

NEAR EAST UNIVERSITY

Faculty Engineering

**Department of Electrical and Electronic
Engineering**

**SPEED CONTROL OF THREE PHASE MOTOR
BY USING PWM TECHNIQUE**

**Graduation Project
EE 400**

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ABSTRACT

Pulse Width Modulation (PWM) technique is proven to be an effective way of controlling speed of induction motor. This project presents the development of the algorithm to perform the PWM operation using Matlab Simulink, which then was interfaced with an induction motor. Hence allowing the real time control. These functions are successfully carried out in Matlab simulation

CHAPTER ONE

Classification of Motors

Electric motors are of many types. The common types of motors are given below in figure 1.2.

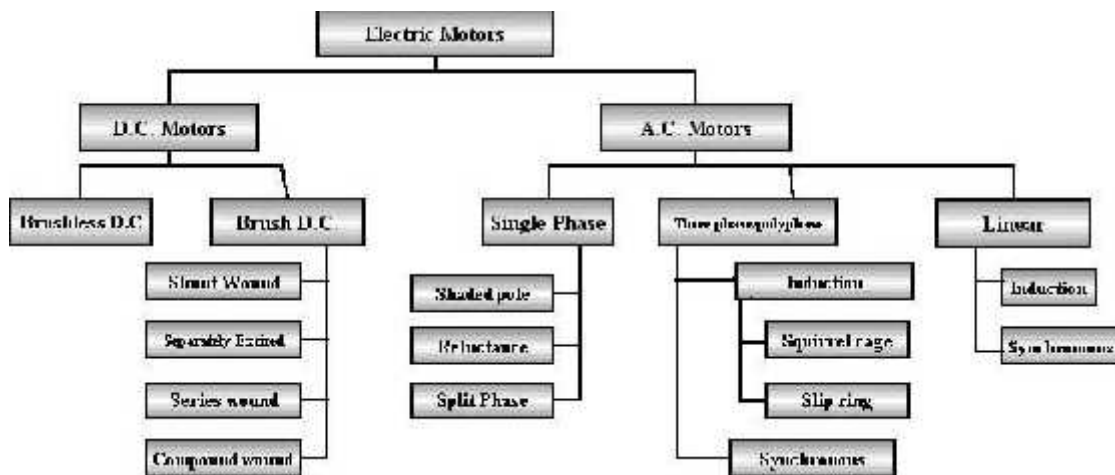


Figure 1.1. Classification of electric motors

Electric motors convert electrical energy into mechanical motion and are broadly classified into two different categories: DC (Direct Current) and AC (Alternating Current). Within these categories are numerous types, each offering unique abilities that suit them well for specific applications. In industry, most commonly used motors are 3 phase squirrel cage induction type. Use of Synchronous motors and DC motors for heavy duty and precision drives etc. are also common.

With the introduction of variable frequency drives for speed and torque control, the 3-phase induction motors are finding increasingly acceptable for applications where DC drives were earlier used.

1.1 DC Motors

- 1.1.1 Shunt DC motor:** The rotor and stator windings are connected in parallel.
- 1.1.2 Separately Excited motor:** The rotor and stator are each connected from a different power supply; this gives another degree of freedom for controlling the motor over the shunt.
- 1.1.3 Series motor:** the stator and rotor windings are connected in series. Thus the torque is proportional to I^2 so it gives the highest torque per current ratio over all other dc motors. It is therefore used in starter motors of cars and elevator motors
- 1.1.4 Permanent Magnet (PMDC) motors:** The stator is a permanent magnet, so the motor is smaller in size.
- 1.1.5 Compounded motor:** the stator is connected to the rotor through a compound of shunt and series windings, if the shunt and series windings add up together, the motor is called cumulatively compounded. If they subtract from each other, then a differentially compounded motor results, which is unsuitable for any application.

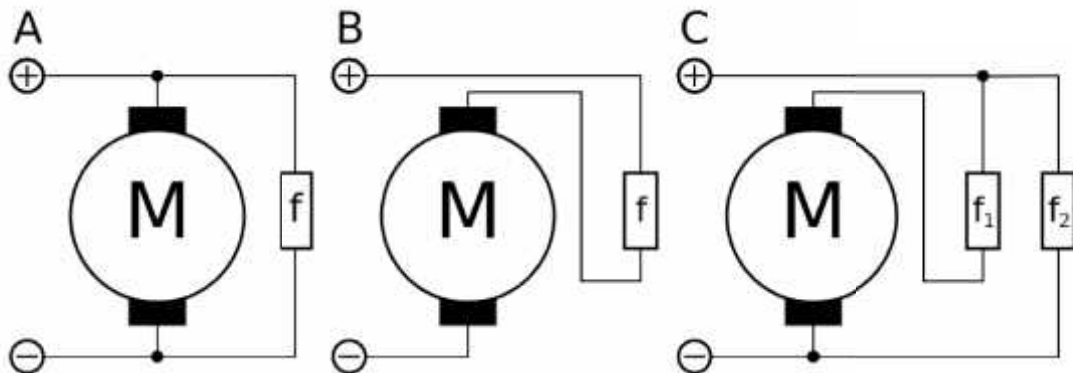


Figure 1.2. Type of DC Motors

Where:

A: shunt B: series C: compound f = field coil

1.2 AC Motors

1.2.1 Asynchronous motor

Induction motor

Three-phase AC induction motors are widely used in industrial and commercial applications. They are classified either as squirrel cage or wound-rotor motors.

These motors are self-starting and use no capacitor, start winding, centrifugal switch or other starting device.

They produce medium to high degrees of starting torque. The power capabilities and efficiency in these motors range from medium to high compared to their single-phase counterparts. Popular applications include grinders, lathes, drill presses, pumps, compressors, conveyors, also printing equipment, farm equipment, electronic cooling and other mechanical duty applications.

Squirrel Cage Motor

Almost 90% of the three-phase AC Induction motors are of this type. Here, the rotor is of the squirrel cage type and it works as explained earlier. The power ratings range from one-third to several hundred horsepower in the three-phase motors. Motors of this type rated one horsepower or larger, cost less and can start heavier loads than their single-phase counterparts.

Wound-Rotor Motor

The slip-ring motor or wound-rotor motor is a variation of the squirrel cage induction motor. While the stator is the same as that of the squirrel cage motor, it has a set of windings on the rotor which are not short-circuited, but are terminated to a set of slip rings. These are helpful in adding external resistors and contactors.

The slip necessary to generate the maximum torque (pull-out torque) is directly proportional to the rotor resistance. In the slip-ring motor, the effective rotor resistance is increased by adding external resistance through the slip rings. Thus, it is possible to get higher slip and hence, the pull-out torque at a lower speed.

A particularly high resistance can result in the pull-out torque occurring at almost zero speed, providing a very high pull-out torque at a low starting current. As the motor

accelerates, the value of the resistance can be reduced, altering the motor characteristic to suit the load requirement. Once the motor reaches the base speed, external resistors are removed from the rotor.

This means that now the motor is working as the standard induction motor. This motor type is ideal for very high inertia loads, where it is required to generate the pull-out torque at almost zero speed and accelerate to full speed in the minimum time with minimum current draw.

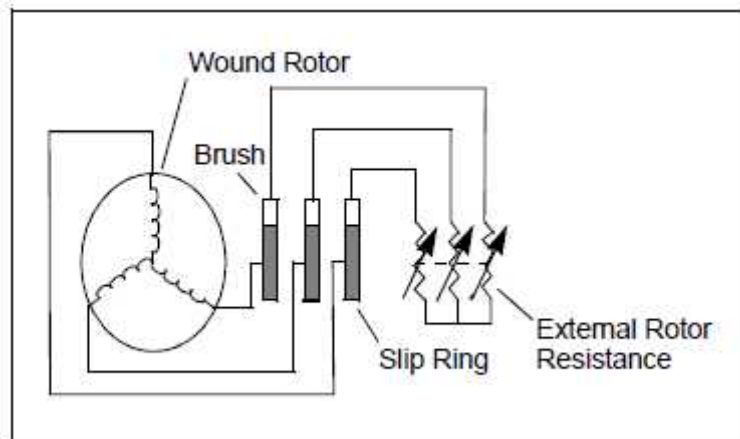


Figure 1.3. Typical wound – Rotor Induction Motor

The downside of the slip ring motor is that slip rings and brush assemblies need regular maintenance, which is a cost not applicable to the standard cage motor. If the rotor windings are shorted and a start is attempted (i.e., the motor is converted to a standard induction motor), it will exhibit an extremely high locked rotor current – typically as high as 1400% and a very low locked rotor torque, perhaps as low as 60%. In most applications, this is not an option. Modifying the speed torque curve by altering the rotor resistors, the speed at which the motor will drive a particular load can be altered. At full load, you can reduce the speed effectively to about 50% of the motor synchronous speed, particularly when driving variable torque/variable speed loads, such as printing presses or compressors. Reducing the speed below 50% results in very low efficiency due to higher power dissipation in the rotor resistances. This type of motor is used in applications for driving variable torque/ variable speed loads, such as in printing presses, compressors, conveyer belts, hoists and elevators.

