4.16$$

$$V_{co} = \frac{2V_{DC}}{\Pi}[\cos(\omega t + 120^0) - \frac{1}{3}\cos 3(\omega t + 120^0) + \frac{1}{5}\cos 5(\omega t + 120^0) - ....] \qquad 4.17$$

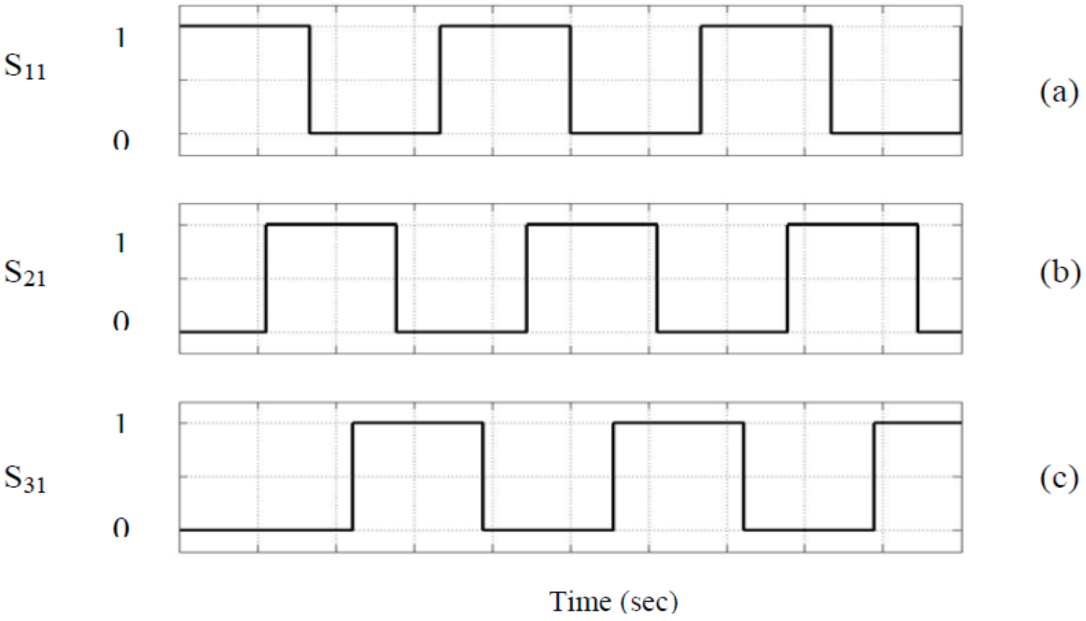


Fig. 4-3 Generation of the switching signals for top devices (a) S11 (b) S21 (c) S31

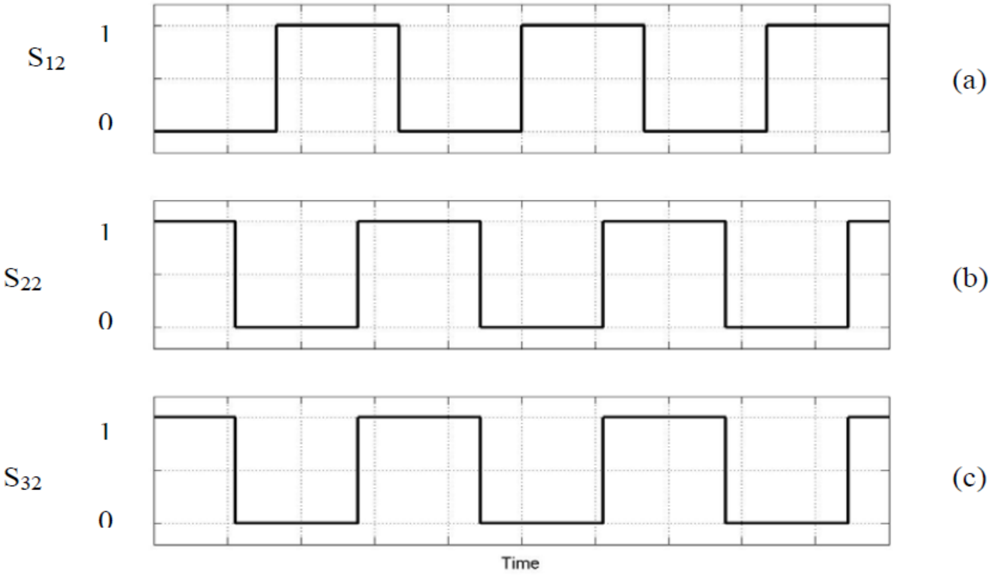


Fig. 4-4 Generation of the switching signals for bottom devices (a) S12 (b) S22(c) S32

The line voltages can thus be obtained from the phase voltages as;

$$v_{ab} = v_{an} - v_{bn}$$

$$v_{ab} = \frac{2\sqrt{3}v_{DC}}{\Pi}[\cos(\omega t + 30^0) - \frac{1}{5}\cos 5(\omega t + 30^0) - \frac{1}{7}\cos 7(\omega t + 30^0) - ....] \qquad 4.18$$

$$v_{bc} = v_{bn} - v_{cn}$$

$$v_{bc} = \frac{2\sqrt{3}v_{DC}}{\Pi}[\cos(\omega t - 90^0) - \frac{1}{5}\cos 5(\omega t - 90^0) - \frac{1}{7}\cos 7(\omega t - 90^0) + ...] \qquad 4.19$$

$$v_{ca} = v_{cn} - v_{an}$$

$$v_{ca} = \frac{2\sqrt{3}v_{DC}}{\Pi}[\cos(\omega t + 150^0) - \frac{1}{5}\cos 5(\omega t + 150^0) - \frac{1}{7}\cos 7(\omega t + 150^0) + ...] \qquad 4.20$$

The fundamental of the line voltages is three times that of the phase voltage, and there is a leading phase-shift of $\frac{\Pi}{6}$. The line voltages waves as shown in Fig. 4-5 have a characteristic six-step wave shape and thus the name for this inverter. The characteristic harmonics in the waveform are $6n \pm 1$, n being an integer.

4-4 Operation of Three Phase Inverter:

A. 180° Degree Conduction Mode:

In the three-phase inverter of each switch conduct 180° of cycle, MOSFET pair in each arm i.e. S11, S12; S21, S22 and S31, S32 are turned on with a time interval of 180°. It means that S11 conduct for 180° and S12 for the next 180° of a cycle. Switch in the upper group i.e. S11, S21, S31 conduct at an interval of 120°. It implies that if S11 is fired at ωt=0°, then S21 must be fired at ωt=120° and S31 at ωt=240°. Same is proved lower group of switches. On the basis of this firing scheme, a table 4-2 in prepared as shown at the top. In this table, first row show that S11 from upper group conducts for 180°, S12 for the next 180° and then again S11 for 180° and so on. In the second row, S21 from the upper group is shown to start conducting 120° after S11 starts conducting. After S21 conduction for 180°, S22 conducts for the next 180°

and again S21 for the next 180° and so on. Further, in the third row, S31 from the upper group start conducting 180° after S21 or 240° after S11. After S31 conduction for 180°, S32 conducts for the 180°, S31 for the next 180° and so on. In this manner, the pattern of firing the six switch is identified. Tis table show that S31, S22, S11 should be gated for step I; S22, S11, S32 for step II ; S11, S32, S21 for step III ;S32, S21, S12 for step IV and so on. Thus, the sequence of firing the MOSFET is S11, S32, S21, S12, S31, S22; S11, S32…. It is seen from the table that is every step of 60° duration, only three switch are conducting one from upper group and two from the lower group or two from the upper group and one from the lower group

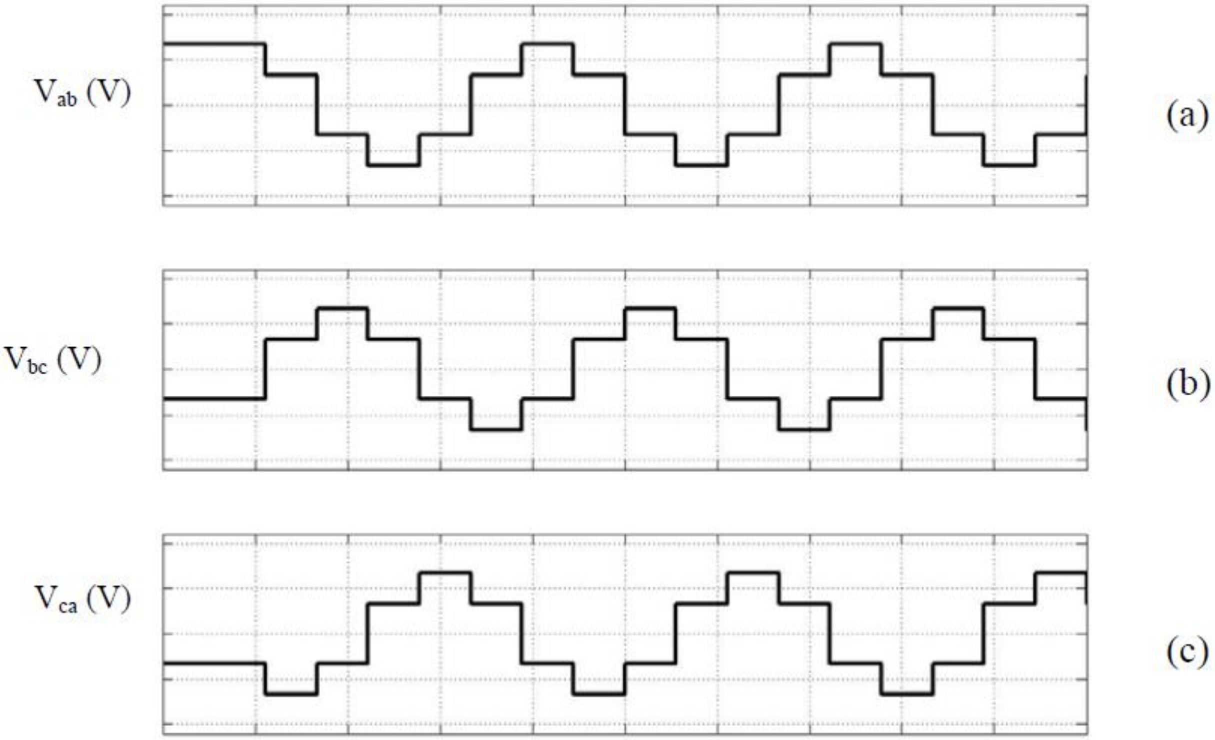
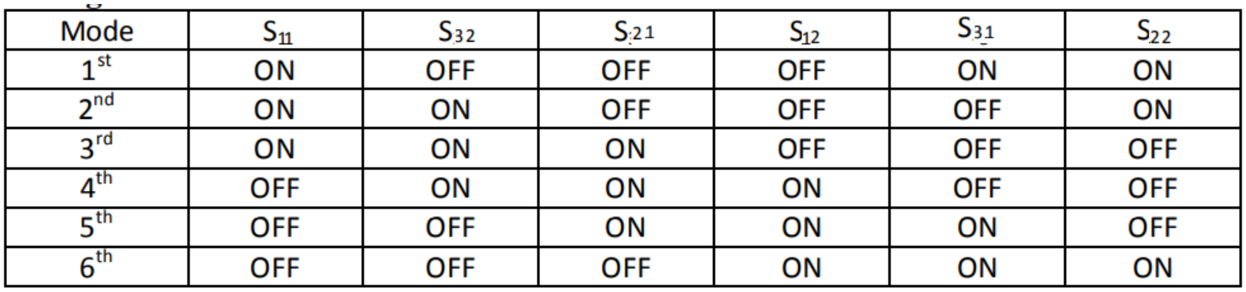


Fig. 4-5 The line voltage of six step inverter

The three-phase fundamental as well as the harmonic components are balanced with a mutual phase-shift angle of 120^0.

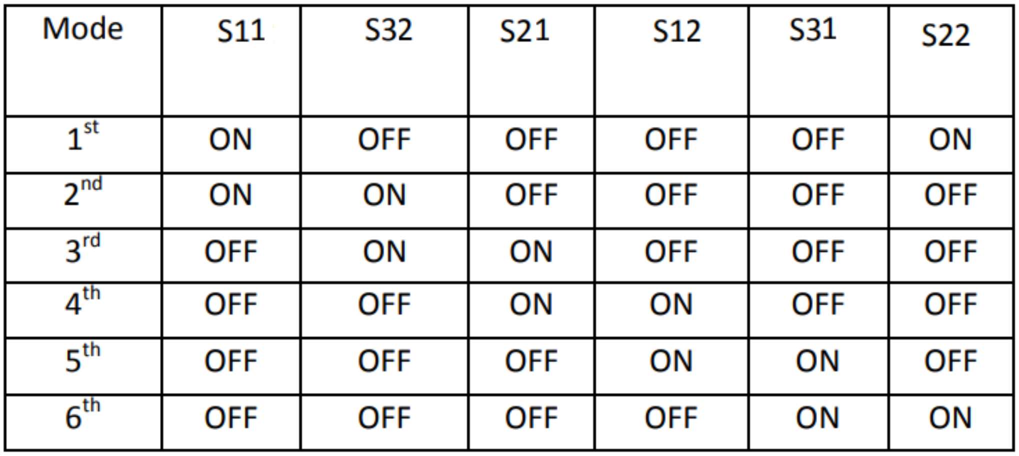


Mode	S_{11}	S_{32}	S_{21}	S_{12}	S_{31}	S_{22}
1st	ON	OFF	OFF	OFF	ON	ON
2nd	ON	ON	OFF	OFF	OFF	ON
3rd	ON	ON	ON	OFF	OFF	OFF
4th	OFF	ON	ON	ON	OFF	OFF
5th	OFF	OFF	ON	ON	ON	OFF
6th	OFF	OFF	OFF	ON	ON	ON

Table 4-2 180^0 conduction band

B. 120° Degree Conduction Mode:

The power circuit diagrams of this inverter is the same as that shown. For the 120°-degree mode VSI, each MOSFET 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. For this inverter too, a table giving the sequence of firing the six MOSFET is prepared as shown in the top. In this table, shown that even conducts for 120° and for the next 60° neither S11 nor S12 conducts. Now S12 is turned on at ωt=180° is further conducts for 120°, i.e. from ωt=180° to at ωt=300°. This means that for 60° interval from ωt=120° to ωt=180°, series connected switch S11, S12 do not conduct. At ωt=300°, S12 is turned off, then 60° interval elapses before S11 is turned on again at ωt=360°. In the second row, S21 is turned on at ωt=120° as in 180° mode inverter. Now S21 conducts for 120°, then 60° interval elapses during which neither S21 nor S32 conducts. At ωt=300°, S32 is turned on, it conducts for 120° and then 60° interval elapses after which S21 is turned on again. The third row is also completed is similarly. This table show that S32, S11 should be gated for step I ; S11, S2 for step II ; S2 ,S21 for step III and so on. The sequence of firing the six MOSFET is the same as for the 180-mode inverter. During each step, only two MOSFETs conducts for this inverter one from the upper group and one from the lower group; but in 180° mode inverter, three MOSFETs conduct in each step.



Mode	S11	S32	S21	S12	S31	S22
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 4-3 120^0 conduction band

CHAPTER FIVE

OPEN LOOP AND CLOSED LOOP THREE PHASE INDUCTION MOTOR

For many years the motor controller was a box which provided the motor speed control and enabled the motor to adapt to variations in the load. Designs were often lossy or they provided only crude increments in the parameters controlled.

Modern controllers may incorporate both power electronics and microprocessors enabling the control box to take on many more tasks and to carry them out with greater precision. These tasks include:

1. Controlling the dynamics of the machine and its response to applied loads.

(speed, torque and efficiency of the machine or the position of its moving elements.)

2. Providing electronic commutation.
3. Enabling self-starting of the motor.
4. Protecting the motor and the controller itself from damage or abuse.
5. Matching the power from an available source to suit the motor requirements (voltage, frequency, number of phases). This is an example of "Power Conditioning" whose purpose is to provide pure DC or sinewave power free from harmonics or interference. Although it could be an integral part of a generator control system, more generally, power conditioning could also be provided by a separate free-standing module operating on any power source.

5-1 Control System Principles:

Any system can be controlled through the open loop control or the closed loop control. These control systems can be explained as the follows;

5-1-1 Open Loop Systems (Manual Control):

An open loop control is very simple control. Its operation is very simple, when an input signal directs the control element to respond, an output will be produced. Fig. 5-1 shows how can the open loop control system work.

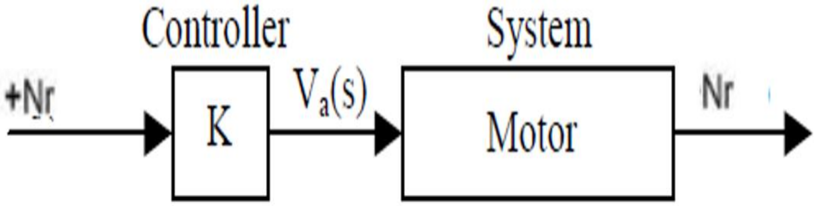


Fig. 5-1 Open loop speed control

Examples of the open loop control systems include washing machines, light switches, gas ovens, etc. The open loop speed control characteristics has been verified using C code. Speed control means intentional change of the drive speed to a value required for performing the specific work process.

In an open loop control system, the controlling parameters are fixed or set by an operator and the system finds its own equilibrium state.

In the case of a motor the desired operating equilibrium may be the motor speed or its angular position. The controlling parameters such as the supply voltage or the load on the motor may or may not be under the control of the operator.

If any of the parameters such as the load or the supply voltage are changed then the motor will find a new equilibrium state, in this case it will settle at a different speed. The actual equilibrium state can be changed by forcing a change in the parameters over which the operator has control.

5-1-2 Closed Loop Systems (Automatic Control):

Once the initial operating parameters have been set, an open loop system is not responsive to subsequent changes or disturbances in the system operating environment such as temperature and pressure, or to varying demands on the system such as power delivery or load conditions.

For continual monitoring and control over the operating state of a system without operator intervention, for more precision or faster response, automatic control systems are needed. The closed loop control system can be seen through Fig. 5-2. Closed loop control systems must act very quickly to implement the error correction without delay, before the system has time to change to a different state. Otherwise the system will possibly become unstable.

Negative feedback:

To meet these requirements "closed loop" systems are necessary. Also called feedback control systems, or negative feedback systems, they allow the user to set a desired operating state as a target or reference and the control system will automatically move the system to the desired operating point and maintain it at that point thereafter.

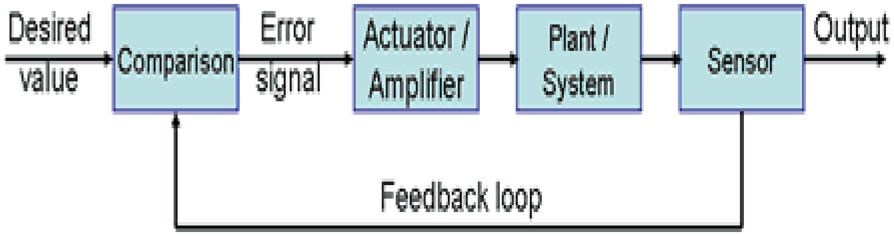


Fig. 5-2 Closed loop control system

A sensor is used to monitor the actual operating state of the system and to feed back to the input of the controller an analogue or digital signal representing the output state. The actual and desired or reference states are continually compared and if the actual state is different from the reference state an error signal is generated which the controller uses to force a change in the controllable parameters to eliminate the error by driving the system back towards the desired operating point.

Loop Gain:

The error signal is usually very small so the controlling circuit or mechanism must contain a high gain "error amplifier" to provide the controlling signal with the power to affect the change.

The amplification provided in the loop is called the loop gain.

Loop Delay:

The response is not always instantaneous as there is usually a delay between sensing the error, or aiming at a new position, and eliminating the error or moving to the new desired position. This delay is called the loop delay.

In mechanical systems the delay may be due to the inertia associated with the lower acceleration possible in getting a large mass to move when a force is applied.

In electrical circuits the delay may be associated with the inductive elements in the circuit which reduce the possible rate of current build up in the circuit when a voltage is applied.

When there is a time lag between sensing of the error and the completion of the corrective action and the loop gain is large enough the system the system may overshoot. If this happens the error will then be in the opposite direction and the control system will also reverse its direction of action in order to correct this new error. The result will be that the actual position will oscillate about the desired position. This instability is called hunting as the system hunts to find its aiming point.

In the worst case, the delayed error correcting response will arrive 180 degrees out of phase with the disturbance it is trying to eliminate. When this happens the direction of the system response will not act so as to eliminate the error, instead it will reinforce the error. Thus, the delay has changed the system response from negative feedback to positive feedback and the system will be critically unstable.

Volts/Hertz control is needed for speed control of induction motors. In an open loop system, the control system converts the desired speed to a frequency reference input to a variable frequency, variable voltage inverter. At the same time, it multiplies the frequency reference by the Volts/Hertz characteristic ratio of the motor to provide the corresponding voltage reference to the inverter. Changing the speed reference will then cause the voltage and frequency outputs from the inverter to change in unison.

In a closed loop system, a speed feedback signal provided from a tachogenerator on the motor output shaft is used in the control loop to derive a speed error signal to drive a Volts/Hertz control function similar to the one outlined above. The following section explained the open loop scalar control and the closed loop scalar control.

5-2 Four Quadrant Speed Control of The Motor:

Four Quadrant DC motor are extremely used in adjustable speed drive and position control application. When an electrical machine is required to work as both a motor and a generator in both forward and reverse directions this is said to be four quadrant operation. A simple motor which only runs in one direction and is never driven as a generator is an example of a single quadrant application. A motor designed for automotive use which must run in forward and reverse directions and which must provide regenerative braking in both directions needs a four quadrant controller.

Control systems for four quadrant applications will obviously be more complex than single quadrant controls. Similarly, in four quadrant operation current is positive and voltage is negative and therefor power is negative which is shown in Fig. 5-3.

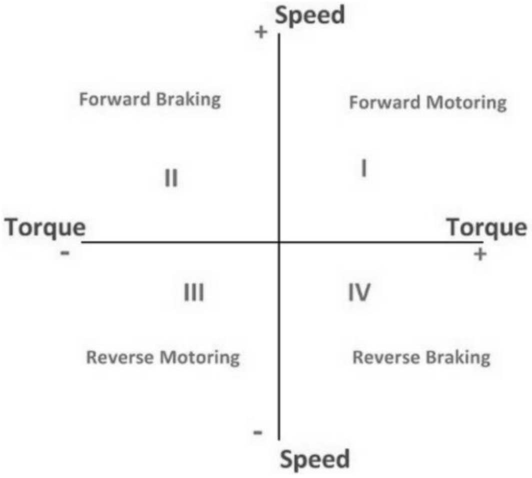


Fig. 5-3 Basic operation of Four quadrant to motor control

At the first quadrant current and voltage are positive then the motor can rotate in the forward direction i.e. forward motoring. If the polarity of armature current and armature voltage changing then the motor can be operated as reveres motoring i.e. (III Quadrant) and when direction of energy is reveres in II and IV Quadrant the motor can operated as a generator braking.

5-3 Scalar V/Hz Controls:

Scalar V/Hz controls, also known as V/f or variable-voltage, variable-frequency controls, manage motor speed as a function of frequency using a simple lookup table. In the V/Hz control, the speed of induction motor is controlled by the adjustable magnitude of stator voltages and frequency in such a way that the air gap flux is always maintained at the desired value at the steady-state. Sometimes this scheme is called the scalar control because it focuses only on the steady state dynamic. It can explain how this technique works by looking at the simplified version of the steady state equivalent circuit as seen in Fig. 5-4. According to in this Fig., the stator resistance (Rs) is assumed to be zero and the stator leakage inductance (Lls) is embedded into the (referred to stator) rotor leakage inductance (Llr) and the magnetizing inductance, which is representing the amount of air gap flux, is moved in front of the total leakage inductance (Ll = Lls + Llr). As a result, the magnetizing current that generates the air gap flux can be approximately the stator voltage to frequency ratio. Its phasor equation (for steady-state analysis) can be seen as:

$$i_m = \frac{v_s}{j\omega_e L_m} \qquad 5.1$$

If the induction motor is operating in the linear magnetic region, the Lm is constant. Then, eq. 5.1 can be shown in terms of magnitude as:

$$i_m = \frac{v_s}{j\,2\Pi f\, L_m} \qquad 5.2$$

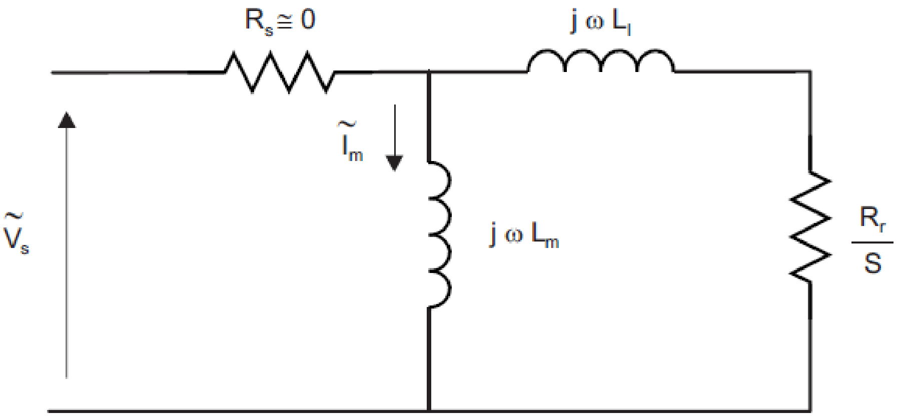


Fig. 5-4 Simplified steady state equivalent circuit of induction motor

From the last equation, it follows that if the ratio V/f remains constant for any change in f, then flux remains constant and the torque becomes independent of the supply frequency. In order to keep motor flux constant, the ratio of Vs / *f* would also be constant at the different speed. As the speed increases, the stator voltages must, therefore, be proportionally increased in order to keep the constant ratio of Vs/f. However, the frequency (or synchronous speed) is not the real speed because of a slip as a function of the motor load. At no-load torque, the slip is very small, and the speed is nearly the synchronous speed. Thus, the simple open-loop Vs/f (or V/Hz) system cannot precisely control the speed with a presence of load torque. The slip compensation can be simply added in the system with the speed measurement. The closed-loop V/Hz system with a speed sensor can be shown in Fig. 5-5.

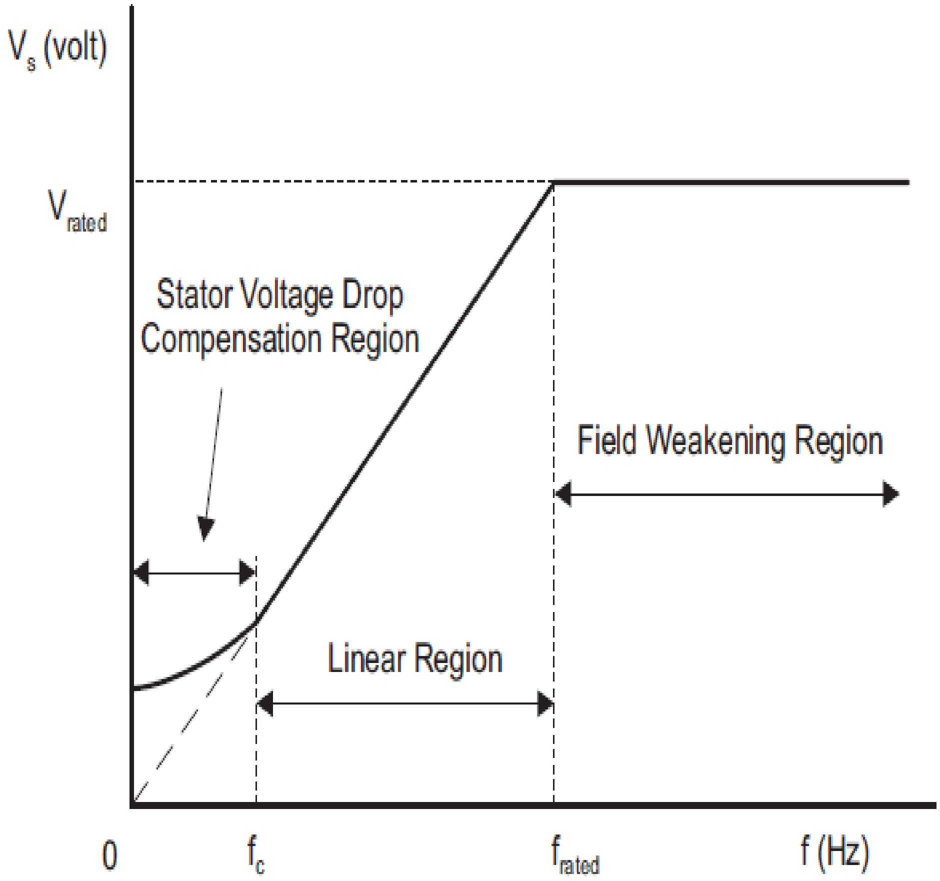


Fig. 5-5 shows a sample V/Hz voltage vs. speed (frequency) profile

In practice, the stator voltage to frequency ratio is usually based on the rated values of these variables. The typical V/Hz profile can be shown in Fig.5-5. Basically, there are three speed ranges in the V/Hz profile as follows:

1. At 0-fc Hz, a voltage is required, so the voltage drop across the stator resistance cannot be neglected and must be compensated for by increasing the Vs. So, the V/Hz profile is not linear. The cutoff frequency (fc) and the suitable stator voltages may be analytically computed from the steady-state equivalent circuit with Rs $\neq$ 0.
2. At fc-frated Hz, it follows the constant V/Hz relationship. The slope actually represents the air gap flux quantity as seen in eq. 5.2.
3. At higher frated Hz, the constant Vs/f ratio cannot be satisfied because the stator voltages would be limited at the rated value in order to avoid insulation breakdown at stator windings. Therefore, the resulting air gap flux would be reduced, and this will unavoidably cause the decreasing developed torque correspondingly. This region is usually so called “field weakening region”. To avoid this, constant V/Hz principle is also violated at such frequencies.

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.

In this implementation, the profile in Fig5-5 is modified by imposing a lower limit on frequency, which is shown in Fig. 5-6. This approach is acceptable to applications such as fan and blower drives where the speed response at low end is not critical.

Since the rated voltage, which is also the maximum voltage, is applied to the motor at rated frequency, only the rated minimum and maximum frequency information is needed to implement the profile.

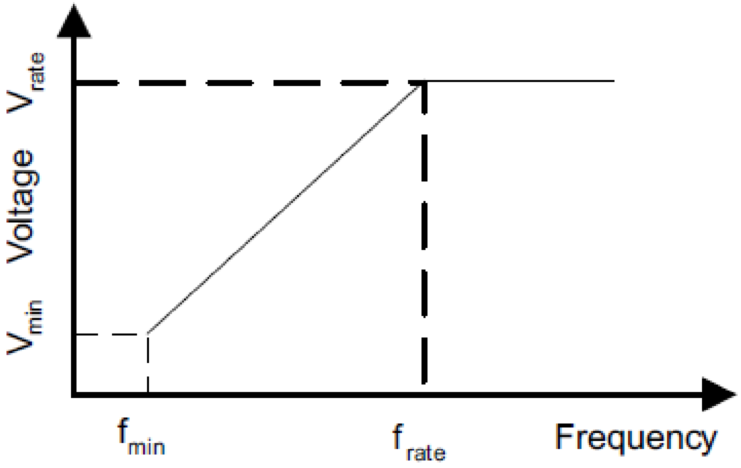


Fig. 5-6. Modified V/Hz profile

5-3-1 Open Loop Scalar Control of Three Phase Induction Motor:

An open-loop scalar V/Hz control fits well when minute or fast changes in motor speed are not required, and when the accuracy requirements of speed changes are lax enough not to warrant the higher cost of a scalar V/Hz closed-loop control, which requires a speed sensor and a more complex and costly control system. With no feedback speed sensors on the motor, the PWM voltage signals are determined based on the desired speed and the assumption that the motor will roughly track the voltage vs. speed profile, with any errors in speed considered minor and acceptable. The open loop six step voltage source inverter with induction motor represents the open loop scalar control. It can be seen in Fig. 5-7. It consists of six step generator, voltage controller, bridge firing unit, inverter and DC bus.

When VSI is operated as a six-step inverter, the transistors are turned ON in the sequence of their numbers with a time interval of T/6 seconds if T is the total time period of one output cycle.

1. Frequency of the inverter output is varied by varying the time period (T) of one cycle.
2. If the supply is DC, then a variable dc voltage is obtained by connecting a chopper between input dc and the inverter.
3. If the input supply is ac, then a variable dc is obtained by connecting a controlled rectifier between the input ac and the inverter
4. If a PWM inverter is used as VSI, the input voltage may be a constant dc which is obtained from a simple diode rectifier. The output of a PWM inverter is a variable voltage and variable frequency.

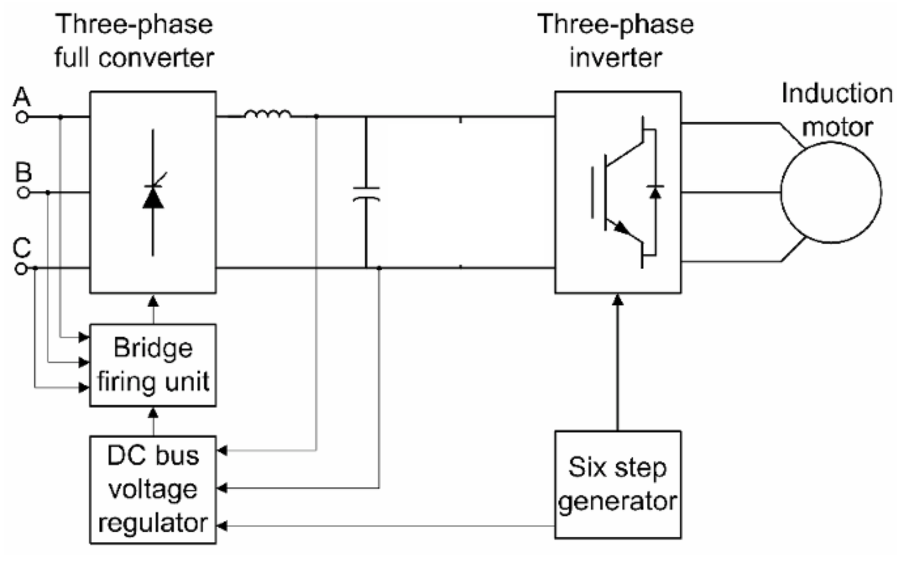


Fig. 5-7 Open loop scalar control

5-3-2 Closed Loop Scalar Control of Three Phase Induction Motor:

When accuracy in speed response is a concern, closed-loop speed control can be implemented with the constant v/f principle through the regulation of slip speed. A

PI controller is employed to regulate the slip speed of the motor to keep the motor speed at its set value. The closed-loop variant of the scalar V/Hz control is essentially the same as the open-loop version with the addition of a speed sensor input to the drive controller. Monitoring of this speed signal provides more accurate values for voltage and frequency, which in turn means better dynamic control and more accurate motor speeds. Torque control improves compared with open-loop controls, but does not approach the performance of a vector control in this regard.

The major blocks consist of a DC source, a three-phase inverter, and an induction motor with load. The speed loop error generates the slip speed command through the proportional–integral controller and limiter. The slip is added to the speed feedback signal to generate the slip frequency command, . The slip frequency command generates the voltage command through a Volts/Hz function generator. A detailed block diagram of a scalar V/Hz closed-loop control system appears in Fig. 5-8. From it, one can see the isolation between the gate drive of the MOSFETs in the inverter, the six (three differential-pair) PWM output signals from the control to the VFD, and the speed feedback signal(s) from the motor to the control system.

A step increase in slip frequency command produces a positive speed error and the slip speed command is set at the maximum value. The drive accelerates at the permissible inverter current, producing the maximum available torque, until the speed error is reduced to a very small value. The drive finally settles at a slip speed for which the motor torque balances the load torque.

A step decrease in slip frequency command produces a negative speed error. The slip speed command is set at the maximum negative value. The drive accelerates under regenerative braking; at the maximum permissible current and the maximum available breaking torque, until the speed error is reduced to a small value.