1.2.2 Synchronous Motor

A synchronous machine is an a.c. machine in which the rotor moves at a speed, which bears a constant relationship to the frequency of the current in the armature winding. As a motor, the shaft speed must remain constant irrespective of the load, provided that the supply frequency remains constant.

As a generator, the speed must remain constant if the frequency of the output is not to vary. The field of a synchronous machine is a steady one. In very small machines this field may be produced by permanent magnets, but in most cases the field is excited by a direct current obtained from an auxiliary generator, which is mechanically coupled to the shaft of the main machine.

Types of Synchronous machines

The armature or main winding of a synchronous machine may be on either the stator or the rotor. The difficulties of passing relatively large current at high voltages across moving contacts have made the stator wound armature the common choice for large machines. Stator-wound armature machines fall into two classes:

salient-pole rotor machines

In salient pole type of rotor consist of large number of projected poles (salient poles) mounted on a magnetic wheel. Construction of a salient pole rotor is as shown in the figure at left. The projected poles are made up from laminations of steel. The rotor winding is provided on these poles and it is supported by pole shoes.

- **Salient pole rotors** have large diameter and shorter axial length.
- They are generally used in lower speed electrical machines, say 100 RPM to 1500 RPM.
- As the rotor speed is lower, more number of poles are required to attain the required frequency. ($N_s = 120f / P$ therefore, $f = N_s \cdot p / 120$ i.e. frequency is proportional to number of poles). Typically number of salient poles is between 4 to 60.
- Flux distribution is relatively poor than non-salient pole rotor, hence the generated emf waveform is not as good as cylindrical rotor.

- Salient pole rotors generally need damper windings to prevent rotor oscillations during operation.
- Salient pole synchronous generators are mostly used in hydro power plants.

Non-salient-pole, or cylindrical-rotor, machines

Non-salient pole rotors are cylindrical in shape having parallel slots on it to place rotor windings. It is made up of solid steel. The **construction of non-salient pole rotor (cylindrical rotor)** is as shown in figure above. Sometimes, they are also called as drum rotor.

- They are smaller in diameter but having longer axial length.
- **Cylindrical rotors** are used in high speed electrical machines, usually 1500 RPM to 3000 RPM.
- Windage loss as well as noise is less as compared to salient pole rotors.
- Their construction is robust as compared to salient pole rotors.
- Number of poles is usually 2 or 4.
- Damper windings are not needed in **non-salient pole rotors**.
- Flux distribution is sinusoidal and hence gives better emf waveform.
- **Non-salient pole rotors** are used in nuclear, gas and thermal power plants.

CHAPTER TWO

Fundamentals

2.1 Principle of Operation

A large percentage of AC motors are induction motors. This implies that there is no current supplied to the rotating coils (rotor windings). These coils are closed loops which have large currents *induced* in them.

Three-phase currents flowing in the stator windings leads establish a rotating magnetic field in the air gap. This magnetic field continuously pulsates across the air gap and into the rotor. Refer figure

2.1. This is a single phase representation of windings and current flow.

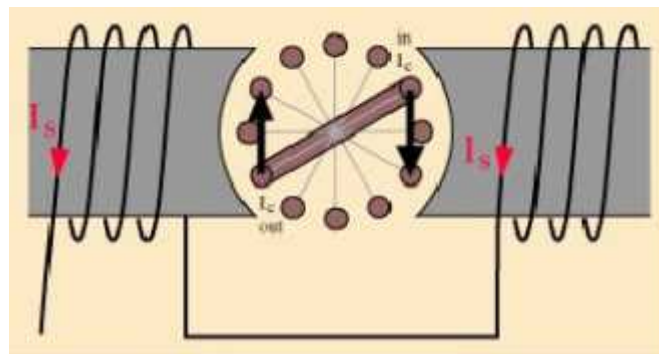


Figure 2.1. Induction motor principle

The rotor consists of copper or aluminum bars connected together at the ends with heavy rings.

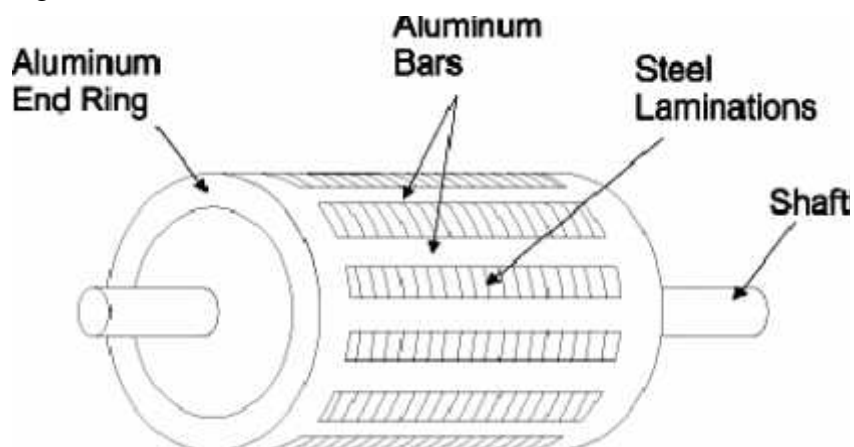


Figure 2.2. Aluminum Rotor

As magnetic flux cuts across the rotor bars, a voltage is induced in them, much as a voltage is induced in the secondary winding of a transformer. Because the rotor bars are part of a closed circuit (including the end rings), a current circulates in them. The rotor current in turn produces a magnetic field that interacts with the magnetic field of the stator. Since this field is rotating and magnetically interlocked with the rotor, the rotor is dragged around with the stator field.

2.1.1 Speed, Torque and Power

Synchronous Speed of an ac induction motor depends on the frequency of the supply voltage and the number of poles for which the motor is wound. The term poles refers to the total number of magnetic north and south poles produced by the stator winding when supplied with poly phase current. The higher the input frequency, the faster the motor runs. The more poles a motor has, the slower it runs at a given input frequency.

Slip represents the inability of the rotor to fully keep up with the moving AC voltage waves generated on the stator. **Slip** of an induction motor defined as:

$$S = \frac{ns - n}{ns}$$

Where,

s = slip

ns = synchronous speed

n = actual speed

Full-load slip varies from less than one percent (in high-HP motors) to more than five percent (infractional-HP motors).

Torque is the force that produces rotation. It causes an object to rotate. Torque consists of force acting on distance. Torque, like work, is measured in Newton-meter. However, torque, unlike work, may exist even though no movement occurs

Power or shaft power takes into account how fast the crank is turned. Turning the crank more rapidly takes more horsepower than turning the crank slowly. It is the rate of doing work. The nameplate power rating of a motor is generally the rated output power.

Rated current & voltage: - It is the current drawn by motor while delivery rated power at rated voltage. The rated current and voltage of the motor are given on the nameplate. Voltage of three phase motor is generally kept at 415 volts. However, these can be operated continuously at $\pm 10\%$ voltage; $\pm 5\%$ frequency and combined voltage and frequency variation of $\pm 10\%$ (Absolute sum).

As per IS: 325, all motors are rated to withstand an overload and excess torque of 60% of their rated torque at rated voltage and frequency for 15 seconds. These are normally designed for 75°C temperature rise (for Class B insulation) above ambient temperature of 45°C

2.1.2 Load Considerations

The driven equipment characteristics decide how much shaft power the motor has to deliver at the operating point. Examples of the common types of loads are given below along with the expected variation in torque and power with speed. Understanding this behavior is important while selecting motors and more so when selecting variable speed drives. Table 2.1 summarizes various types of loads

Constant torque: Most frequently encountered type of load (essentially friction loads), where the torque required by the load is constant throughout the speed range. The constant torque characteristic is needed to overcome friction. Friction loads require the same amount of torque at low speeds as at high speeds. For example, a 10-ton load on a conveyor requires about the torque whether the conveyor speed is 5 or 50 feet per minute. The horsepower requirement, however, increases with speed. Common applications include general machinery, hoists, conveyors, printing presses, etc.

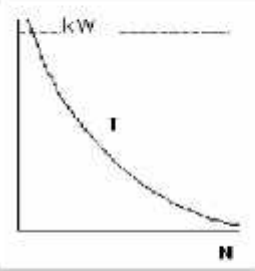
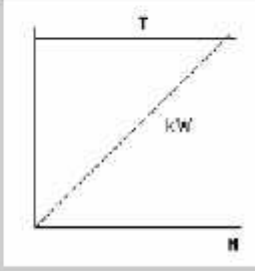
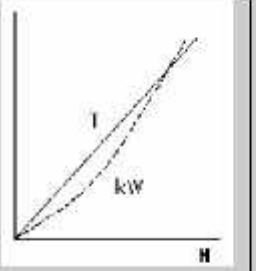
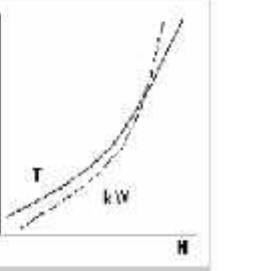
$T \propto 1/N$	$T \propto \text{Constant}$	$T \propto N$	$T \propto N^2$
$kW \propto \text{Constant}$	$kW \propto N$	$kW \propto N^2$	$kW \propto N^3$
			
Winders Facing lathes Rotary cutting machines	Hoisting gear Belt conveyors process machines involving forming Rolling mills planers	Calendars with viscous friction Eddy-current brakes	Pumps Fans Centrifuges

Table 2.1. Load Characteristics

Constant power: In this group, the load decreases with increasing speed. Common applications are processes that are changing diameters such as lathes, winders, unwinders, and metal-cutting tools operating over wide speed ranges. With an initial large diameter work piece, maximum torque and slow speeds are required. As the work piece diameter decreases, torque decreases; but speed increases to provide constant surface speed.

Variable Torque: These loads increase with speed and are usually associated with centrifugal fan and pump loads, where, in theory, the horsepower requirement varies as the cube of the speed change. When driving positive-displacement pumps, some mixers, and some types of extruders, in theory, the horsepower requirement varies as the square of the speed change. These applications usually have the greatest opportunities for energy savings as well as improved control.

Shock Loads: These loads may range from a small fraction of rated load to several hundred percent for a small fraction of the time. Examples include crushers, separators, grinders, and, perhaps, conveyors, winches, and cranes. Under these conditions, the drive has two fundamental tasks: to move the load and to protect the prime mover and driven equipment. For example, the electric motor as a prime mover can experience bearing damage from shock loads.

2.1.3 Power Factor

Power factor is not a measure of efficiency. It is a ratio of Real Power, in total kilowatts, to total Apparent Power, in kilovolt amps. If a load draws Reactive Power, the power factor is said to be "lagging." Most electric motors have a lagging power factor. The operation of electrical systems with low power factor results in reducing the overall power carrying capacity of the power supply system.

As an incentive for customers to operate at high power factors, utilities levy power factor penalties to customers whose overall power factor falls below certain levels.

An understanding of the difference between the three aspects of power, kilowatts, kilovolt-amps, and kilovolt-amps reactive, is essential to an understanding of power factor. Useful mechanical work derives from "real power," the energy consumed by the load. Real power is expressed in kilowatts. Figure 2.3 gives the vector diagram showing all three types of power for lagging p.f. load.

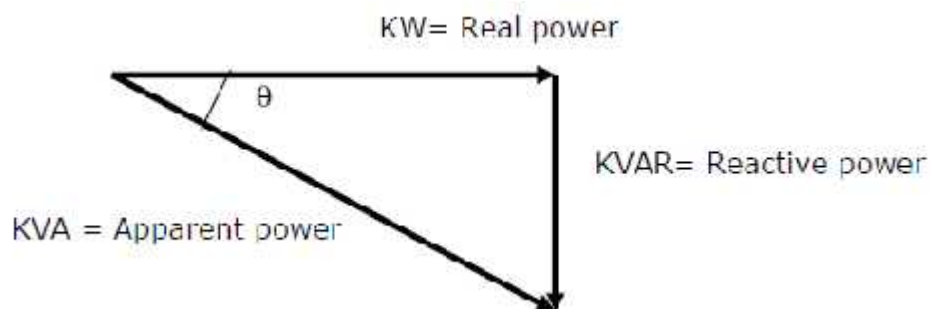


Figure 2.3. Vector diagram

A motor is an inductive load. The current drawn by the motor lag behind the voltage applied. In this situation, the reactive power is drawn by the motor. Reactive power does not provide useful mechanical work. However, most AC motors do require reactive power for developing magnetic fields. Reactive power is expressed as Kilovolt-amps Reactive, or kVAR. The vector sum of Real Power and Reactive Power is Apparent Power, expressed as kilovolt-amps or kVA. Apparent Power is calculated by multiplying voltage and amperage.

A motor operating at a given load and supply voltage, draws active and reactive power. If the motor is connected to the grid, without any capacitors, the entire active and reactive power is drawn from the grid. Refer fig 2.3 (a).

A capacitor is a device which draws a leading current, and is ready to discharge current when motor need it. If capacitor is connected at the motor, the reactive power drawn by the motor from the grid will be less or almost nil in case of unity power factor correction. Refer fig 2.4(b).

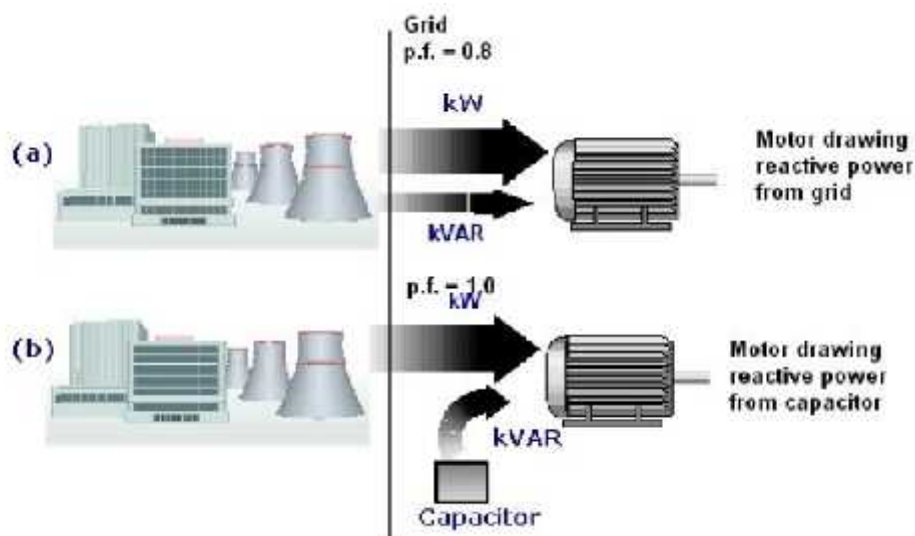


Figure 2.4. Power factor correction by use of capacitors

It is not necessarily to have higher power factor for a high efficiency motor. It is often difficult to get a good a motor design by concentrating on high power factor. The motor designer has to consider a number of parameters such as temperature rise, torque characteristics and efficiency, as well as power factor, and he can't optimize them all. It's costly to try to design both high power factor and high efficiency into a motor, and

some of the design changes that improve power factor, such as a reduced air gap, actually have the opposite effect on efficiency.

2.1.4 Efficiency

Motor efficiency is a measure of the effectiveness with which a motor converts electrical energy input to mechanical energy output to drive a load. It is defined as a ratio of motor power output to source power input. The difference between the power input and power output comprises electrical and mechanical losses. Higher horsepower ratings generally correspond to higher efficiency ratings. Small fractional horsepower motors tend to have low operating efficiency, while large integral horsepower motors are generally very efficient.

At a particular operating voltage and shaft load, the motor efficiency is fixed by design; it cannot be changed externally, while power factor can be corrected externally.

The power consumed by a 3-phase AC motor is given by:

$$\text{Power input} = \sqrt{3} \times \text{line voltage} \times \text{line current} \times \text{power factor}$$

If the voltage is in volts and the current in amperes, the power will be in watts (w). The power in watts divided by 1000 is Kilowatts (kW). The power input to the motor varies with the output shaft load.

$$\text{Electric Power Input (kW)} = \frac{\text{Mechanical shaft output in kW} \times 100}{\text{Motor Efficiency (\%)}}$$

$$\text{Electric Power Input (kVA)} = \frac{\text{Power Input (kW)} \times 100}{\text{Power Factor (\%)}}$$

Typical variations of motor efficiency and power factor with load are shown in fig 2.5.

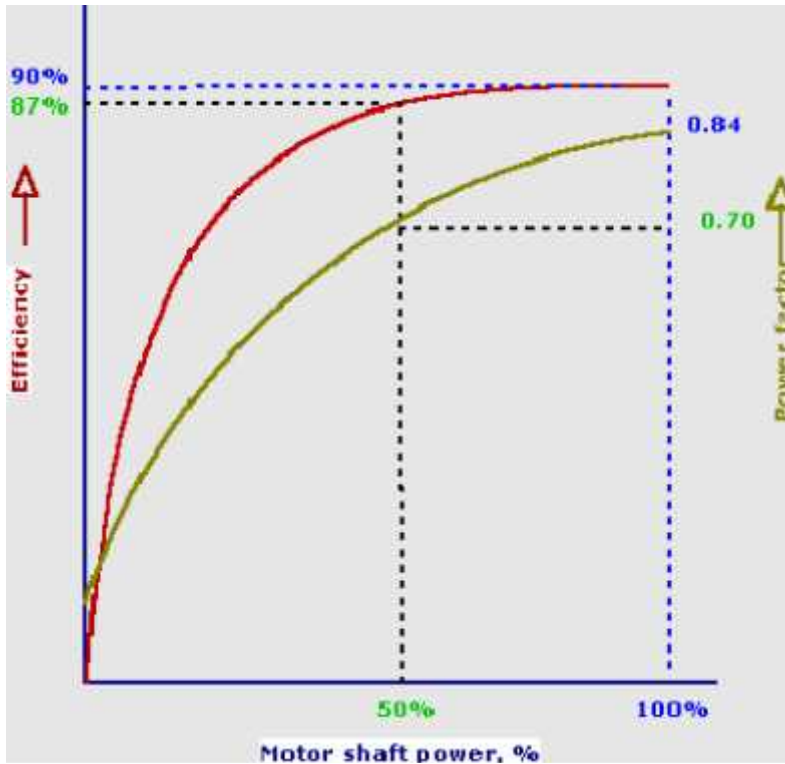


Figure 2.5. Motor efficiency and power factor

The following may be noted from these curves.