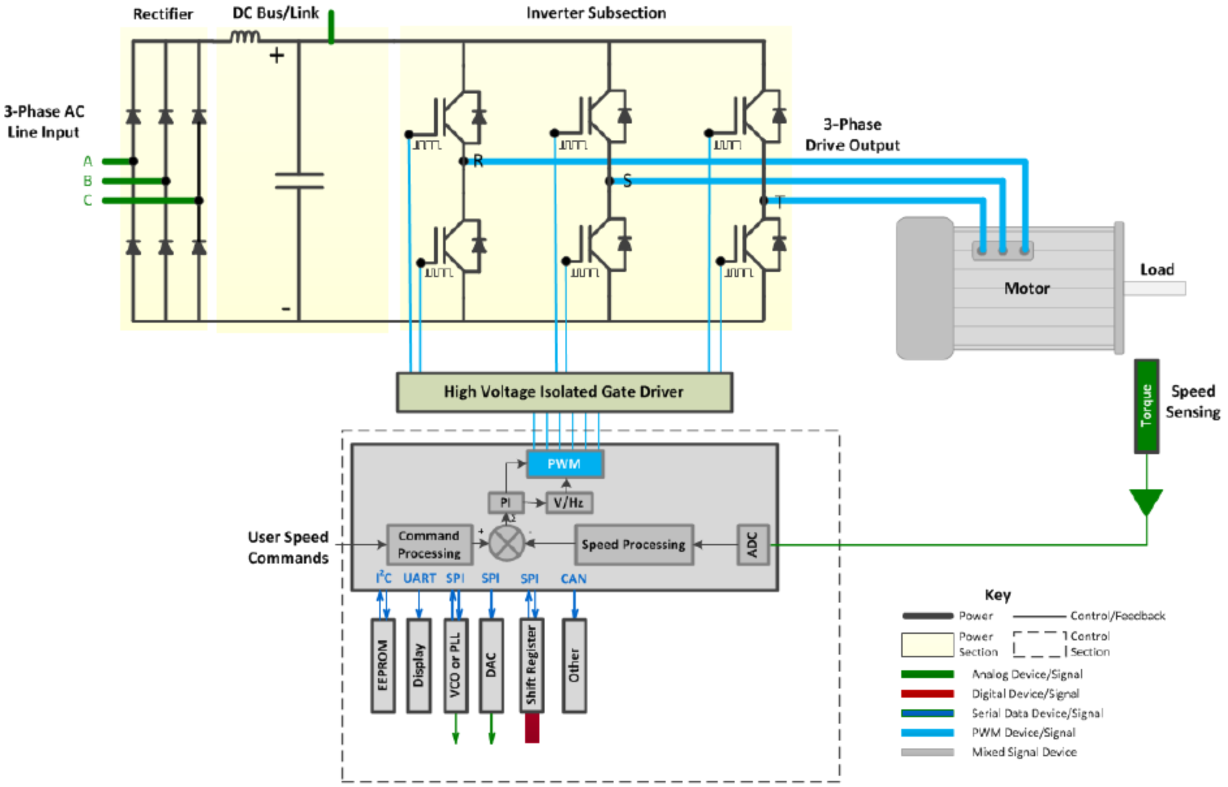


Fig. 5-8 scalar V/Hz closed-loop control system employs isolation between the control circuitry and the gate driver and also between the control circuitry and the speed sensor.

CHAPTER SIX

MATLAB SIMULATION AND ANALYSIS OF THE DRIVE SYSTEM

MATLAB (matrix laboratory) is a multi-paradigm numerical computing environment and proprietary programming language developed by MathWorks. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, C#, Java, Fortran and Python. The interface of this program can be seen in Fig. 6-1. Also, the Simulink interface can be seen in Fig. 6-2. It is a simulation and model-based design environment for dynamic and embedded systems. You can use Simulink to model a system and then simulate the dynamic behavior of that system. The basic techniques to create a simple model in this tutorial are the same as those you use for more complex models. integrated with MATLAB which enables you to export the simulation results into MATLAB for further analysis. Simulink, is a graphical programming environment for modeling, simulating, analyzing multi domain dynamical systems, automatic controlling and digital signal processing. In Simulink, systems are drawn on screen as block diagrams. Many elements of block diagrams are available, such as transfer functions, summing junctions, etc., as well as virtual input and output devices such as function generators and oscilloscopes. Simulink is integrated with MATLAB and data can be easily transferred between the programs.

Simulink is supported on Unix, Macintosh, and Windows environments; and is included in the student version of MATLAB for personal computers.

<u>6-1 Starting Simulink:</u>

Simulink is started from the MATLAB command prompt

>> Simulink

Alternatively, you can hit the New Simulink Model button at the top of the MATLAB command window

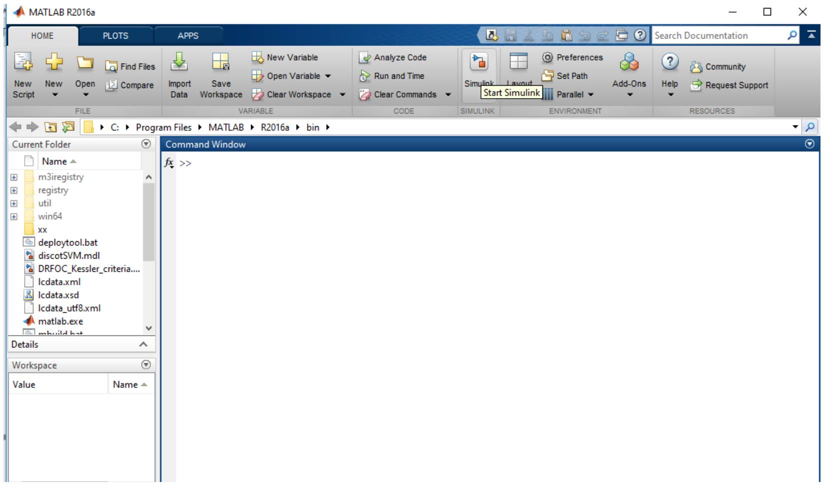


Fig. 6-1 Interface of MATLAB program

When it starts, Simulink brings up the main Simulink window When it starts, Simulink brings up the main Simulink window and a blank, untitled, model window. This is the window into which a new model can be drawn.

In Simulink, a model is a collection of blocks which, in general, represents a system.

There are two major classes of items in Simulink: blocks and lines.

Blocks are used to generate, modify, combine, output, and display signals. Lines are used to transfer signals from one block to another.

Blocks

There are several general classes of blocks:

1. Sources: Used to generate various signals
2. Sinks: Used to output or display signals

3. Discrete: Linear, discrete-time system elements (transfer functions, state-space models, etc.)
4. Linear: Linear, continuous-time system elements and connections (summing junctions, gains, etc.)
5. Nonlinear: Nonlinear operators (arbitrary functions, saturation, delay, etc.)
6. Connections: Multiplex, Demultiplex, System Macros, etc.

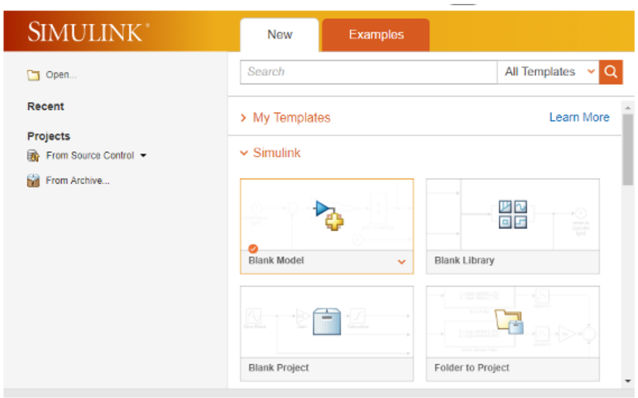


Fig. 6-2 MATLAB interface

Lines

Lines transmit signals in the direction indicated by the arrow.

Lines must always transmit signals from the output terminal of one block to the input terminal of another block.

One exception to this is a line can tap off of another line, splitting the signal to each of two destination blocks

6-2 Step by Step to Build the Simulink Models of This Project:

In this project, the molding of the three-phase induction motor, inverter and control units are built through the MATLAB Simulink for both open and closed loop controls under effect of different load conditions.

6-2-1 molding of the three-phase induction motor:

By helping of eqs. 3.12 to 3.22, the molding of the three-phase induction motor can be constructed inside MATLAB Simulink. Fig. 6-3 shows the overall model of the three-phase induction motor and the details of this model can be seen in Fig. 6-4.

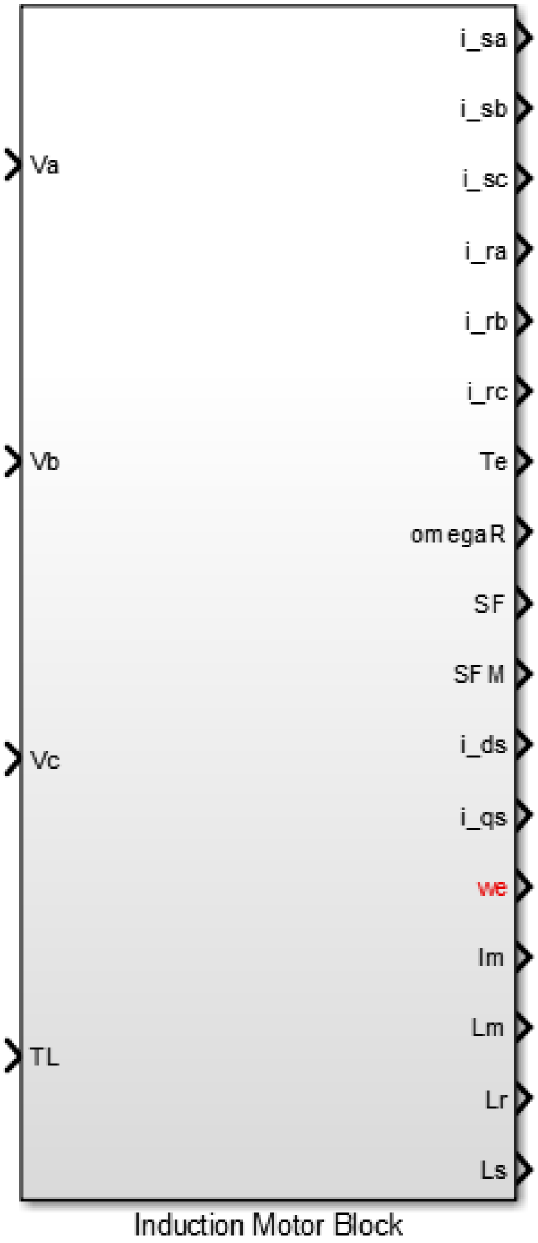


Fig. 6-3 The block of the three-phase induction motor overall

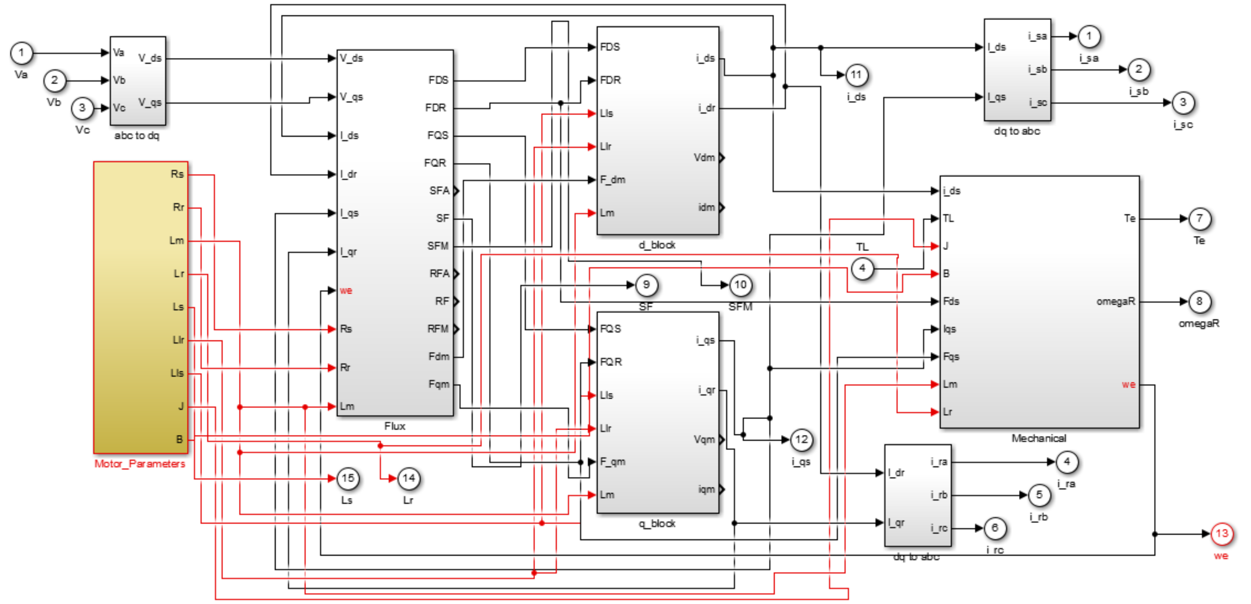


Fig. 6-4 Block details for the three-phase induction motor

This motor model can be tested in case of no load and full load at rated conditions.

<u>Firstly, at no load:</u>

When the motor running at no load, and feeding from sinusoidal supply, the motor current can be seen in Fig. 6-5. From this Fig can be concluded that, the stator current is about 40% of the rated current at steady.

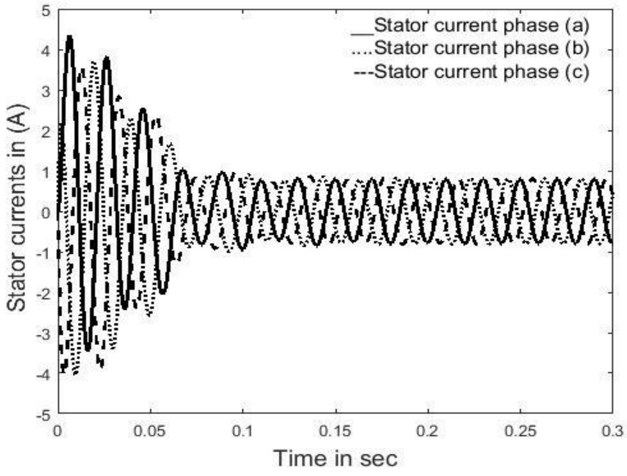


Fig. 6-5 The motor current at no load

The motor torque can be seen in Fig. 6-6. From this Fig can be concluded that,

The starting torque is high and reaches approximately zero due to no load is applied.

The motor speed can be seen in Fig. 6-7. From this Fig can be concluded that,

The motor reaches the rated speed.

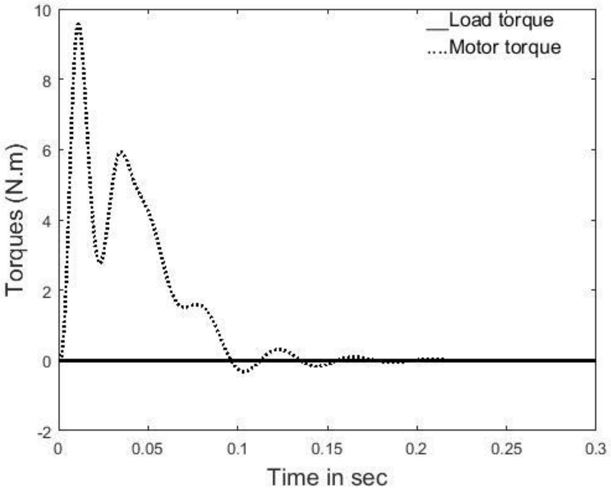


Fig. 6-6 The motor torque at no load

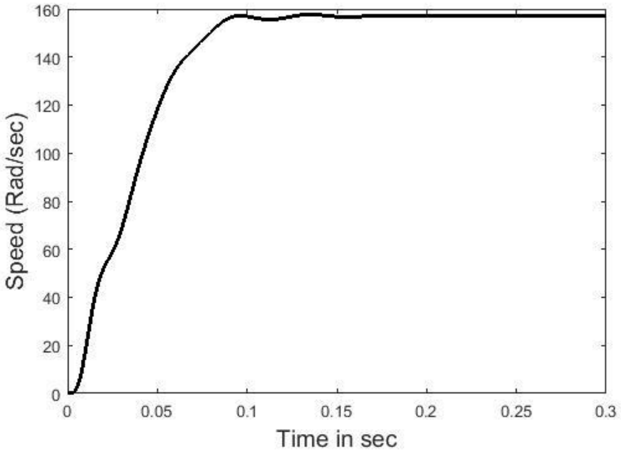


Fig. 6-7 The motor speed at no load

Secondly, at full load:

When the motor running at full load, the motor current can be seen in Fig. 6-8. From this Fig can be concluded that, The motor reaches the rated current due to use the rated load.

The motor torque can be seen in Fig. 6-9. From this Fig can be concluded that, the rated torque reaches the rated value.

The motor speed can be seen in Fig. 6-10. From this Fig can be concluded that, The motor reaches the rated speed.