1. The motor efficiency remains almost constant up to 40% load, below which the efficiency drops significantly and becomes zero at 0% load.
2. For a particular operating voltage and shaft load, the motor efficiency is determined by design, it cannot be changed externally.
3. The power factor reduces with load. At no load the p.f. is in the range of 0.05 to 0.2 depending on size of the motors.
4. Note that at 50% load, the efficiency has dropped by 3%, where as the power factor has dropped from 0.84 to 0.7 for the same load change.

5. At no load, the power consumption is only about 1 to 5%; just sufficient to supply the iron, friction and windage losses.

6. The no load current is however, of the order of 30 to 50% of the full load current. This magnetizing current is required because of air gap in the motor.

2.1.5 Torque & Current /vs. Speed Characteristics of Motors

Torque speed and current speed characteristics of different types of motors are shown in fig. 2.6

Torque speed curve shows how a motor's torque production varies with the different conditions of its operation.

Starting torque, also called **locked rotor torque**, is produced by a motor when it is initially turned on. Starting torque is the amount required to overcome load friction at standstill.

Pull-up torque is the minimum torque generated by a motor as it accelerates from standstill to operating speed. If a motor's pull-up torque is less than that required by its application load, the motor will overheat and eventually stall.

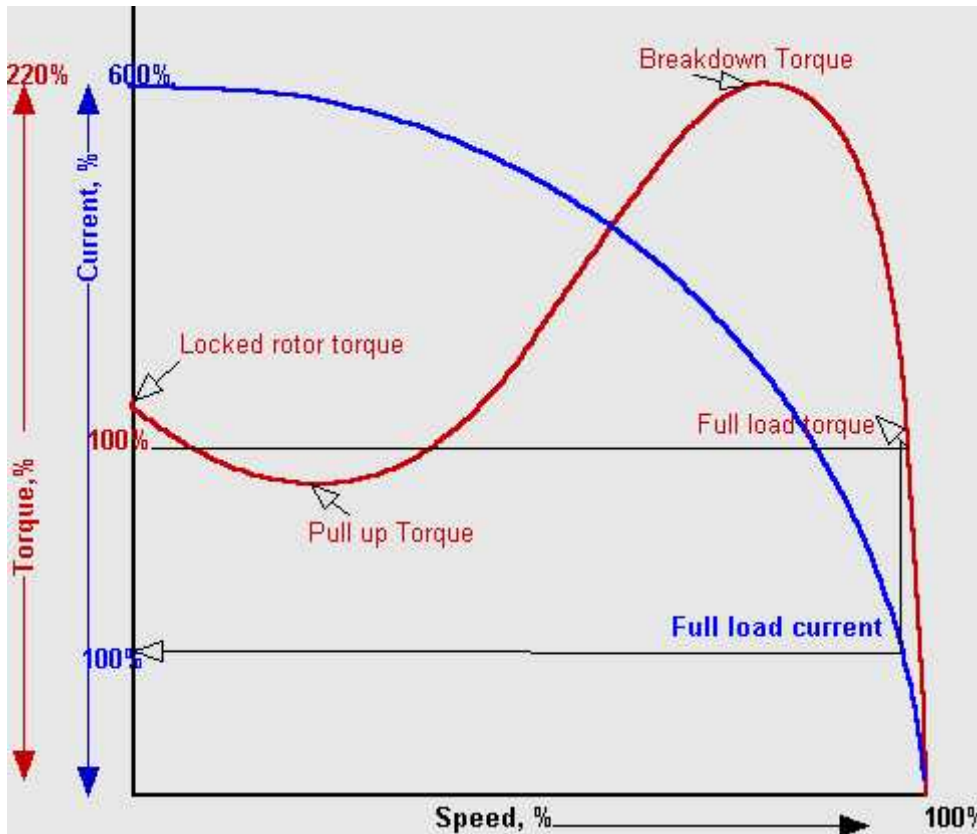


Figure 2.6. Torque & Current .vs. Speed

Breakdown torque is the greatest amount of torque a motor can generate without stalling. High breakdown torque is necessary for applications that may undergo frequent but short time overloading. One such application is a conveyor belt. Often, conveyor belts have more products placed upon them than their rating allows. High breakdown torque enables the conveyor to continue operating under these conditions.

Full load torque is produced by a motor functioning at a rated speed and horsepower. The operating life is significantly diminished in motors continually run at levels exceeding full load torque.

Note:

1. The starting torque is 100% to 200%; the maximum torque is 200% to 300% of rated torque.
2. The current remains at a high value of more than 500% of rated current up to 75% to 80% speed and then drop sharply.

CHAPTER THREE

Classification of Speed Control Methods

The Speed of Induction Motor is changed from Both Stator and Rotor Side

❖ The speed control of three phase induction motor from **stator** side are further classified as :

1. V / f control or frequency control.
2. Controlling supply voltage
3. Changing the number of stator poles.
4. Adding rheostat in the stator circuit.
5. Controlling the supply frequency.

❖ The speed controls of three phase induction motor from **rotor** side are further classified as:

1. Adding external resistance on rotor side.
2. Cascade control method.
3. Injecting slip frequency EMF into rotor side.

3.1 Speed Control from Stator Side

3.1.1 V / f control or frequency control

Synchronous speed can be controlled by varying the supply frequency. Voltage induced in the stator is $E_1 \propto f$ where ϕ is the air-gap flux and f is the supply frequency. As we can neglect the stator voltage drop we obtain terminal voltage $V_1 \propto f$. Thus reducing the frequency without changing the supply voltage will lead to an increase in the air-gap flux which is undesirable. Hence whenever frequency is varied in order to control speed, the terminal voltage is also varied so as to maintain the V/f ratio constant. Thus by maintaining a constant V/f ratio, the maximum torque of the motor becomes constant for changing speed.

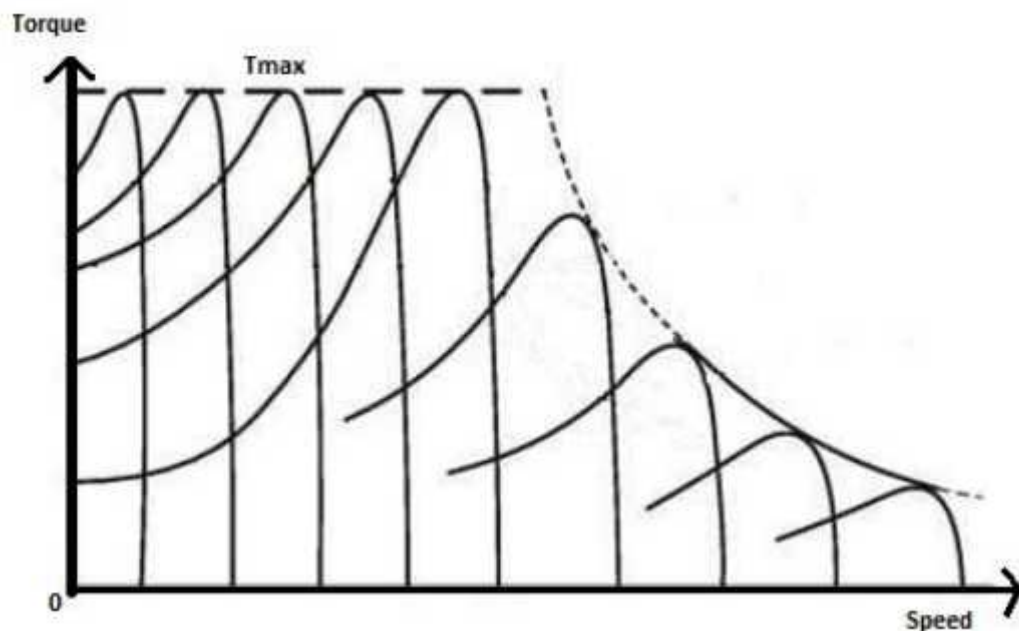


Figure 3.1. Torque-Speed characteristics for V/f Controlled Induction Motor

As can be seen, when V/f Control is implemented, for various frequencies inside the operating region, the maximum torque remains the same as the speed varies. Thus maintaining the V/f ratio constant helps us to maintain a constant maximum torque while controlling the speed as per our requirement

Whenever three phase supply is given to three phase induction motor rotating magnetic field is produced which rotates at synchronous speed given by

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

In three phase induction motor emf is induced by induction similar to that of transformer which is given by

$$E \text{ or } V = 4.44\phi K.T.f \text{ or } \phi = \frac{V}{4.44KTf}$$

Where K is the winding constant, T is the number of turns per phase and f is frequency. Now if we change frequency synchronous speed changes but with decrease in frequency flux will increase and this change in value of flux causes saturation of rotor and stator cores which will further cause increase in no load current of the motor . So, it's important to maintain flux , constant and it is only possible if we change voltage . i.e. if we decrease frequency flux increases but at the same time if we decrease voltage flux will also decrease causing no change in flux and hence it remains constant. So, here we are keeping the ratio of V/ f as constant. Hence its name is V/ f method. For controlling the speed of three phase induction motor by V/ f method we have to supply variable voltage and frequency which is easily obtained by using converter and inverter set.

3.1.2 Controlling supply voltage:

The torque produced by running three phase induction motor is given by

$$T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

In low slip region $(sX_2)^2$ is very small as compared to R_2 . So, it can be neglected.

So torque becomes

$$T \propto \frac{sE_2^2}{R_2}$$

Since rotor resistance, R_2 is constant so the equation of torque further reduces to

$$T \propto sE_2^2$$

We know that rotor induced emf $E_2 \propto V$. So, $T \propto sV^2$.

From the equation above it is clear that if we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remain the same and it is only possible if we increase the slip and if the slip increases the motor will run at reduced speed. This method of speed control is rarely used because small change in speed requires large reduction in voltage, and hence the current drawn by motor increases, which causes over heating of induction motor.

3.1.3 Changing the number of stator poles:

The stator poles can be changed by two methods:

1. Multiple stators winding method

In this method of speed control of three phase induction motor, the stator is provided by two separate windings. These two stator windings are electrically isolated from each other and are wound for two different pole numbers. Using switching arrangement, at a time, supply is given to one winding only and hence speed control is possible. A disadvantage of this method is that the smooth speed control is not possible. This method is more costly and less efficient as two different stator windings are required. This method of speed control can only be applied for squirrel cage motor.

2. Pole amplitude modulation method (PAM)

In this method of speed control of three phase induction motor the original sinusoidal mmf wave is modulated by another sinusoidal mmf wave having different number of poles.

3.1.4 Adding rheostat in the stator circuit

In this method of speed control of three phase induction motor rheostat is added in the stator circuit due to this voltage gets dropped. In case of three phase induction motor torque produced is given by $T \propto sV^2$. If we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remain the same and it is only possible if we increase the slip and if the slip increases the motor will run at reduced speed.

3.2 Speed Control from Rotor Side

3.2.1 Adding external resistance on rotor side

In this method of speed control of three phase induction motor external resistance is added on the rotor side. The equation of torque for three phase induction motor is

$$T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX)^2}$$

The three phase induction motor operates in the low slip region. In the low slip region term $(sX)^2$ becomes very very small as compared to R_2^2 . So, it can be neglected. and also E_2 is constant. So the equation of torque after simplification becomes,

$$T \propto \frac{s}{R_2}$$

Now if we increase rotor resistance, R_2 torque decreases but to supply the same load torque must remain constant. So, we increase slip, which will further result in decrease in rotor speed. Thus by adding additional resistance in the rotor circuit we can decrease the speed of the three phase induction motor.

The main advantage of this method is that with addition of external resistance starting torque increases but this method of speed control of three phase induction motor also suffers from some disadvantages:

The speed above the normal value is not possible.

Large speed change requires large value of resistance and if such large value of resistance is added in the circuit it will cause large copper loss and hence reduction in efficiency.

Presence of resistance causes more losses.

This method cannot be used for squirrel cage induction motor.

3.2.2 Cascade control method

In this method of speed control of three phase induction motor, the two three phase induction motor are connected on common shaft and hence called cascaded motor. One motor is called the main motor and another motor is called the auxiliary motor. The three phase supply is given to the stator of the main motor while the auxiliary motor is derived at a slip frequency from the slip ring of main motor.

3.2.3 Injecting slip frequency EMF into rotor side

When the speed control of three phase induction motor is done by adding resistance in rotor circuit, some part of power called, the slip power is lost as I^2R losses. Therefore the efficiency of three phase induction motor is reduced by this method of speed control. This slip power loss can be recovered and supplied back in order to improve the overall efficiency of three phase induction motor and this scheme of recovering the power is called slip power recovery scheme and this is done by connecting an external source of emf of slip frequency to the rotor circuit. The injected emf can either oppose the rotor induced emf or aids the rotor induced emf. If it oppose the rotor induced emf, the total rotor resistance increases and hence speed decreases and if the injected emf aids the main rotor emf the total resistance decreases and hence speed increases. Therefore by injecting induced emf in rotor circuit the speed can be easily controlled. The main advantage of this type of speed control of three phase induction motor is that wide range of speed control is possible whether its above normal or below normal speed.

CHAPTER FOUR

PULSE WIDTH MODULATION

4.1 Introduction

Pulse Width Modulation (PWM) technique is an effective way of controlling the speed of induction motor, and thus allowing the motor to be applied in the area requiring speed control. Available techniques to control the speed of induction motor are: varying the slip by changing rotor resistance or terminal voltage and varying synchronous speed by changing number of poles or supply frequency. Changing rotor resistance requires wound-rotor induction motor and any resistances inserted to the rotor circuit will reduce the efficiency of the machines. Changing terminal voltage has limited range of speed control. Changing the number of poles requires a motor with special stator windings. The best method is to change the electrical frequency because it is applicable to any types of induction motor. The speed of induction motor depends on the rate of rotation of its magnetic fields or the synchronous speed, which is directly proportional to any change of electrical frequency. PWM technique is used to control the electrical frequency of the 3-phase voltage supplied to the motor from the Insulated Gate Bipolar Transistors (IGBTs) inverter circuit, hence allowing the speed to be varied with respect to the frequency of the reference signal, input to the PWM signal generator. The Real time workshop from Math Works is an industrial PC for use in performing real-time analysis, simulation, and testing of control systems and digital signal processing (DSP) systems. The box works with Real time workshop software, a host-target environment that lets users connect models created in Math Works design tools such as Simulink, Matlab, and Real-Time Workshop, to physical systems, and execute them in real time. The Matlab/Real time workshop was used in some application other than induction motor speed control. This paper presents the development of the algorithm to perform the PWM operation using Matlab Simulink. Then the Matlab/Real time workshop was used to interface with the actual induction motor, finally through the I/O interface circuit and 23 Simulink slider gain, the speed of induction motor was controlled. The control algorithm also developed to switch the rotational direction of the motor, i.e. forward or reverse direction.

4.2 METHODOLOGY AND PROCEDURE IDENTIFICATION

The first stage was to develop the algorithm to perform the PWM and to execute simulation in Matlab Simulink environment. The process started with developing the PWM signal generator. The set point value was represented by *Signal* block. The fundamental principle of AC machine operation is that if a balanced three-phase set of voltages, each with equal magnitude and shifted in phase by 0° , -120° and 120° respectively, the magnetic field produced inside the stator winding will rotate in the same direction of the phase rotation. If any two of the three-phase voltages are swapped, the magnetic field will reverse its rotational direction. If the phase input signal for three-phase PWM generator is in order of 0° , -120° , 120° , the rotational direction can be switched by changing the phase sequence order to 0° , 120° , and -120° . In the PWM generator block, the phase block was divided into two blocks, which are *Forward* and *Reverse*. The *Forward* block has the value of $[0 \ -2\pi/3 \ 2\pi/3]$, while the *Reverse* has the value of $[0 \ 2\pi/3 \ -2\pi/3]$, where the sequence for phase B and C was swapped. Then, the PWM signal generator was connected to the IGBTs' model and induction motor's model in Matlab Simulink. The simulation proved that the developed algorithm could control the speed of induction motor. The second stage was to implement the PWM inverter model on actual IGBT module and actual induction motor. Using the control algorithm in the Matlab Simulink was linked through Real-Time Workshop to the hardware. After the connection was established, PWM signal was connected in real time to the IGBTs module. The IGBT module consists of six IGBTs. The module also contains electronics circuit that isolates the gate of IGBTs and protects the IGBTs against overheating, overvoltage, and over current. The controllable DC voltage was supplied to the IGBT module. There is a capacitor in the module, which is used to maintain a smooth DC voltage in spite of the current pulsation produced by the IGBTs. The Real time workshop was used to interface between the host PC and the IGBT inverter circuit. Communication link uploaded the data from the host PC to the Real time workshop. I/O card at the target PC executed the control algorithm by providing the necessary signal to the IGBT inverter circuit. The switching sequence of the IGBTs followed the necessary signal of PWM technique that has been set in the control algorithm, thus converted the DC source to the PWM voltage output for the induction motor. There were two options to provide the input frequency to the control signal. The

input/output blocks were included into the Matlab Simulink model to enable the connection of the actual motor, IGBTs and keypad to the host PC.

4.3 VOLTAGE SOURCE INVERTERS (VSI)

The main objective of static power converters is to produce an ac output waveform from a dc power supply. These are the types of waveforms required in adjustable speed drives (ASDs), uninterruptible power supplies (UPS), static var compensators, active filters, flexible ac transmission systems (FACTS), and voltage compensators, which are only a few applications. For sinusoidal ac outputs, the magnitude, frequency, and phase should be controllable.

According to the type of ac output waveform, these topologies can be considered as voltage source inverters (VSIs), where the independently controlled ac output is a voltage waveform. These structures are the most widely used because they naturally behave as voltage sources as required by many industrial applications, such as adjustable speed drives (ASDs), which are the most popular application of inverters. Similarly, these topologies can be found as current source inverters (CSIs), where the independently controlled ac output is a current waveform. These structures are still widely used in medium-voltage industrial applications, where high-quality voltage waveforms are required. Static power converters, specifically inverters, are constructed from power switches and the ac output waveforms are therefore made up of discrete values. This leads to the generation of waveforms that feature fast transitions rather than smooth ones.