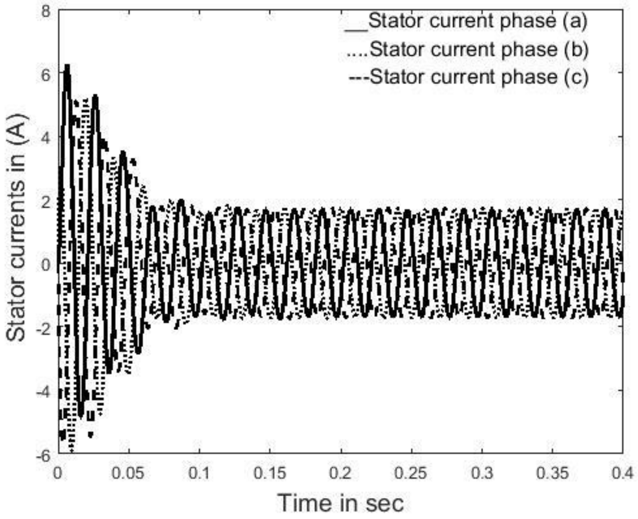


Fig. 6-8 The motor current at full load

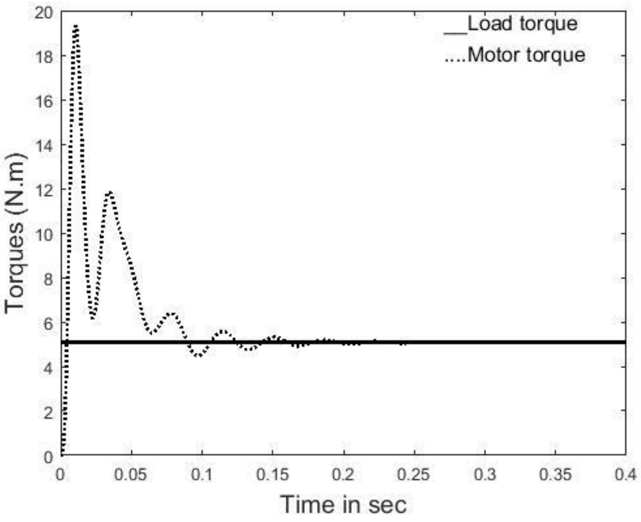


Fig. 6-9 The motor torque at full load

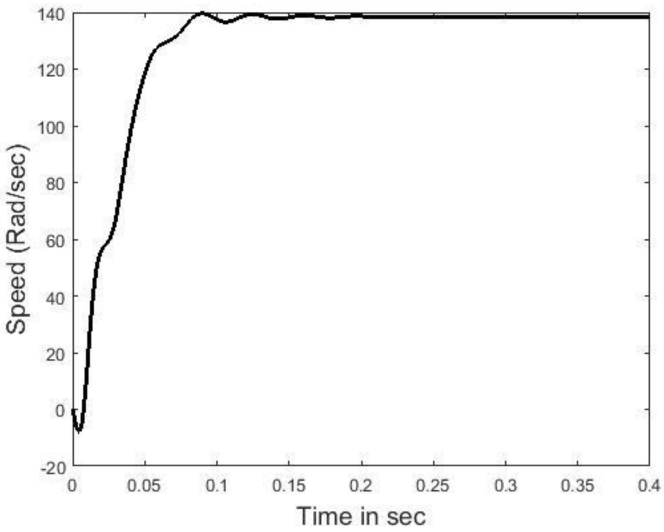


Fig. 6-10 The motor speed at full load

6-2-2 Simulation of six step voltage source inverter:

Fig. 6-11 shows simulating of six step voltage source inverter with R-L load. Six step inverter is built depending up on the analysis in the chapter four. The connections and power switches for six-step inverter can be seen through Fig. 6-12. To drive this inverter use the pulse generator. Fig. 6-13 shows inside the pulse generator and how it operates. Inside this model, the variable frequency can be generated with the variable frequency oscillator. The output of the frequency oscillator changes from two phase into three phase and carrier wave is compared to the three-phase generated to generate the main pulses to drive the inverter. Due to generate pulses and applying on the inverter, the output of inverter is applied on the R-L load. When this model is tested under R-L loading it is found that,

The output pulses which drive the inverter can be seen in Fig. 6-14 and in Fig. 6-15. in Fig. 6-14 we can see the shape and time of the pulse for the upper switch in phase A and Fig. 6-15 shows the shape and time of the pulse for the lower switch in the same phase (phase A). From these Figs. can be concluded that, these switches are complementary. This means that, when the upper switch is on the lower switch is off and vis versa.

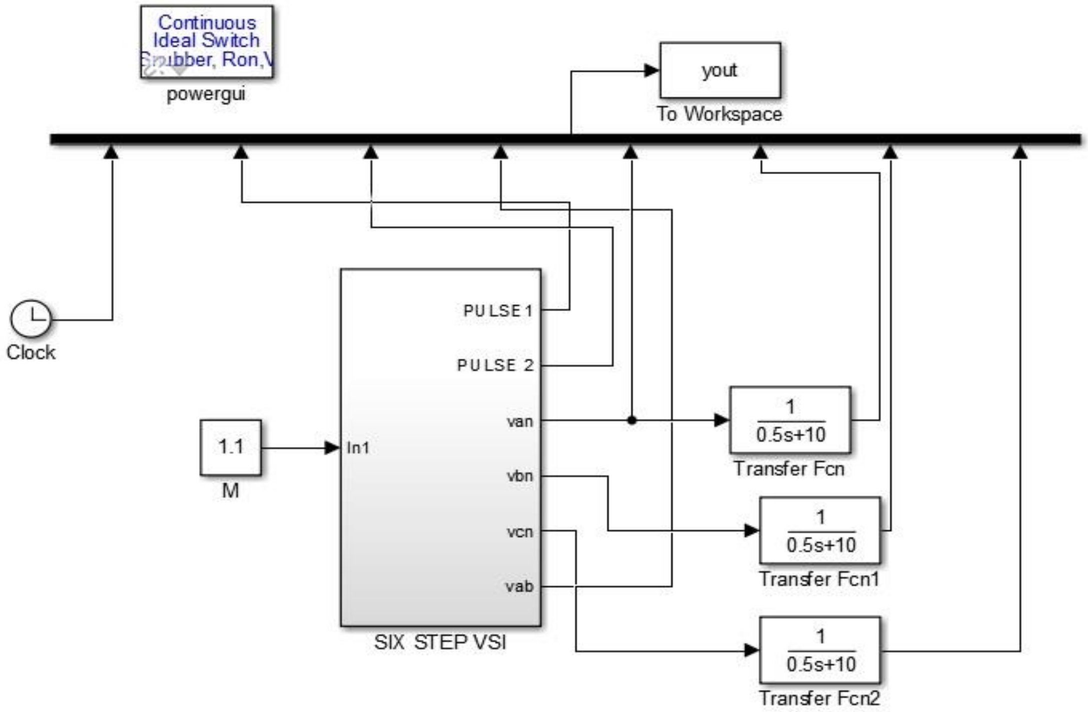


Fig. 6-11 Six step voltage source inverter with load

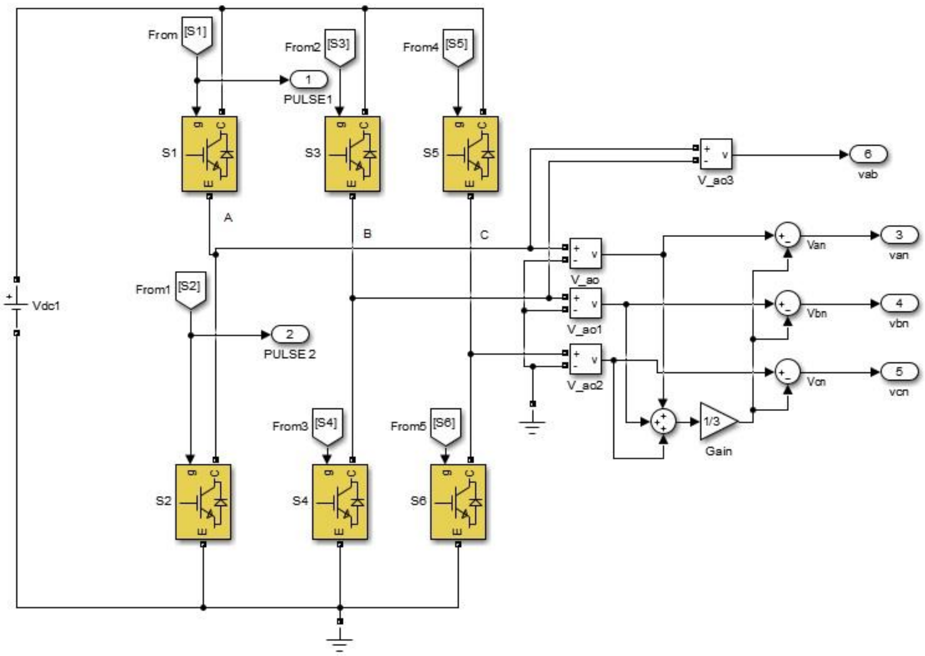


Fig. 6-12 Power switch and connections of inverter

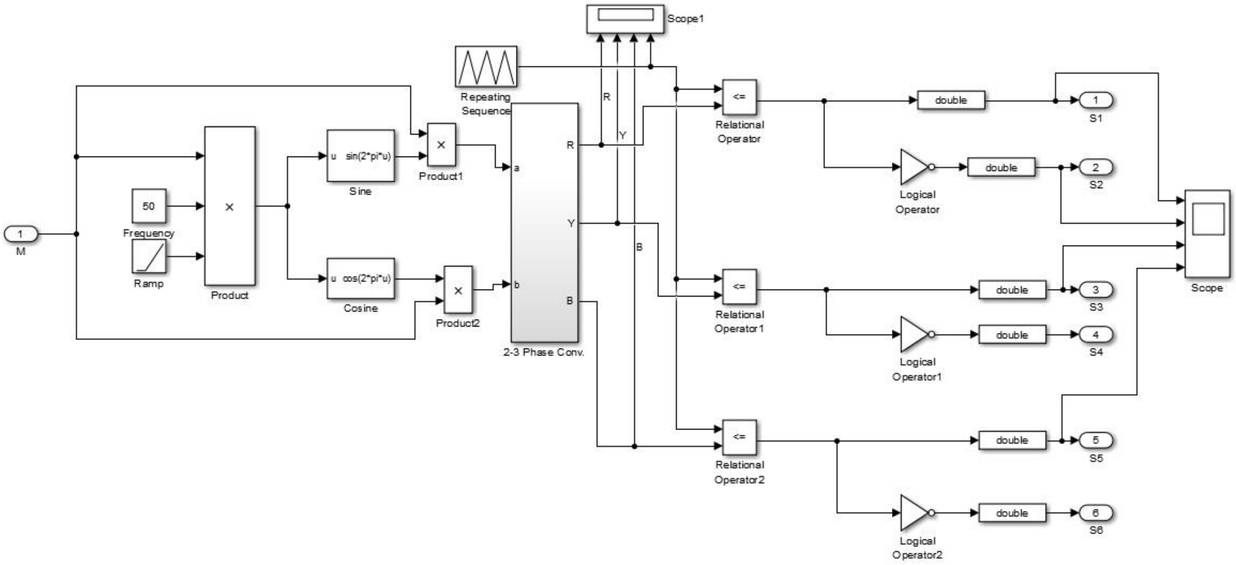


Fig. 6-13 Inside the pulse generator

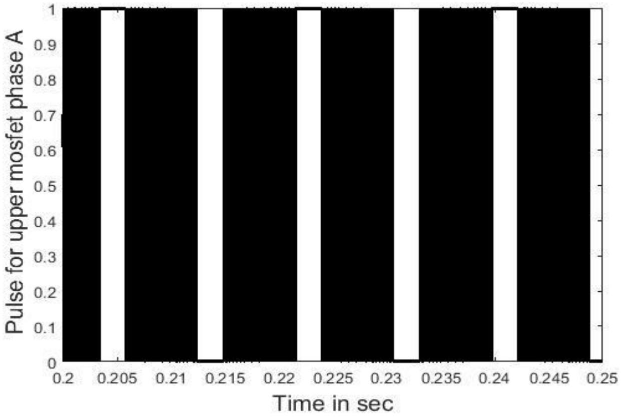


Fig. 6-14 The output pulse of upper switch phase A

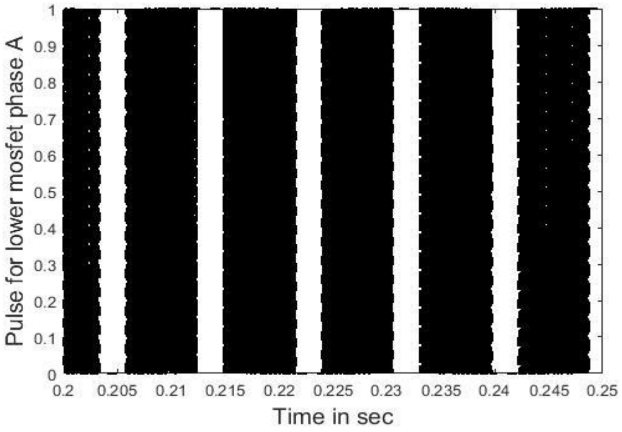


Fig. 6-15 The output pulse of lower switch phase A

The line to line output voltage of six step voltage source inverter can be seen in Fig. 6-16. This voltage has square wave due to this voltage is the difference between any two-phase voltages. Also, the phase voltage can be seen in Fig. 6-17 where this voltage has six step so, this method is called six step voltage source inverter. The load current can be seen in Fig. 6-18. This load current has sinusoidal shape due to apply R-L load.

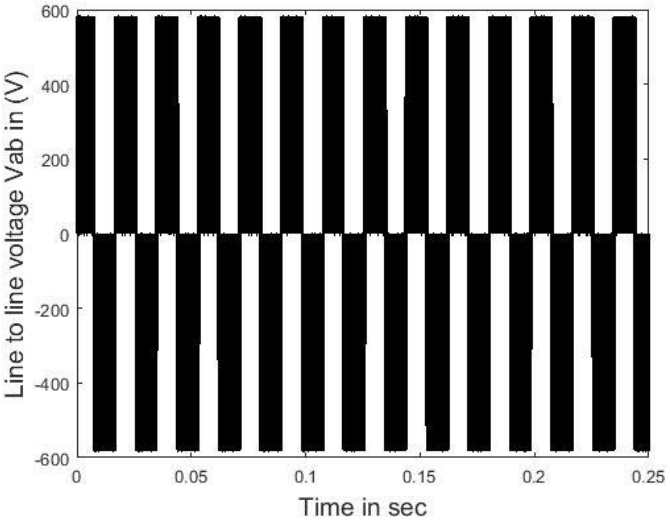


Fig. 6-16 The line to line output voltage

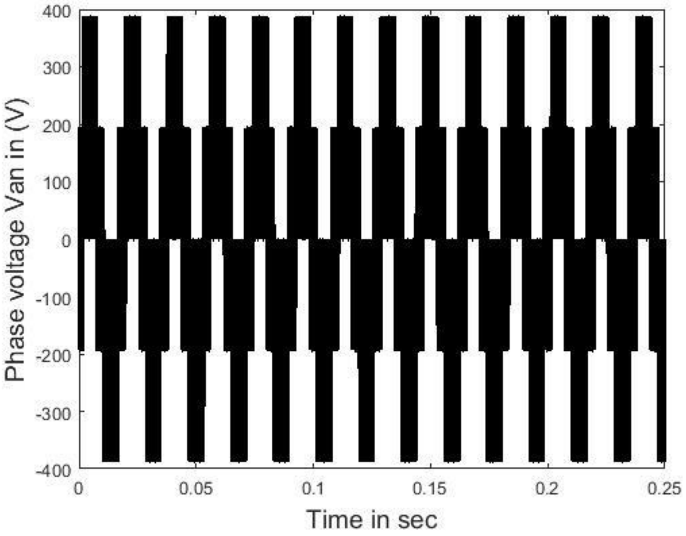


Fig. 6-17 The line to neutral output voltage

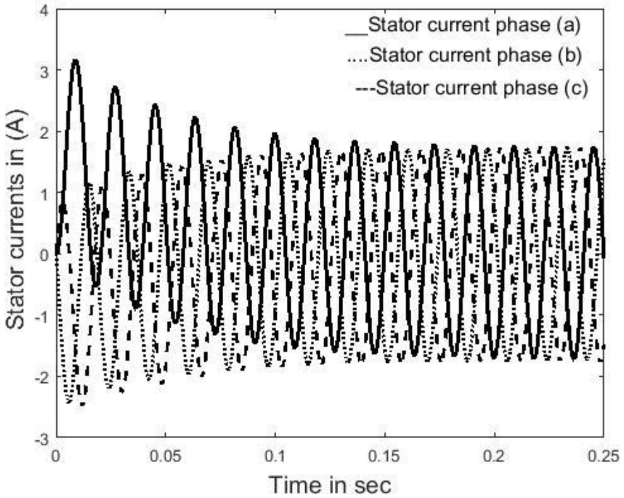


Fig. 6-18 The load current

6-3 Simulation of the Open Loop Control Three Phase Induction Motor Via Six Step Voltage Source Inverter:

Fig. 6-19 shows overall system which is used to simulate the project after connected the six-step inverter with the three-phase induction motor model. This system is simulated at different loads. These loads are constant load and fan load. The performance characteristics of the three-phase induction motor with each load are discussed in the following paragraphs.

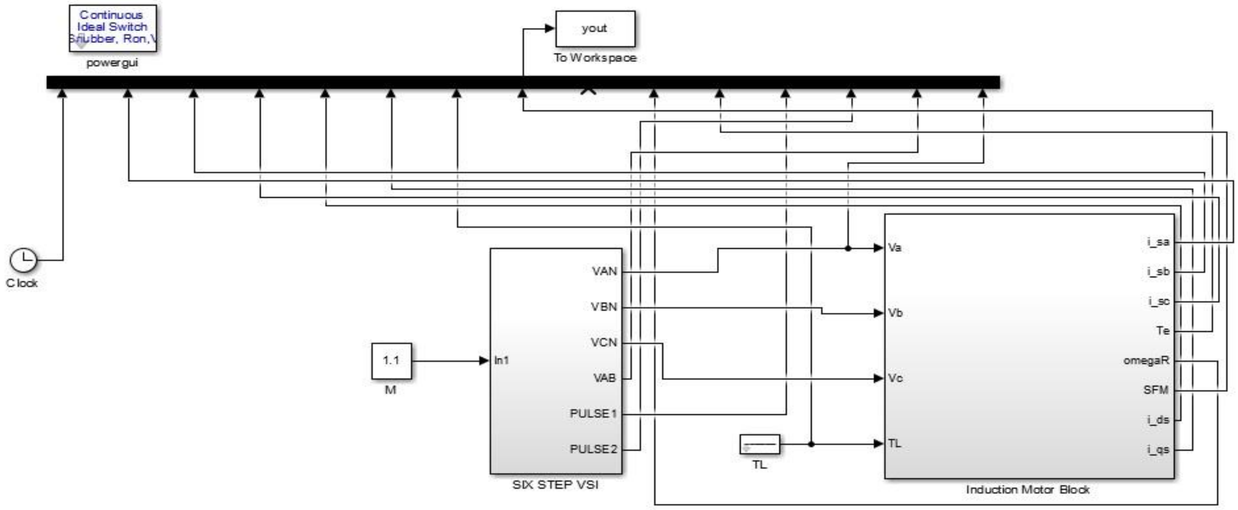


Fig. 6-19 Overall simulation system

6-3-1 Simulation of the system under constant load:

The performance characteristics of the three-phase induction motor when fed from six step voltage source inverter under constant load and open loop control are discussed here. Fig. 6-20 shows the shape of the upper pulse of phase A where complementary pulse of the same phase can be seen in Fig. 6-21.