For instance, the ac output voltage produced by the VSI of a standard ASD is a three-level waveform (Fig. 6.1c). Although this waveform is not sinusoidal as expected (Fig. 6.1b), its fundamental component behaves as such. This behavior should be ensured by a modulating technique that controls the amount of time and the sequence used to switch the power valves on and off. The modulating techniques most used are the carrier-based technique (e.g., sinusoidal pulse width modulation, SPWM), the space-vector (SV) technique, and the selective-harmonic-elimination (SHE) technique.

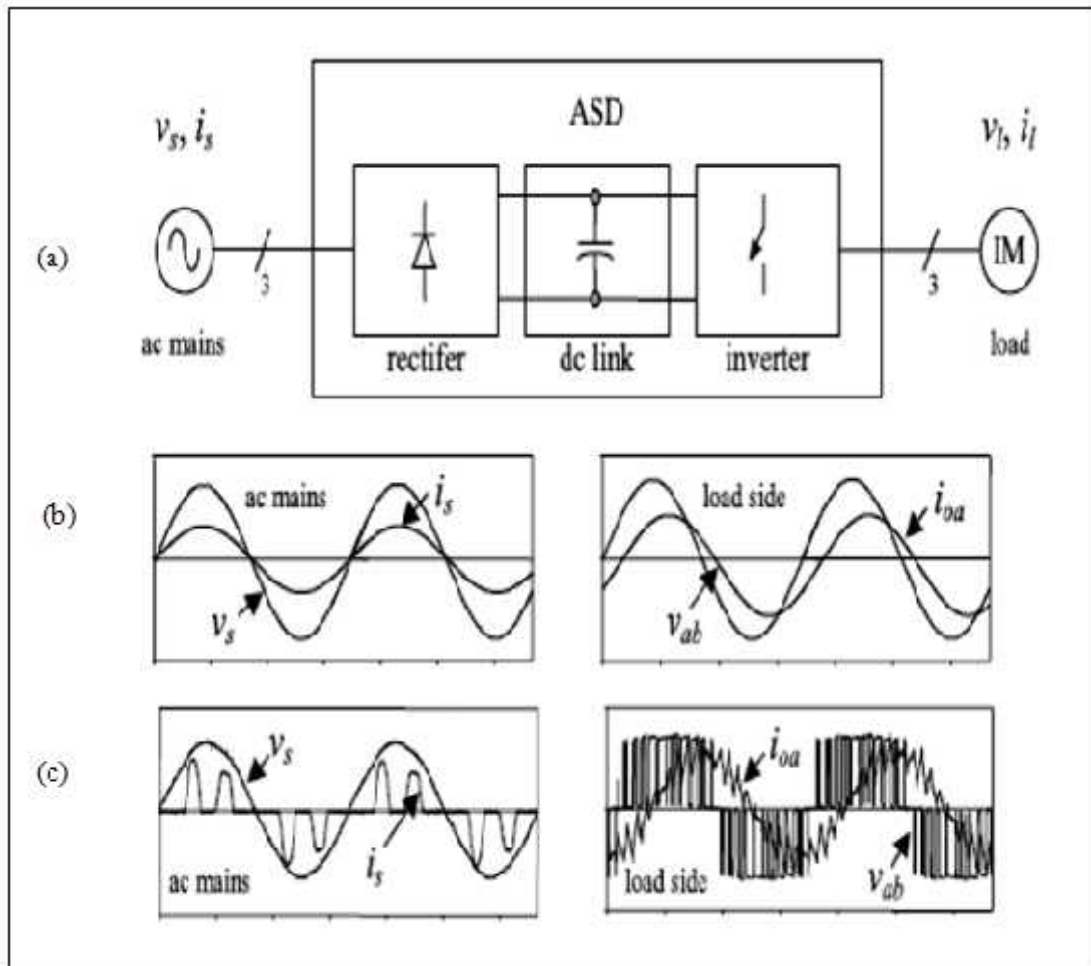


Figure 4.1. The ac output voltage produced by the VSI of a standard ASD

- a) The electrical power conversion topology;
- b) The ideal input (ac mains) and output (load) waveforms; and
- c) The actual input (ac mains) and output (load) waveforms.

4.4 PULSE WIDTH MODULATION IN INVERTERS

Pulse-width modulation (PWM) is a very efficient way of providing intermediate amounts of electrical power between fully on and fully off. A simple power switch with a typical power source provides full power only when switched on. PWM is a comparatively recent technique, made practical by modern electronic power switches. PWM can be used to reduce the total amount of power delivered to a load without losses normally incurred when a power source is limited by resistive means. This is because the average power delivered is proportional to the modulation duty cycle. With a sufficiently high modulation rate, passive electronic filters can be used to smooth the pulse train and recover an average analog waveform

4.4.1 OBJECTIVE OF PWM

Control of inverter output voltage

Reduction of harmonics

Disadvantages of PWM

Increase of switching losses due to high PWM frequency

Reduction of available voltage

EMI problems due to high-order harmonics

4.4.2 PWM METHODS

- 1) Sine PWM
- 2) Hysteresis (Bang-bang)
- 3) Space Vector PWM

4.4.3 SINE PWM

The pulses are generated by comparing a triangular carrier waveform to a reference modulating signal. The amplitude (modulation), phase, and frequency of the reference signals are set to control the output voltage (on the AC terminals) of the bridge connected to the PWM Generator block.

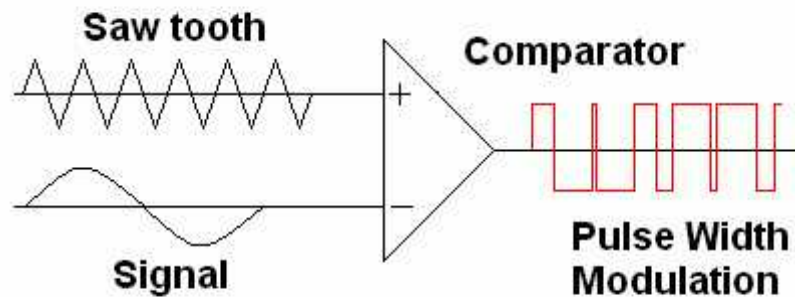


Figure 4.2. Principle of PWM generation

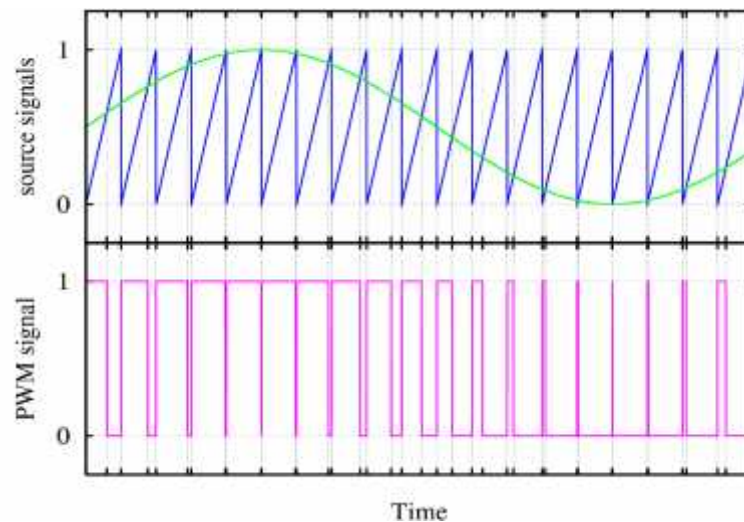


Figure 4.3. Wave form of Sine PWM

4.4.4 Pulse Width Modulated VSI

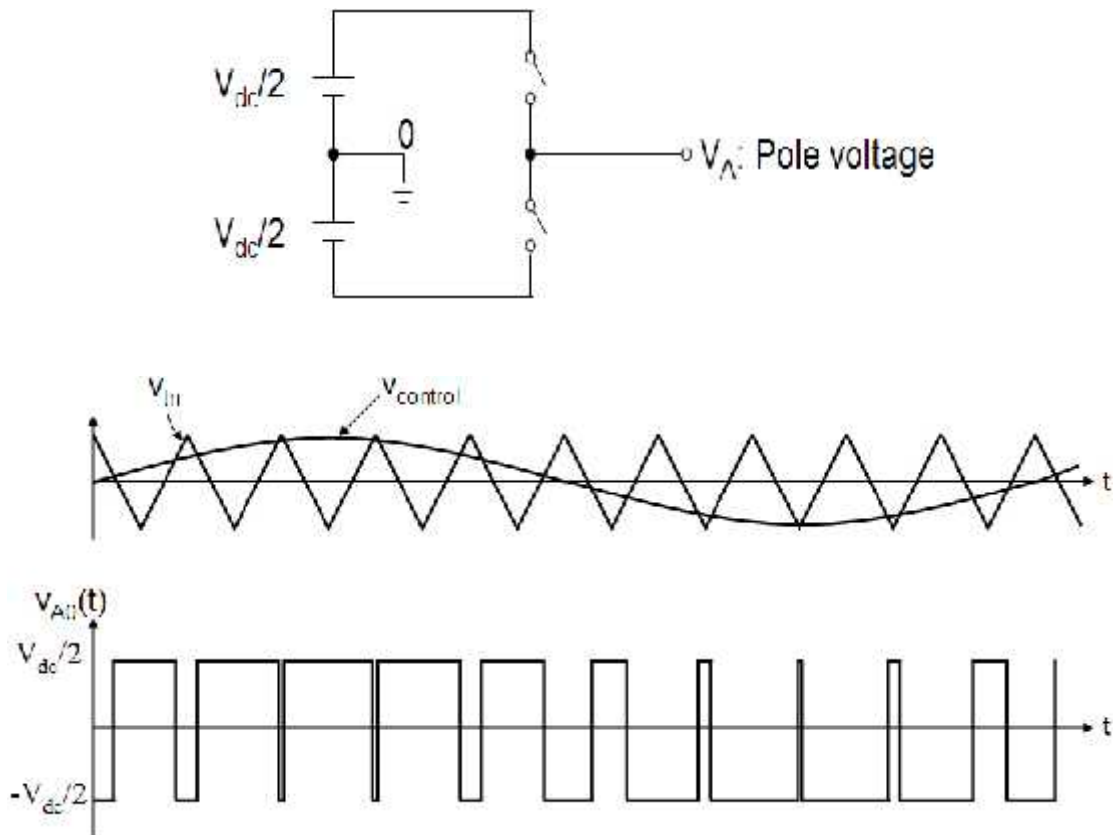


Figure 4.4. Pulse-width modulation.

INVERTER OUTPUT VOLTAGE

When $v_{control} > v_{tri}$, $V_{A0} = V_{dc}/2$

When $v_{control} < v_{tri}$, $V_{A0} = -V_{dc}/2$

CONTROL OF INVERTER OUTPUT VOLTAGE

PWM frequency is the same as the frequency of v_{tri}

Amplitude is controlled by the peak value of $v_{control}$

Fundamental frequency is controlled by the frequency of $v_{control}$

Modulation Index (m)

$$\therefore m = \frac{v_{control}}{v_{tri}} = \frac{\text{peak of } (V_{A0})_1}{V_{dc}/2},$$

where, $(V_{A0})_1$: fundamental frequency component of V_{A0}

4.4.5 Three-Phase Sine PWM Waveforms

Frequency of v_{tri} and $v_{control}$

Frequency of $v_{tri} = f_s$

Frequency of $v_{control} = f_1$

where, $f_s = \text{PWM frequency}$

$f_1 = \text{Fundamental frequency}$

Inverter output voltage

When $v_{control} > v_{tri}$, $V_{A0} = V_{dc}/2$

When $v_{control} < v_{tri}$, $V_{A0} = -V_{dc}/2$

where, $V_{AB} = V_{A0} - V_{B0}$

$V_{BC} = V_{B0} - V_{C0}$

$V_{CA} = V_{C0} - V_{A0}$

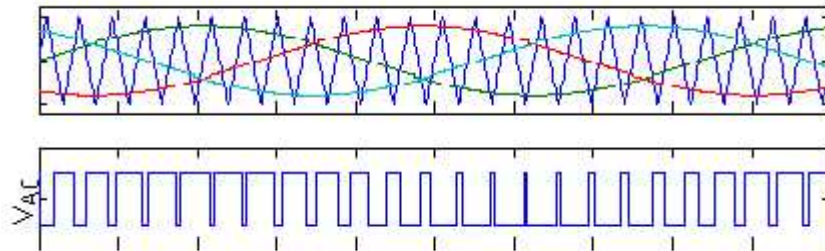


Figure 4.5. Waveforms of three-phase sine PWM inverter.

4.4.6 THREE PHASE INVERTER

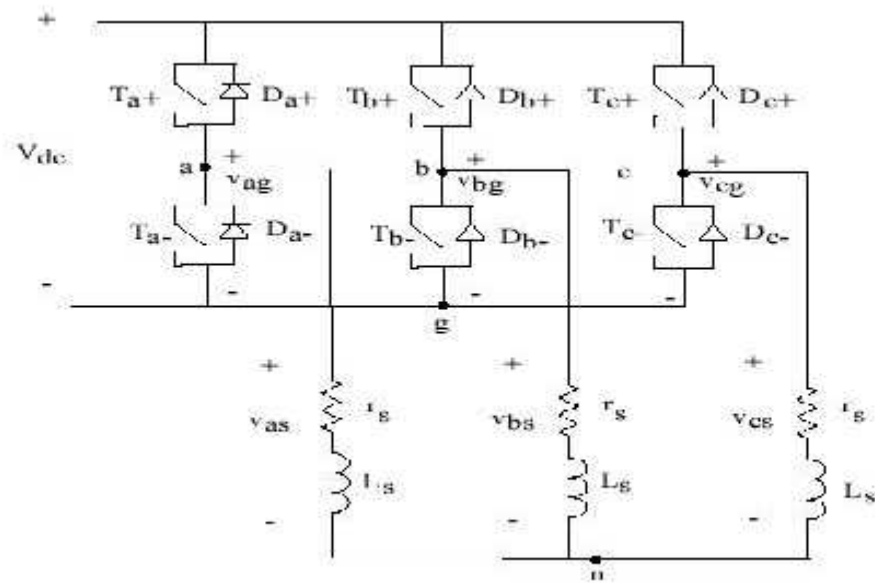


Figure 4.6. Three phase inverter

Switching states of IGBT

- $V_{\text{control(phase - a)}} > V_{\text{triangle}}$, T_{a+} is On
- $V_{\text{control(phase - a)}} > V_{\text{triangle}}$, T_{a-} is On
- $V_{\text{control(phase - b)}} > V_{\text{triangle}}$, T_{b+} is On
- $V_{\text{control(phase - b)}} > V_{\text{triangle}}$, T_{b-} is On
- $V_{\text{control(phase - c)}} > V_{\text{triangle}}$, T_{c+} is On
- $V_{\text{control(phase - c)}} > V_{\text{triangle}}$, T_{c-} is On

CHAPTER FIVE

SIMULATION

5.1 Introduction

Use of simulation studies as a valid tool for testing new ideas and schemes has now come of age. Simulation studies offer a number of other advantages. They help on determining optimal parameters. Destructive tests that could not have been done in the laboratory can be easily simulated and responses to fault and abnormal conditions can be analyzed. Simulated waveforms at different places, not really accessible from outside can be easily monitored. Component ratings are not needed before hand during simulation.

A number of simulation packages are available which enable us to develop simulation programs for electric drive system. Basically there are two types of simulators, namely, circuit based simulators and equation based simulators. In the former case of simulators power electronics circuits can be simulated, taking into account, the real dynamics of switching processes the disadvantage with such simulators is that they need machines also to be represented by their equivalent circuits. The accuracy of simulation in this case may not be to desired level. On the other hand , the latter type of simulators are basically equation solvers. Semiconductor devices can either be represented as ideal switches or can be represented using the corresponding dynamic equations during switching. Machines can be accurately represented as a number of differential equation in the state space form. MATLAB/SIMULINK is such a powerful equation based simulator which can meet the requirements of simulation of electric drive system.

5.2 Simulink As a Tool for System Simulation

SIMULINK is an extension of MATLAB and is a program for simulating dynamic systems. It helps in representing systems in a block diagram fashion. There are a lot of built in blocks available in its library. It is also possible to create new function using the S-function facility. Normally one goes about the simulation procedure by bringing in fundamental blocks from the library and suitably inter connecting them to perform the task of a subsystem. It is possible to use this subsystem obtained by grouping the fundamental blocks as a single block where ever such a subsystem is to be connected. Various subsystems blocks so generated are interconnected to simulate the entire system. In SIMULINK , a number of simulation algorithm are available at the users' disposal e.g. integration algorithm like Runge-kutta, Dormand Prince, and Euler. The appropriate choice of method and careful selection of simulation parameters are important considerations for obtaining accurate results.

5.3 SIMULATION SETUP

Figure shows the entire simulation set up. The main blocks involved are motor block, inverter block and controller block