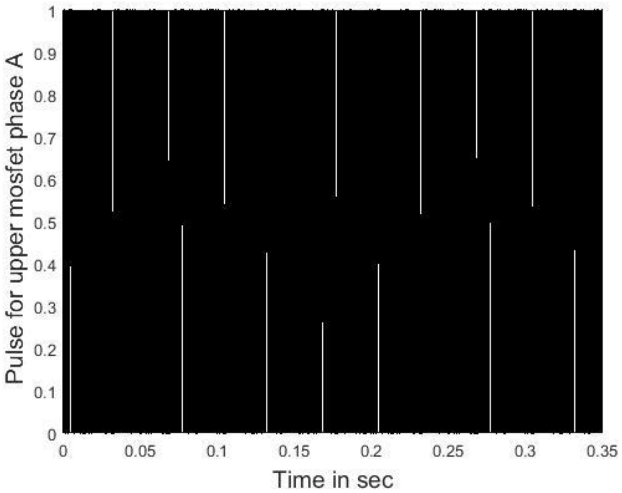


Fig. 6-20 The output pulse of upper switch phase A

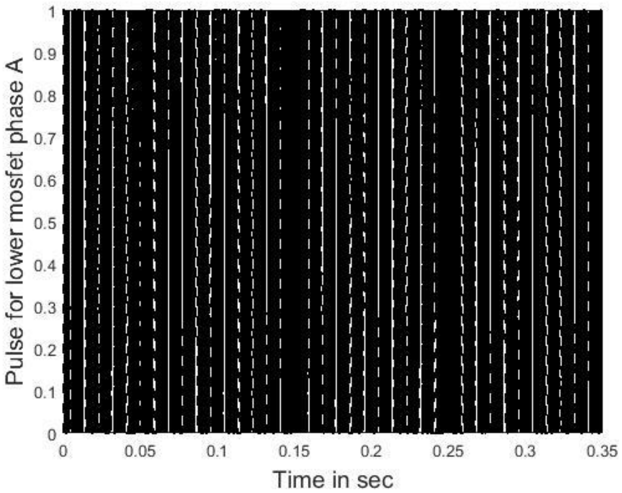


Fig. 6-21 The output pulse of lower switch phase A

Fig. 6-22 shows the shape of the line voltage at constant load due to apply the pulses

Fig. 6-23 shows the shape of the phase voltage at constant load due to apply the pulses.

Fig. 6-24 shows the shape of the motor current at constant load. The motor current here means the stator current. From this Fig can be concluded that, the starting current is acceptable if it is compared to the steady state.

Fig. 6-25 shows the motor torque compared to load torque where it is found that;

The motor torque reaches steady state at 0.2 sec. the motor torque has high ripples due to more harmonics in the stator currents.

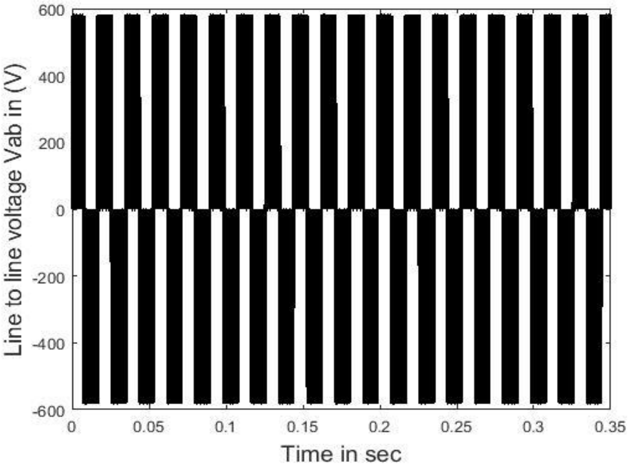


Fig. 6-22 The line to line output voltage

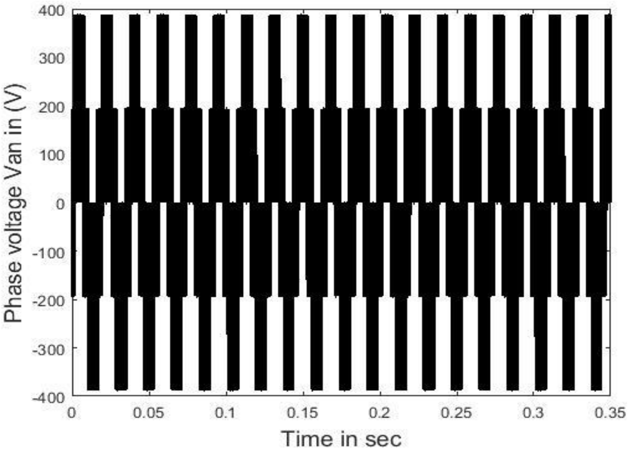


Fig. 6-23 The line to neutral output voltage

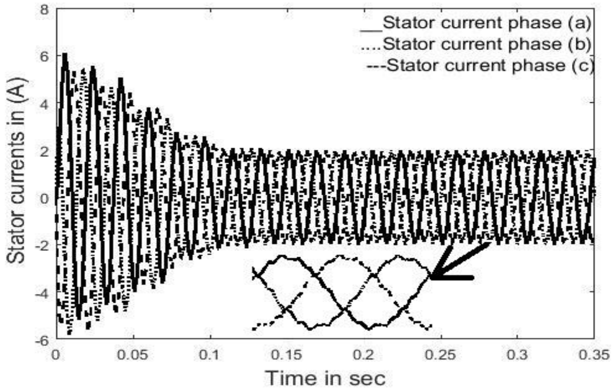


Fig. 6-24 The motor current

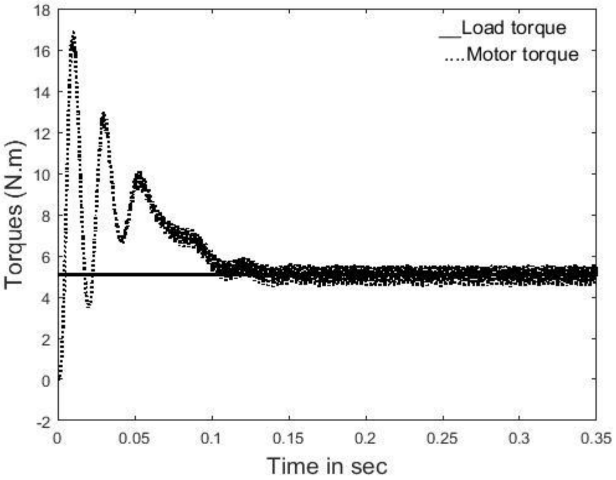


Fig. 6-25 The motor torque versus load torque

Fig. 6-26 shows the shape of the motor speed at constant load where it is found that, the motor reaches to steady state ate 0.25 sec.

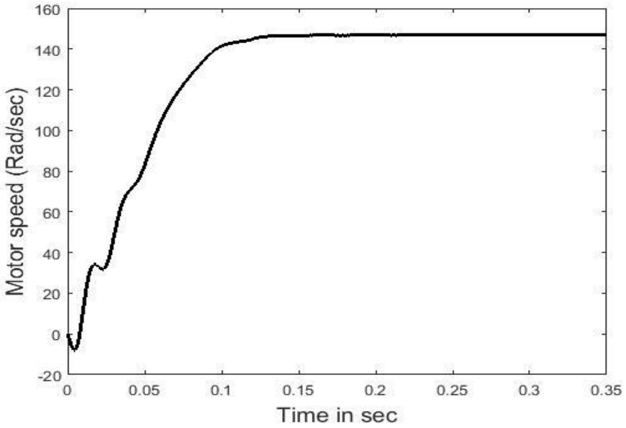


Fig. 6-26 the motor speed

6-3-2 Simulation of the system under fan load:

Fan load is chosen because it is a wide spread load. It used in many industrial applications. By studying the performance characteristics of the three-phase induction motor under fan load it is found that,

Fig. 6-27 shows the shape of the motor current under effect of fan load. From this Fig can be concluded that,

At starting, the motor starting current is approximately reached three times of the rated motor current and this ratio is acceptable value. After that, the motor current is decreased and closed to the rated value at 0.1 sec.

The motor torque compared to load torque can be seen in Fig. 6-28 where it is found that,

At starting the motor torque is at zero because the load depends upon the squared of the motor speed and firstly the motor speed is zero. The maximum motor torque reaches three times of the rated torque. it reaches steady state at 0.1 second.

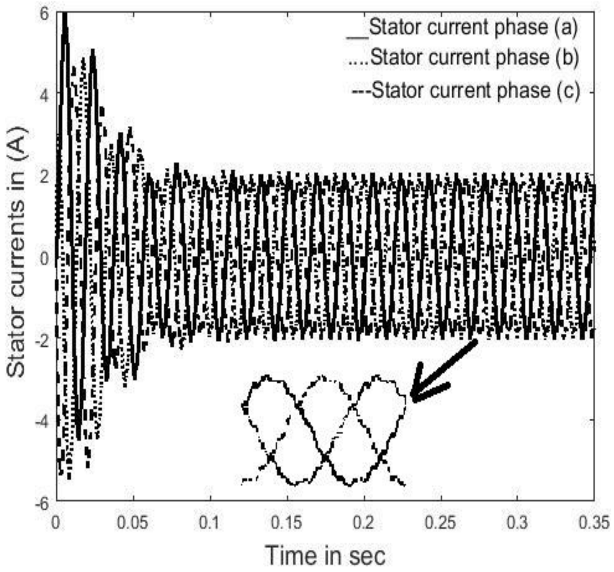


Fig. 6-27 The variation of the stator current with fan load

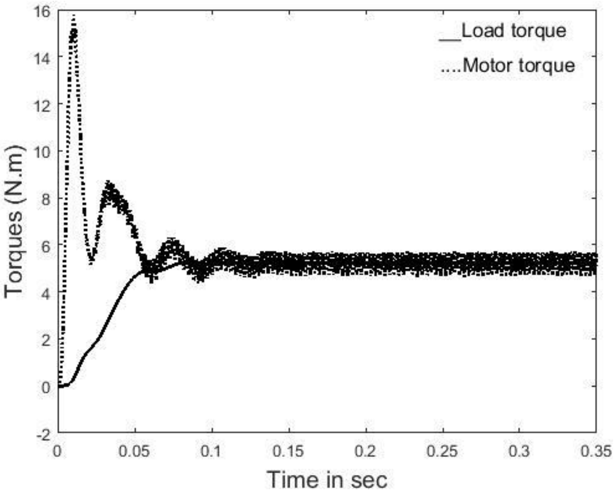


Fig. 6-28 The motor torque compared to fan load

The motor speed can be seen in Fig. 6-29 where it is found that,

The motor speed increases gradually and reaches steady state 0.1 second.

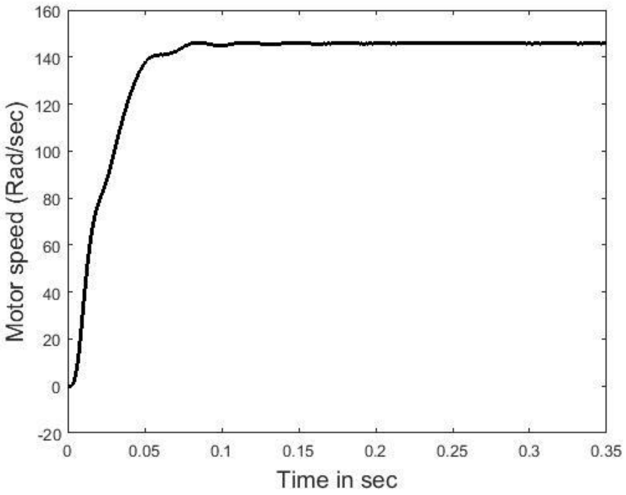


Fig. 6-29 The variation the motor speed with fan load

6-4 Simulation of The Closed Loop Control for The Six Step Three Phase Voltage Source Inverter of The Three Phase Induction Motor:

In this simulation, the closed system can be seen in Fig. 6-30. This system consists of mechanical load, induction motor, inverter, control circuit and AC power supply.

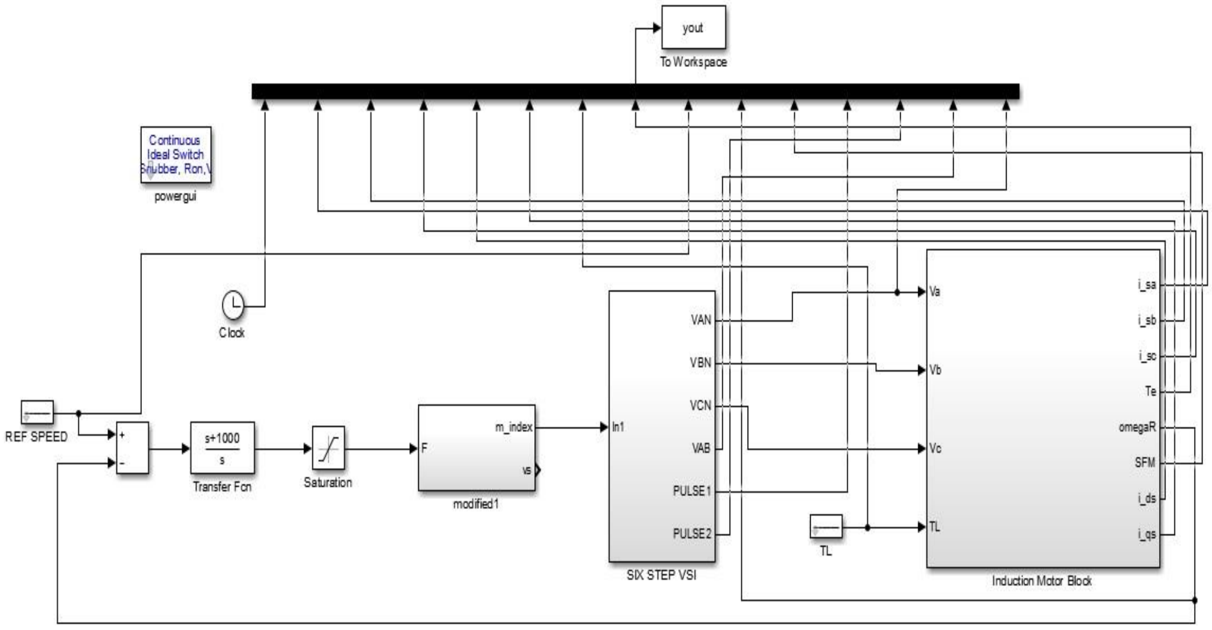


Fig. 6-30 The simulating closed system

Two loads are studied through the MATLAB simulation. The first load under study is a constant load and the second load is a fan load. In this simulation, the reference speed is compared to the actual speed and the error is introduced to PI controller. The output controller is used to generate the frequency of inverter. To limit this frequency, a limiter is used from MATLAB tools. The output of this limiter is used to generate modulation index. The medullation index is used to generate the pulses through variable frequency oscillator. The following sections shows effect of these loads on the motor performance.

6-4-1 Simulation of the system under constant load:

Fig. 6-31 shows the shape of the motor current at constant load. From this Fig can be concluded that,

At starting, the motor current reaches less than three times of the steady state motor current. At 0.05 second, the motor current is decreased closed to steady state value. At 0.08 second, the motor current reaches to the steady state value.

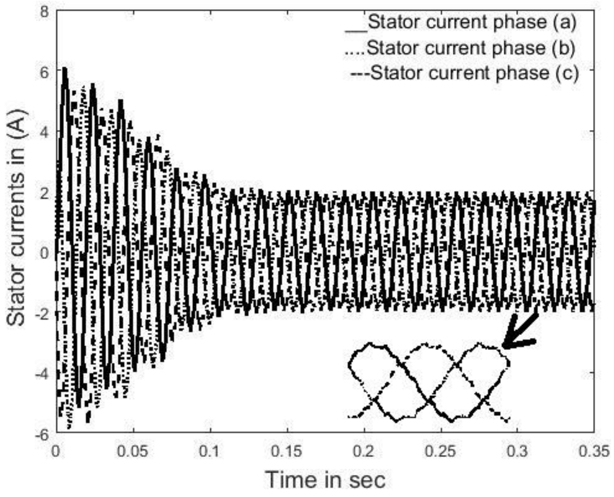


Fig. 6-31 The motor current

The motor torque compared to load torque can be seen in Fig. 6-32 where it is found that,

At starting the motor torque reaches three times of rated torque. it reaches steady state at 0.1 second.

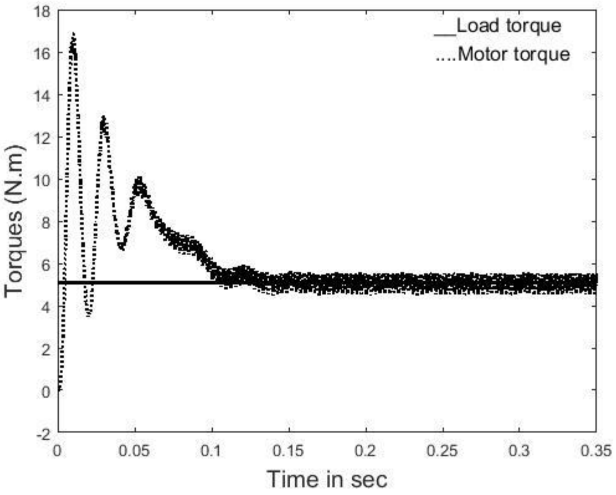


Fig. 6-32 The motor torque versus the load torque

The motor speed can be seen in Fig. 6-33 where it is found that,

The motor speed reaches to steady state at 0.1 second.

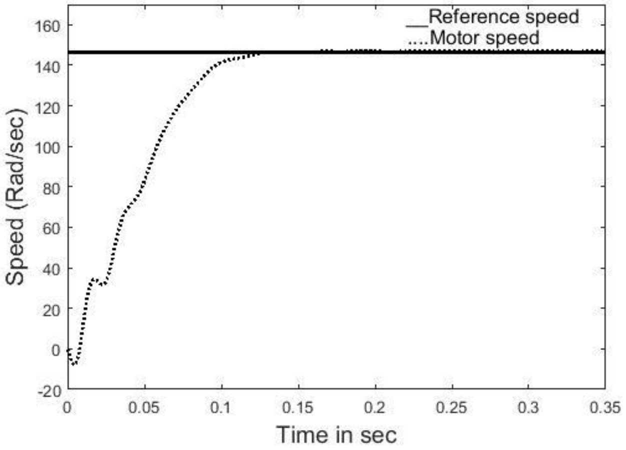


Fig. 6-33 The motor speed

6-4-2 Simulation of the system under fan load:

Fan load is chosen because it is a wide spread load. It used in many industrial applications. By studying the performance characteristics of the three-phase induction motor under fan load it is found that,

Fig. 6-34 shows the shape of the motor current under effect of fan load. From this Fig can be concluded that, at starting, the motor current is approximately reached three times of the rated motor current. At 0.05 second, the motor current is decreased and closed to the rated value. At 0.07 second, the motor current reaches to the steady state value.

The motor torque compared to load torque can be seen in Fig. 6-35 where it is found that, at starting the motor torque is at zero because the load depends upon the squared of the motor speed. The maximum motor torque reaches three times of the rated torque. it reaches steady state at first and half second.

The motor speed can be seen in Fig. 6-36 where it is found that, the motor speed reaches to steady state at 0.07 second.

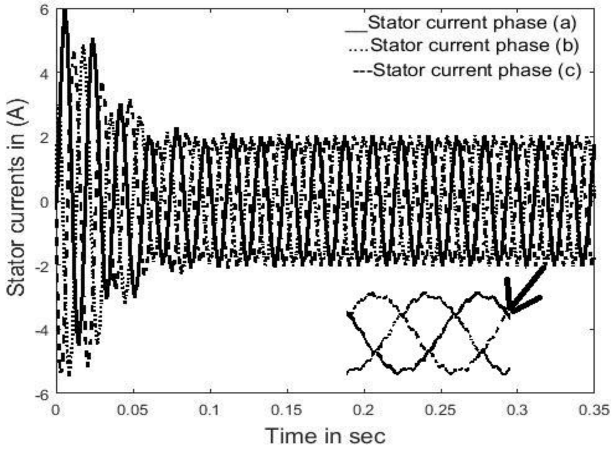


Fig. 6-34 The motor current

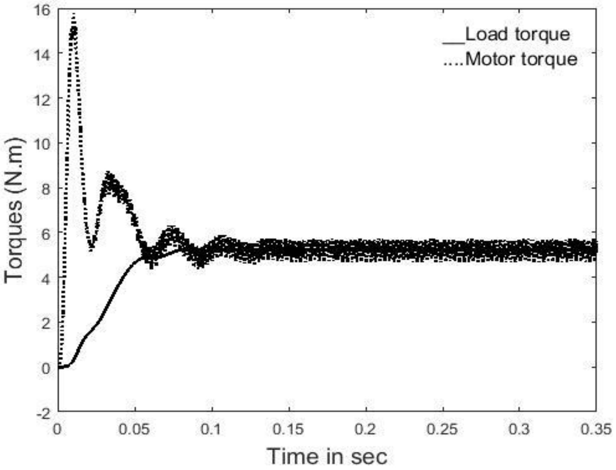


Fig. 6-35 The motor torque versus the load torque

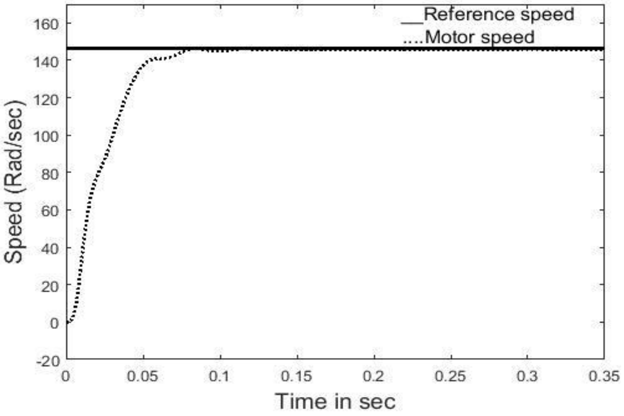


Fig. 6-36 The motor speed

CHAPTER SEVEN

HARDWARE CONFIGURATION SOFTWARE PROGRAM AND EXEPRIMENTAL RESULTS

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

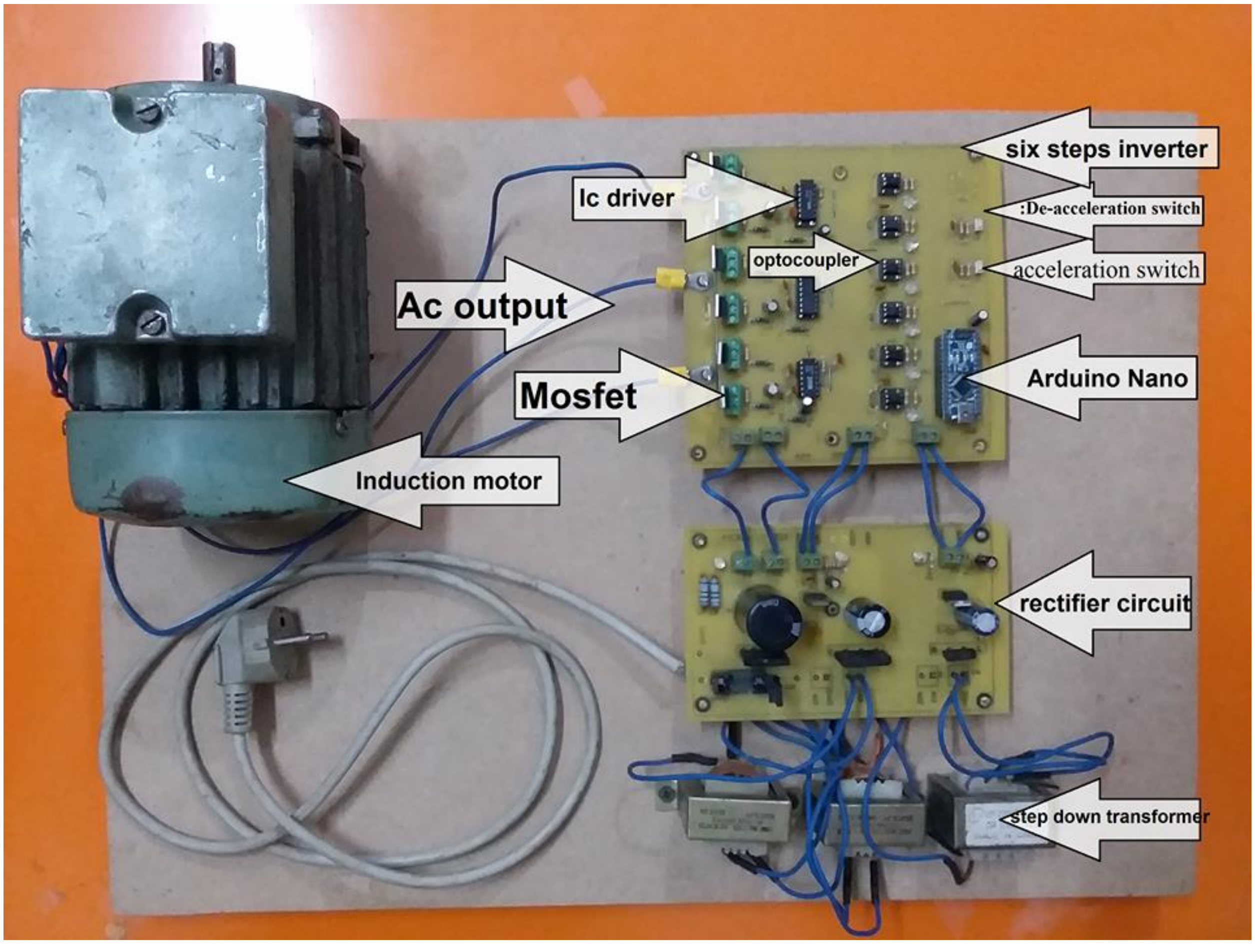


Fig. 7-1The hardware overall

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.

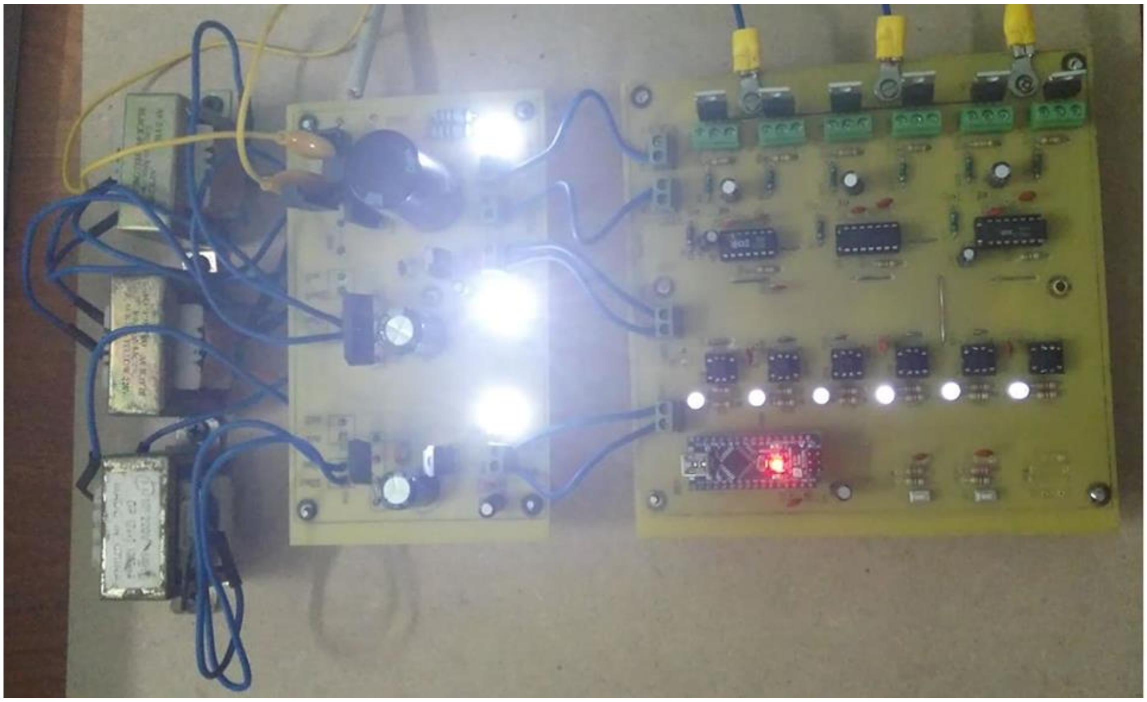


Fig. 7-2 The overall electronic circuits of the project

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;

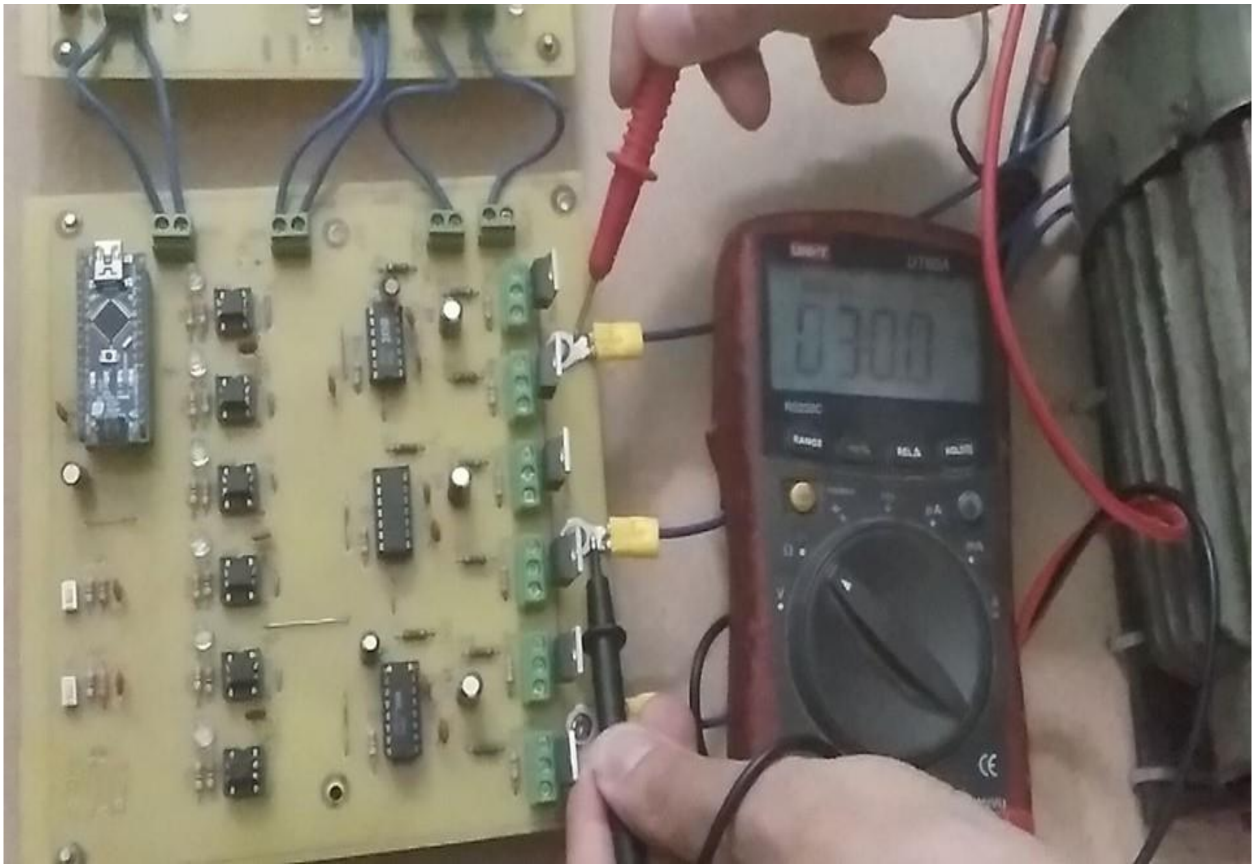


Fig. 7-5 The inverter circuit

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.

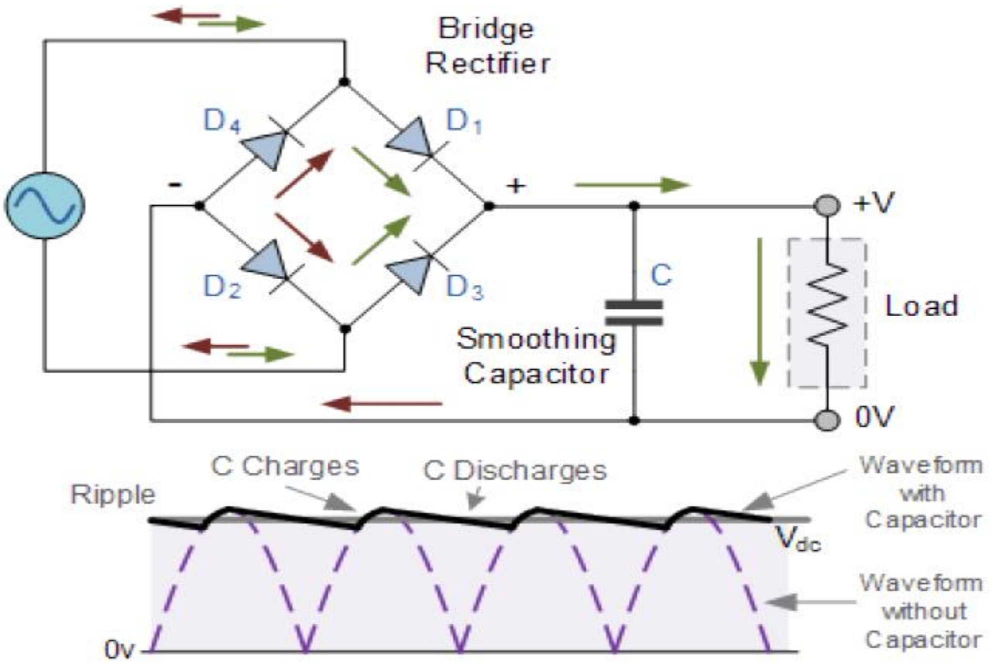


Fig. 7-6 The main rectifier circuit in the first PCB

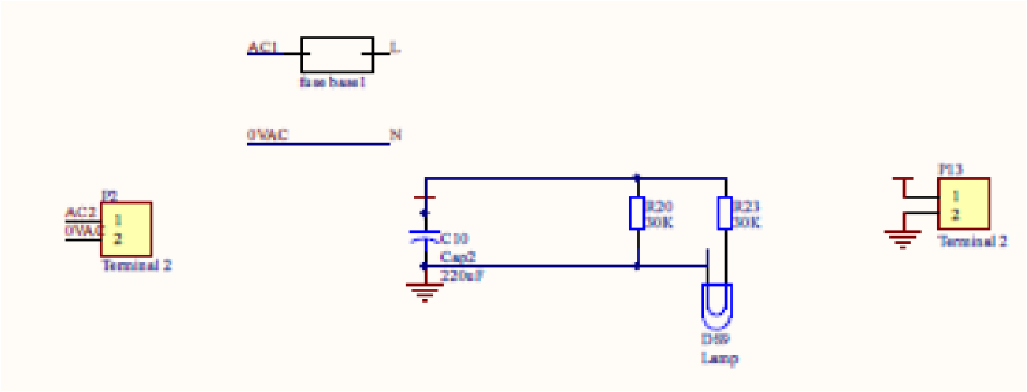


Fig. 7-7. The stigmatic of the main rectifier circuit in the first PCB

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.

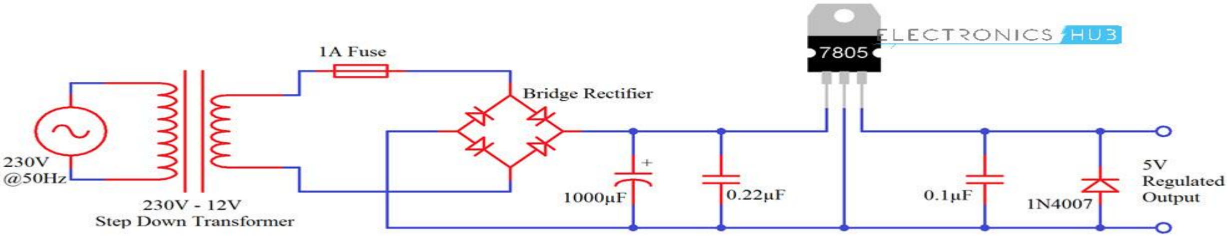


Fig. 7-8 The rectifier circuit to drive the microcontroller

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.

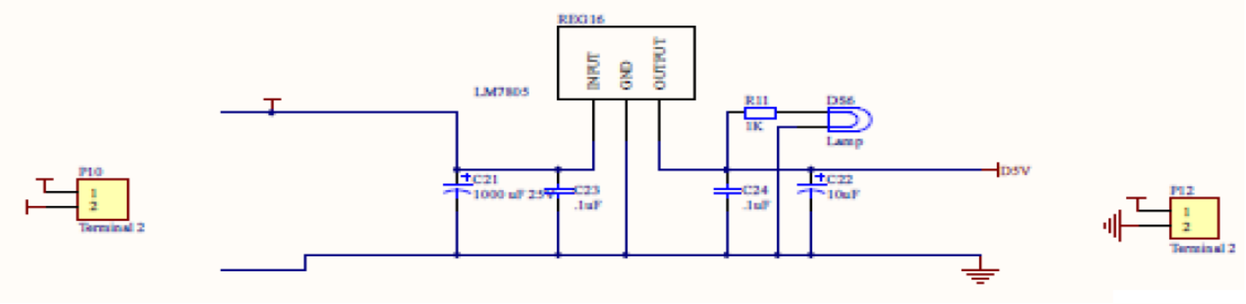


Fig. 7-9 The stigmatic from Altium program of the rectifier circuit that drive the Arduino

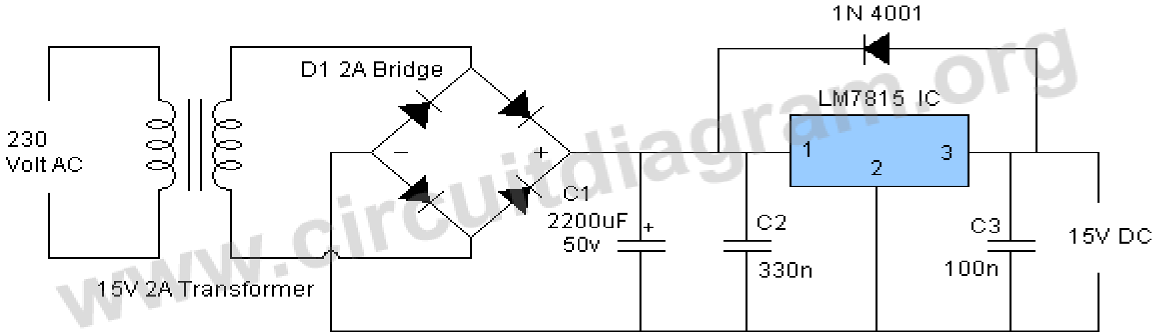


Fig. 7-10 The rectifier circuit to drive the other component in the second PCB

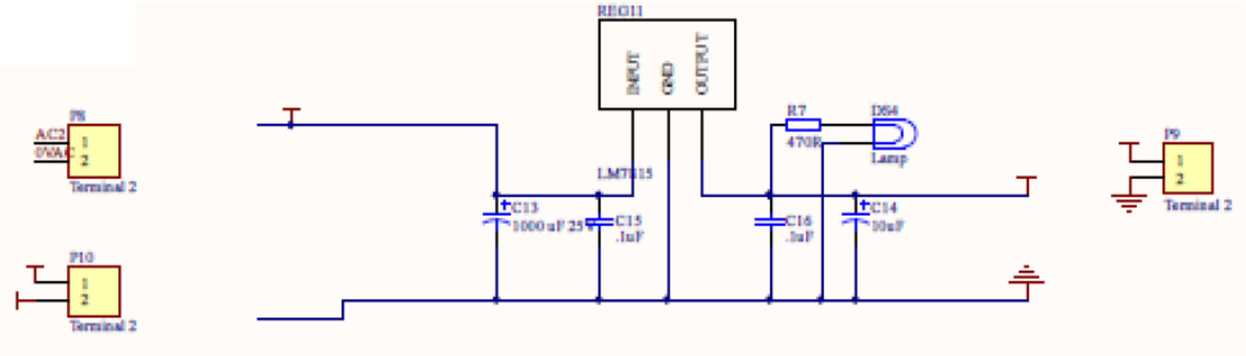


Fig. 7-11 The stigmatic from Altium program of the rectifier circuit that drive the other component in the second PCB

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;

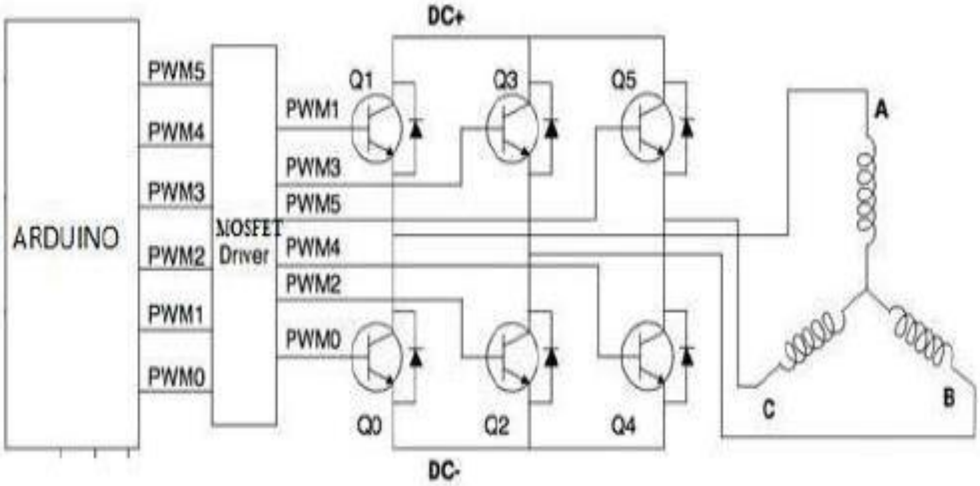


Fig. 7-12 Block diagram of the PCB two

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.

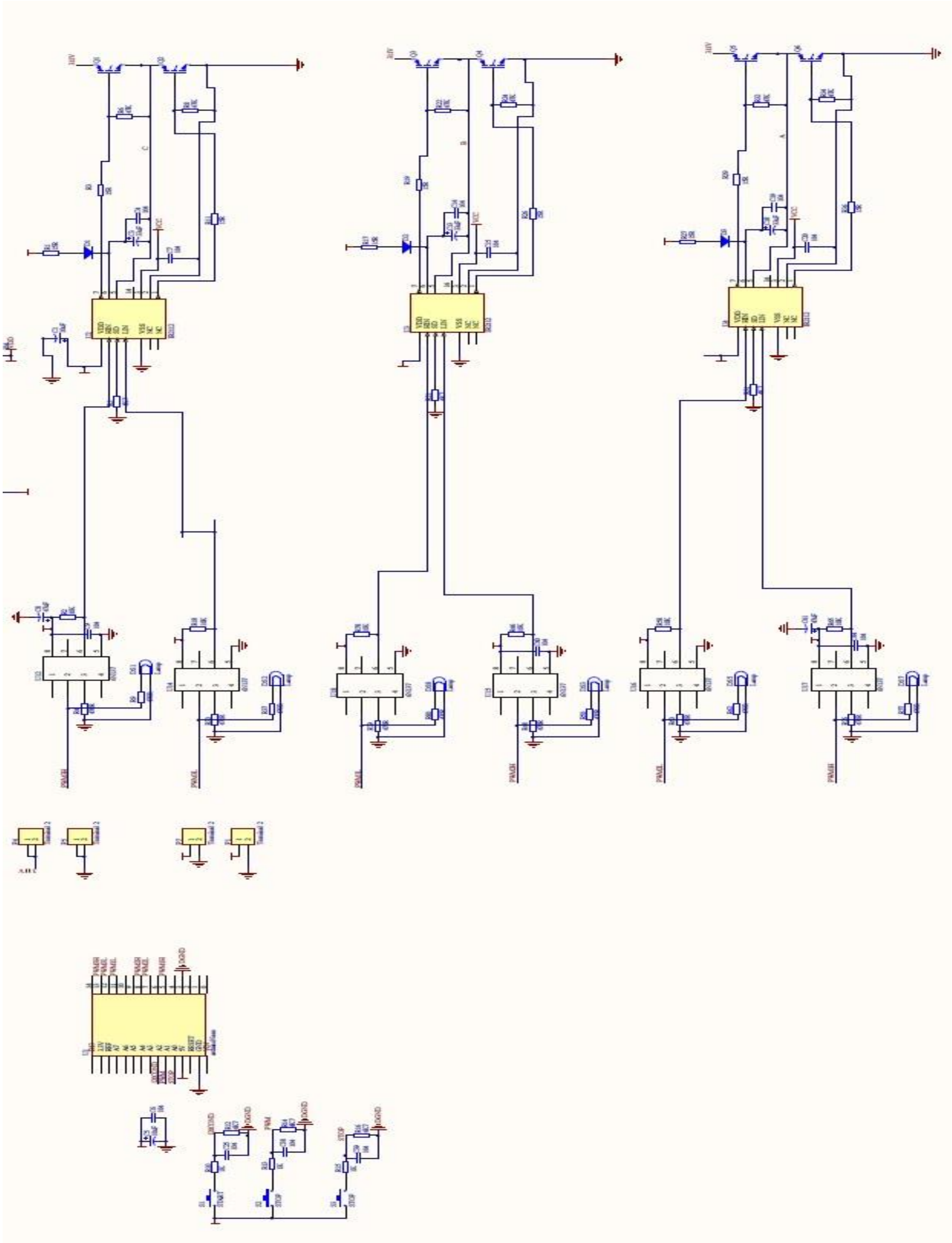


Fig. 7-13 The stigmatic of the second PCP through the Altium program

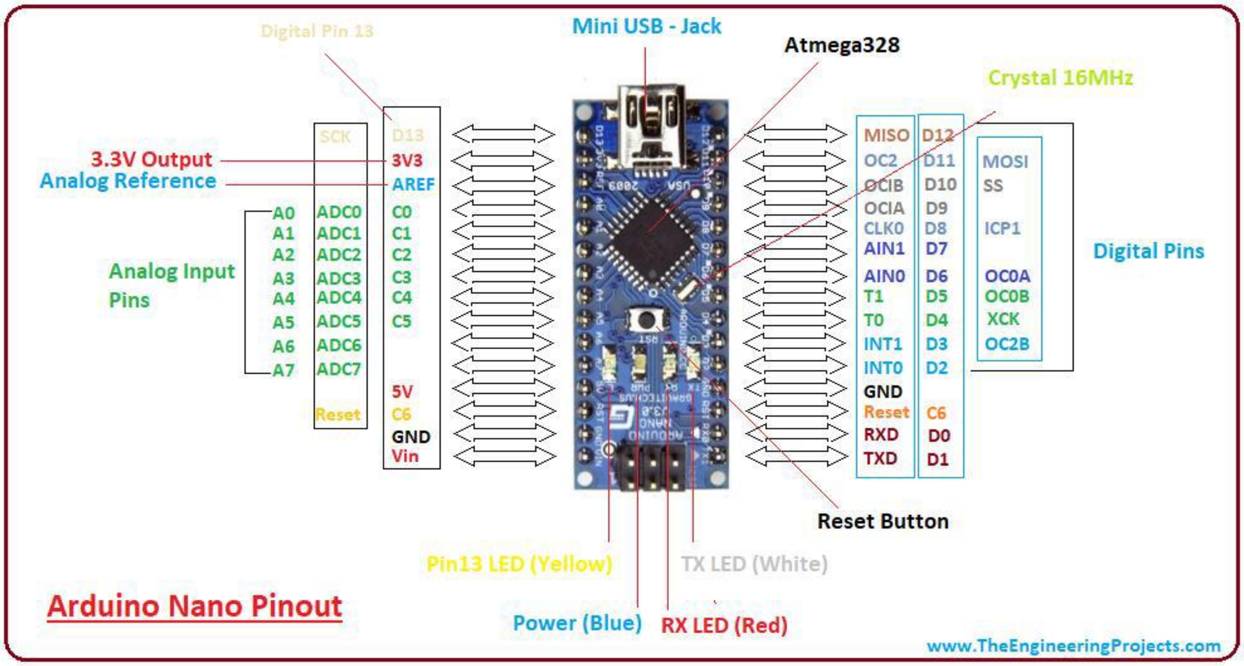


Fig. 7-14 The pinout of Arduino Nano

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.

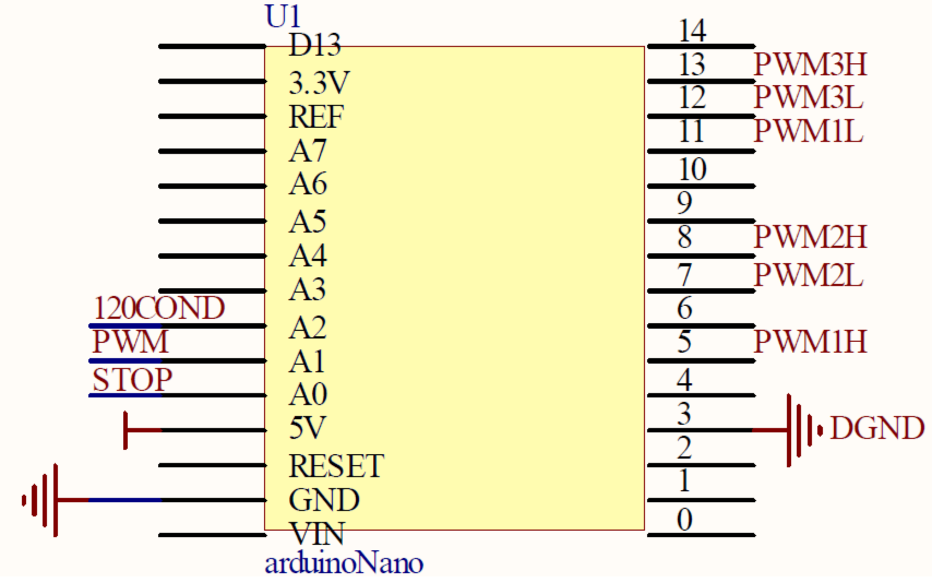


Fig. 7-15 Legs used through the Altium program

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.

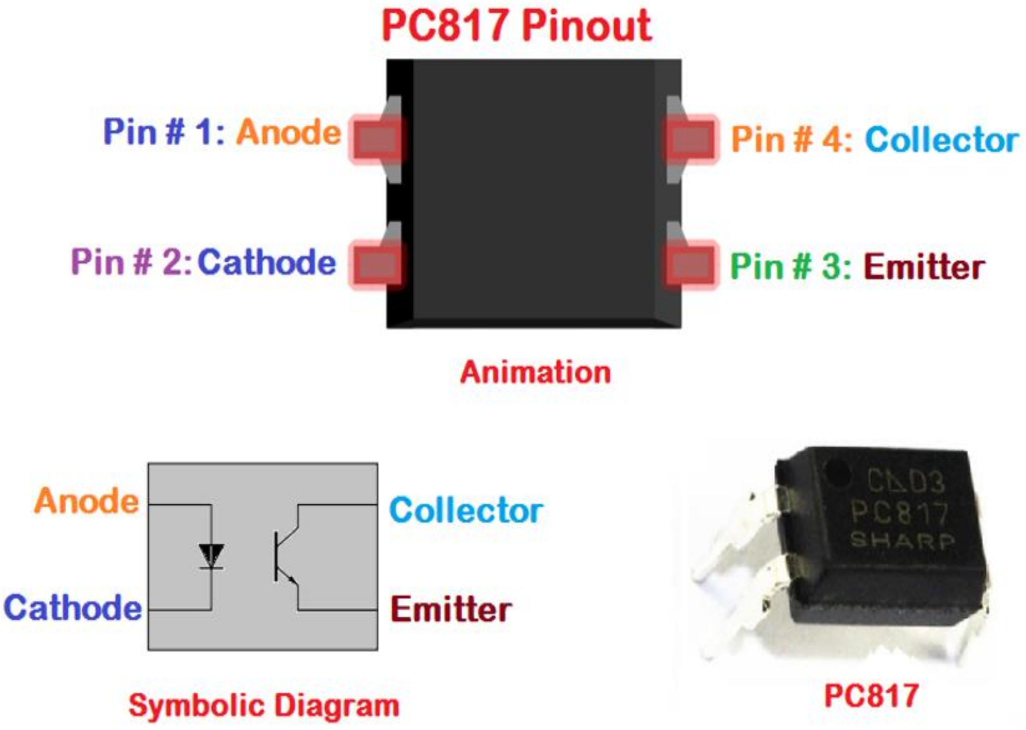


Fig. 7-16 The optocoupler and the animation of the optocoupler

<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.

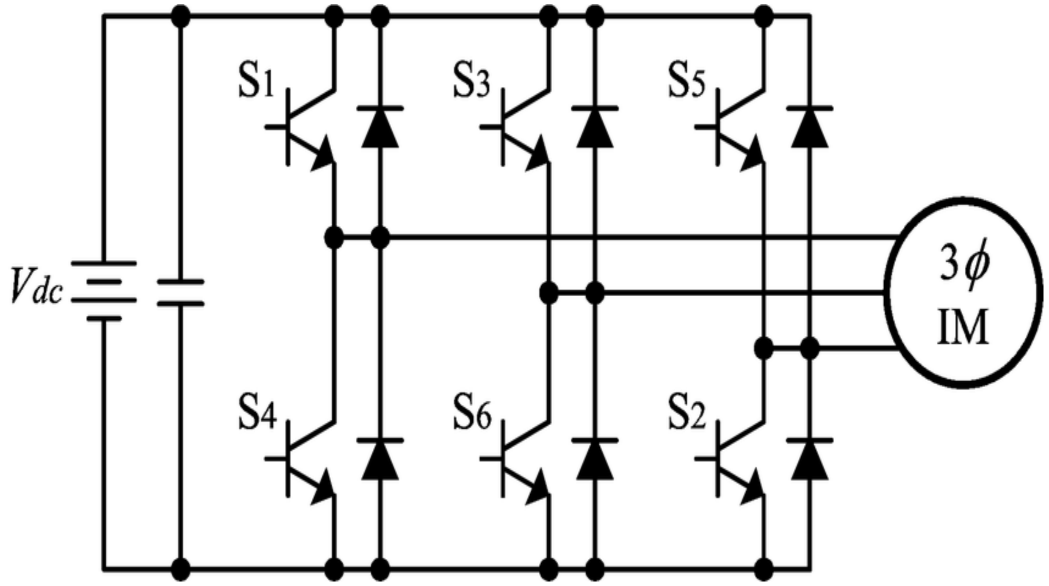


Fig. 7-17 Six step power circuit of inverter

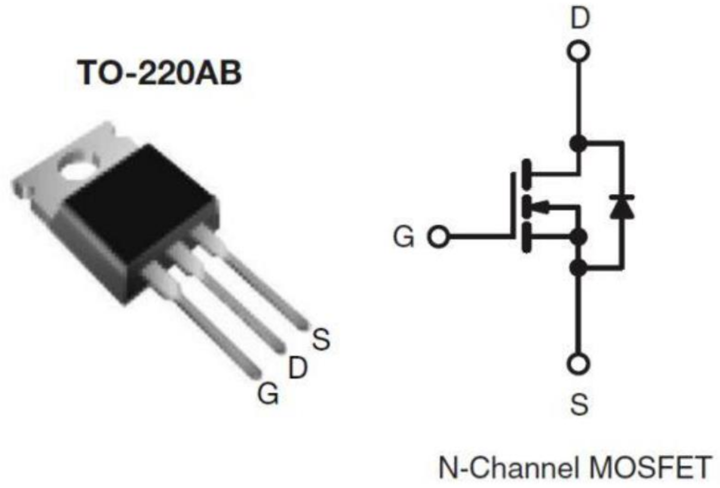


Fig. 7-18 The package of this MOSFET

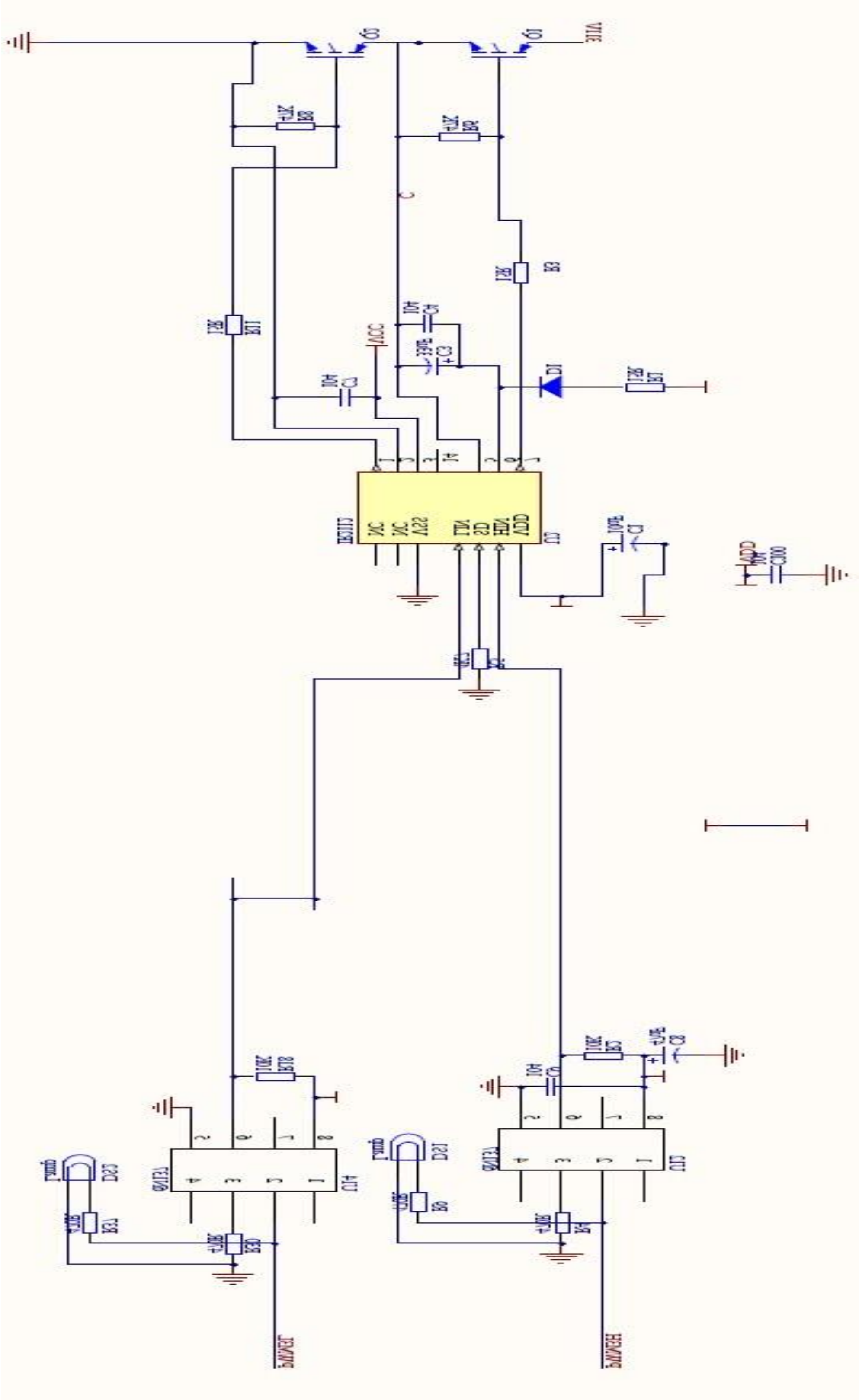


Fig. 7-19 The overall drive circuit including the optocoupler

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.

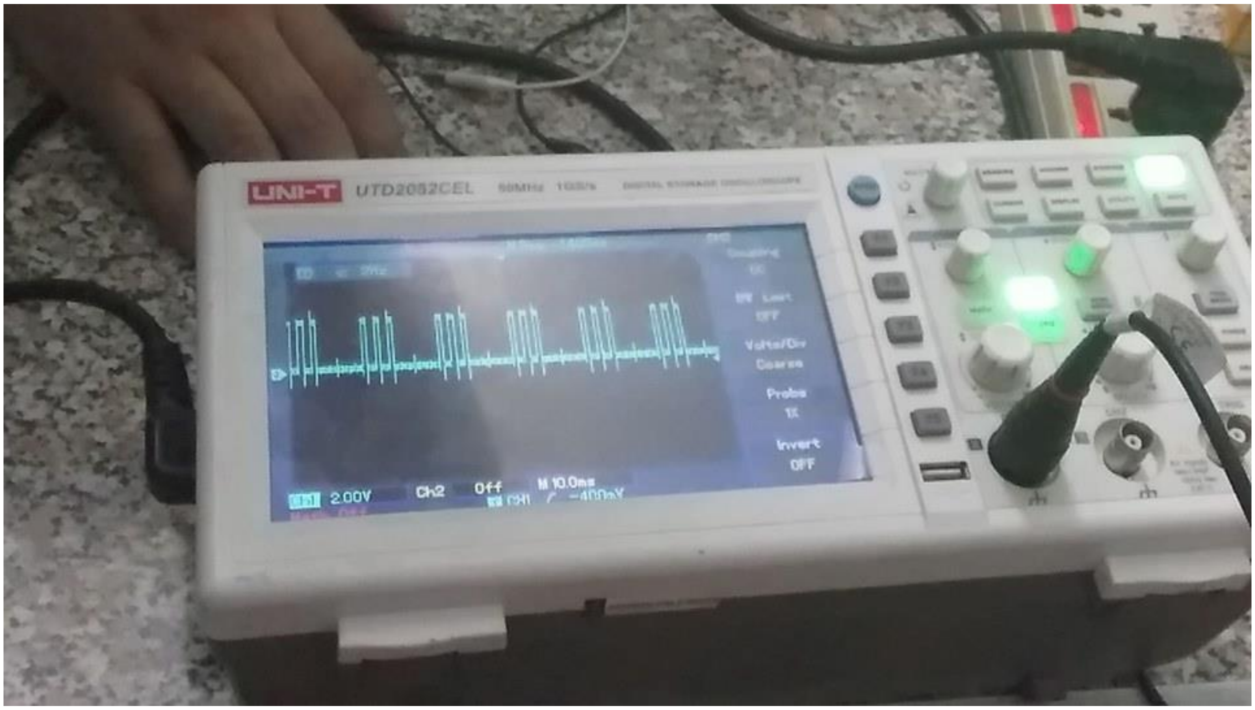


Fig. 7-20 The pulse width modulation for one switch at Arduino

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.

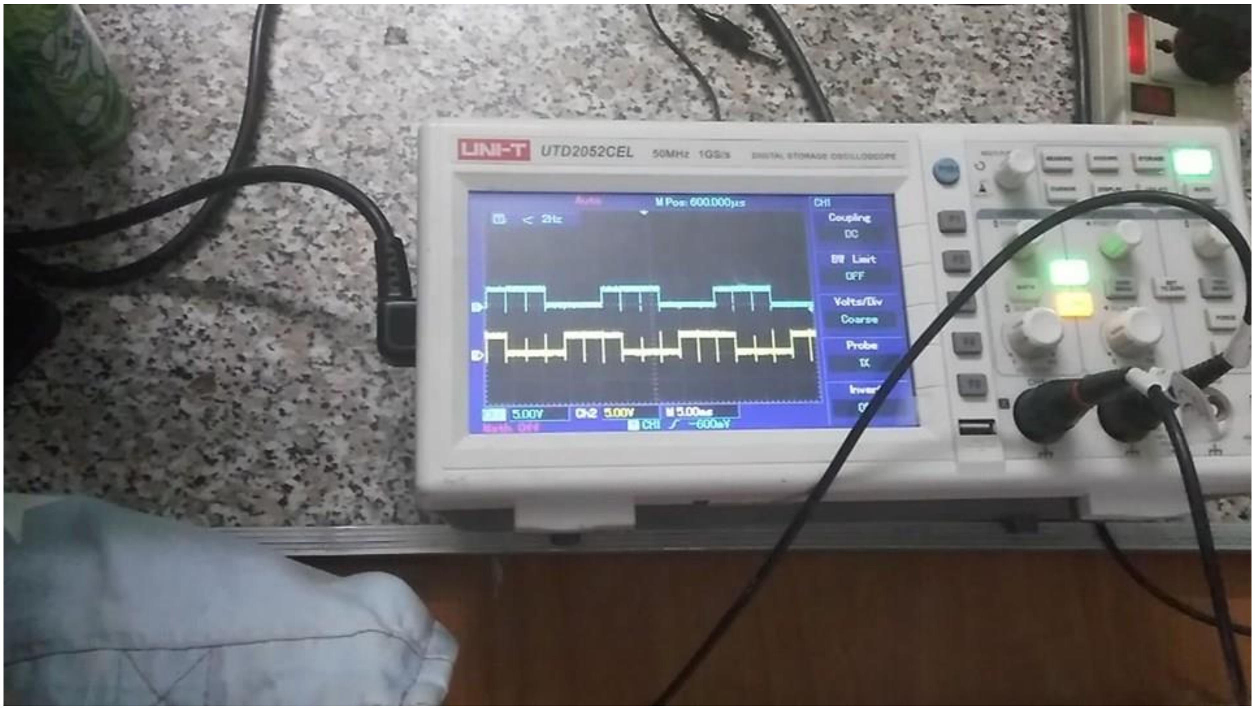


Fig. 7-21 Duty cycle for two different switches in the different legs

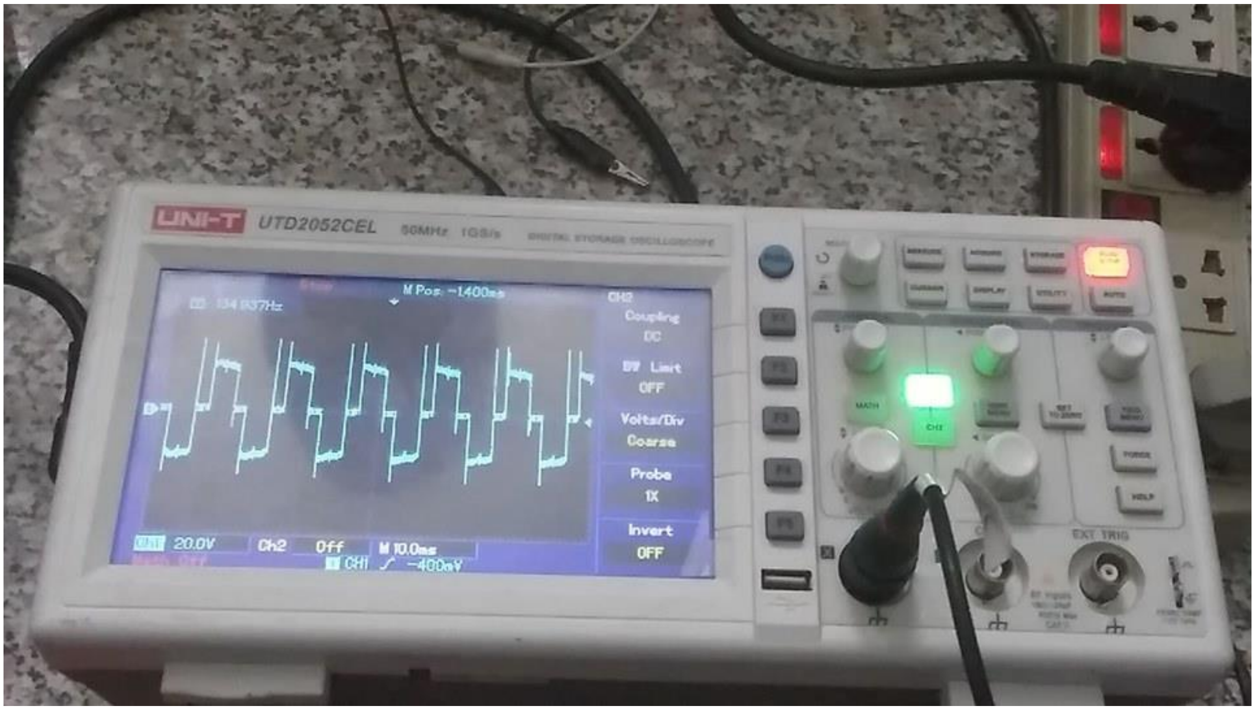


Fig. 7-22 The output line to line voltage between phase a and phase b

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.

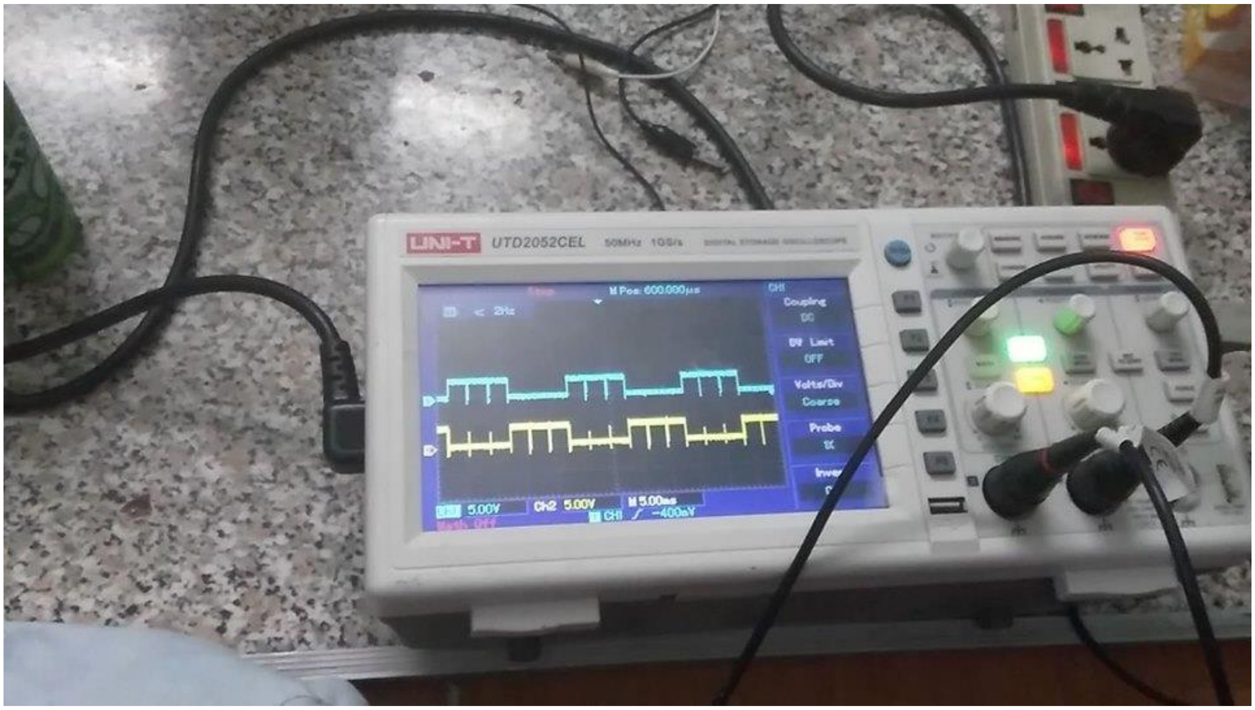


Fig. 7-23 The pulse width modulation for two complementary switches

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.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATION

8-1 Conclusions:

This project discussed the operation of the Three-phase induction motor under effect of the six-step inverter. It displayed the construction of the Three-phase induction motor, mathematical model, starting methods, the performance characteristics, power flow and efficiency. Also, it displayed the six-step inverter, how to control it, mathematical models for different types and make analysis for them. The simulation for motor and different types of the inverter are made and tested individually. The overall simulated system with different loads is constructed. Effect of these loads on the performance characteristics of the three-phase induction motor are made in case of open loop control and closed loop control. The hardware and software are made and tested in case of open loop control by varying the pulse width modulation.

The speed of a three-phase induction motor has been successfully controlled by using six-step inverter as a converter and proportional integral as the controller for closed loop speed control system. Initially a simplified closed loop model for speed control of three-phase induction motor is considered and requirement of PI controller is studied. Then a generalized modeling of motor is done. The MATLAB/SIMULINK model shows good results under below the rated speed during simulation. In this project (under simulation) some loads are tested as, the constant load and fan load. The hardware gives good performance when running at different mode of operation with each varying pulse width modulation. This occurs from 15% to 66% duty cycle which the motor speed is increasing smoothly by increasing the duty cycle and the motor speed is decreasing gradually by decreasing the duty cycle. The variation of the pulse width modulation is depending upon the program which burned on the PIC microcontroller.

8-2 Recommendation for the Future Work:

We suggest the following for the future work

1. Repeat this work on the Three-phase synchronous motor

2. Repeat this work under closed loop control from practical side and compare between these works.

3. Study the different mode of operation from practical side.

4. Compare between the different control methods of the three-phase induction motor through the simulation and through the setup.

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