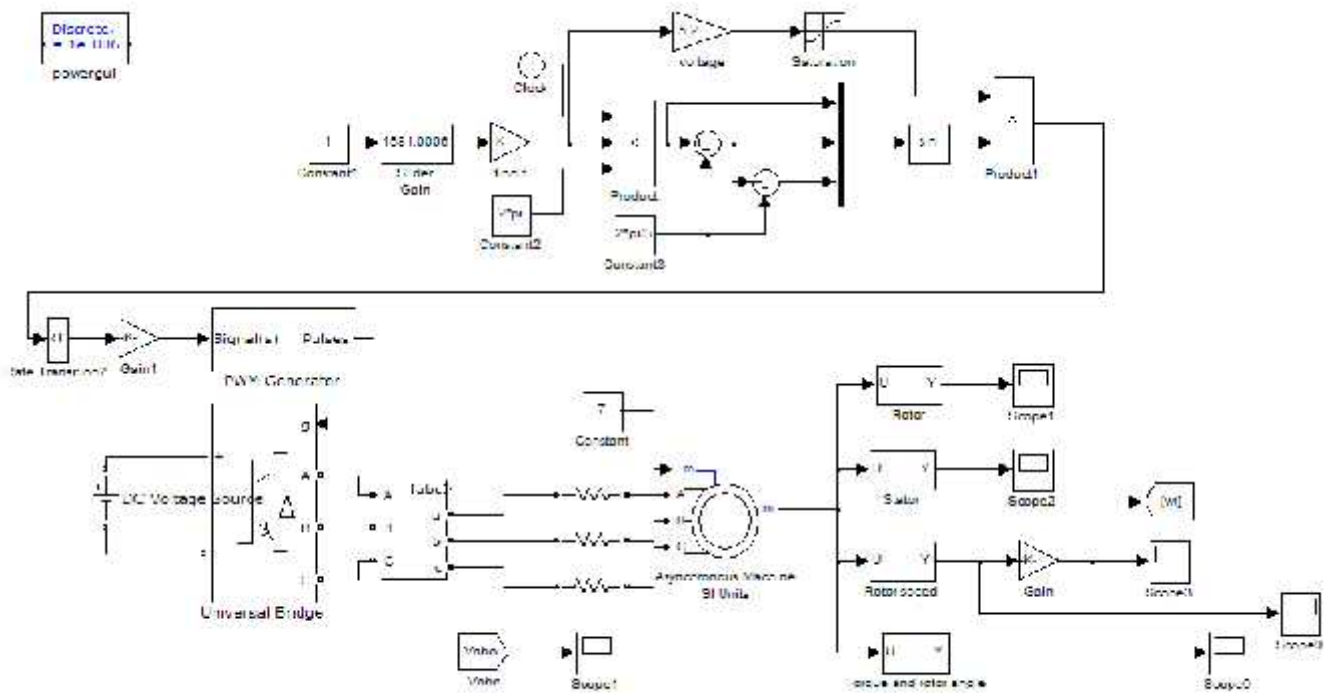


Figure 5.1. Complete simulation model in Matlab Simulink

5.4 Implementation

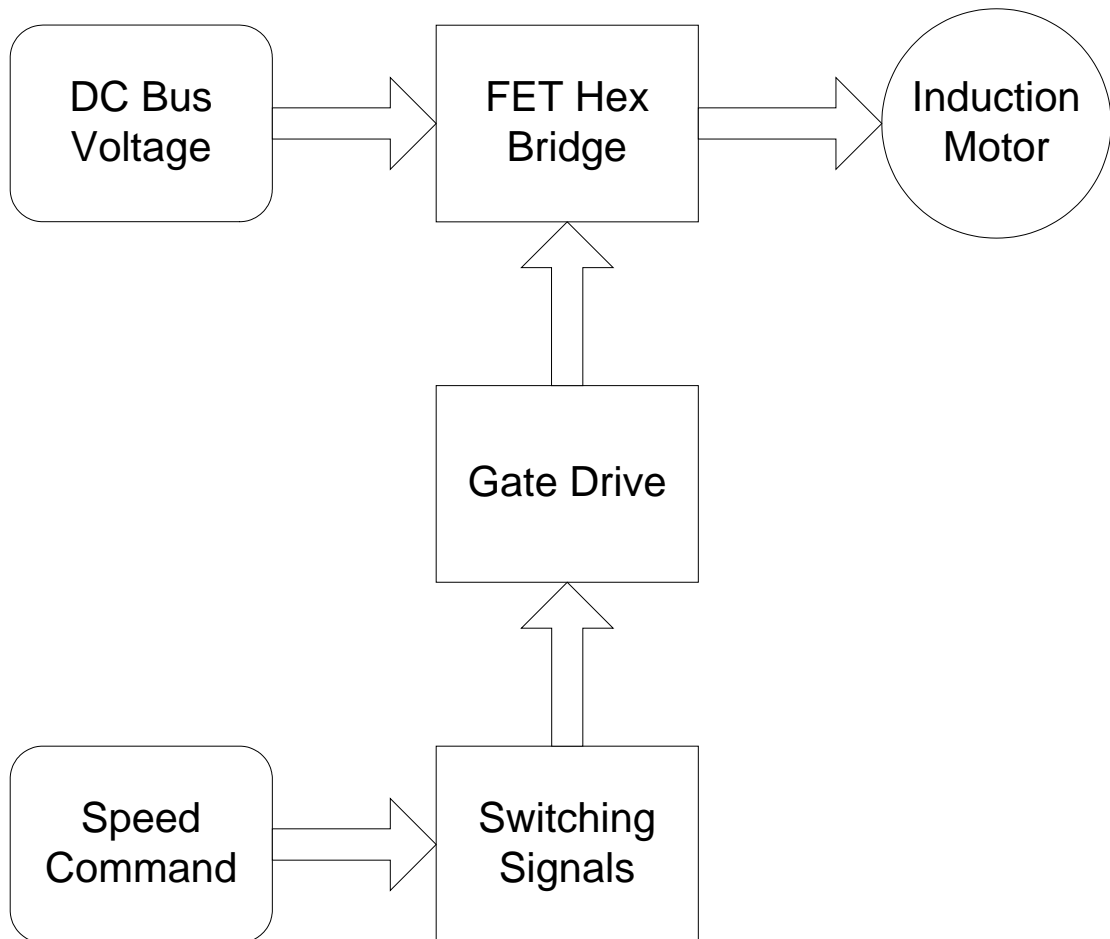


Figure 5.2. Overall block diagram of the project

CHAPTER SIX

RESULTS

The simulation results of open-loop ac drive system, classical optimal control system and genetic algorithm-based optimal control system are presented. All these results are supported by figures.

The figure (6.1) represents stator current versus time relationship for open loop

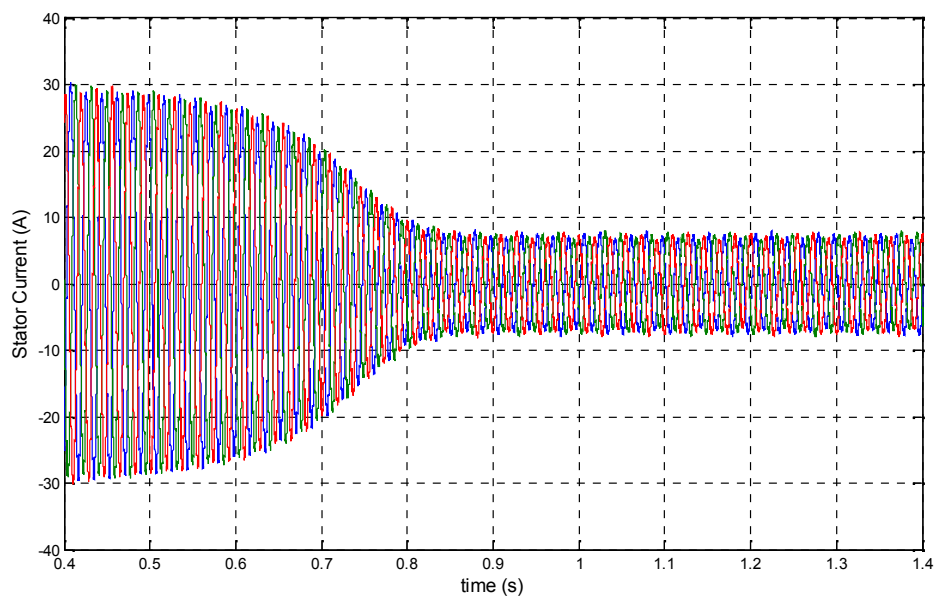


Figure 6.1. Stator current versus time relationship

The figure (6.2) represents input voltage of motor versus time

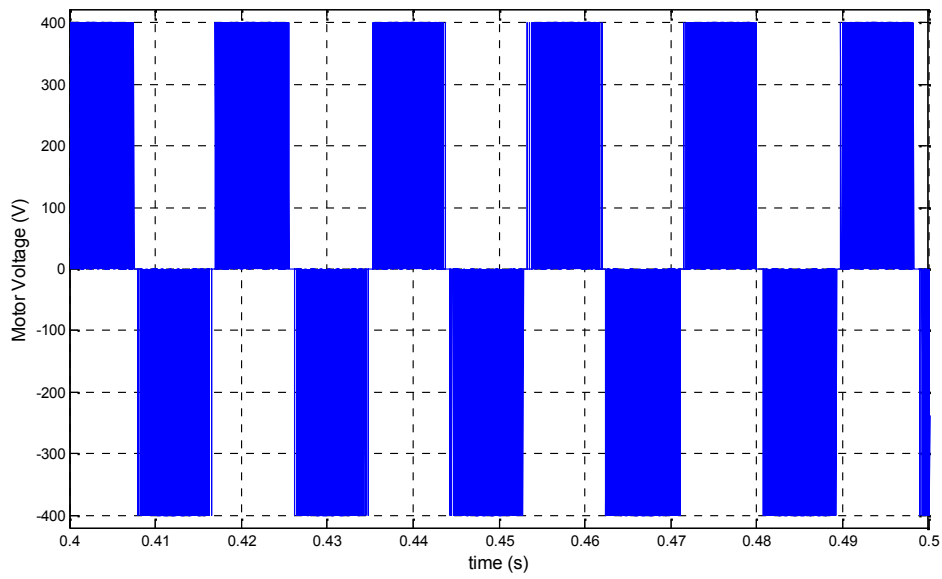


Figure 6.2. Input voltage of motor

The figure (6.3) represents the motor speed at the beginning and when its reach the saturation. In addition to the reference speed

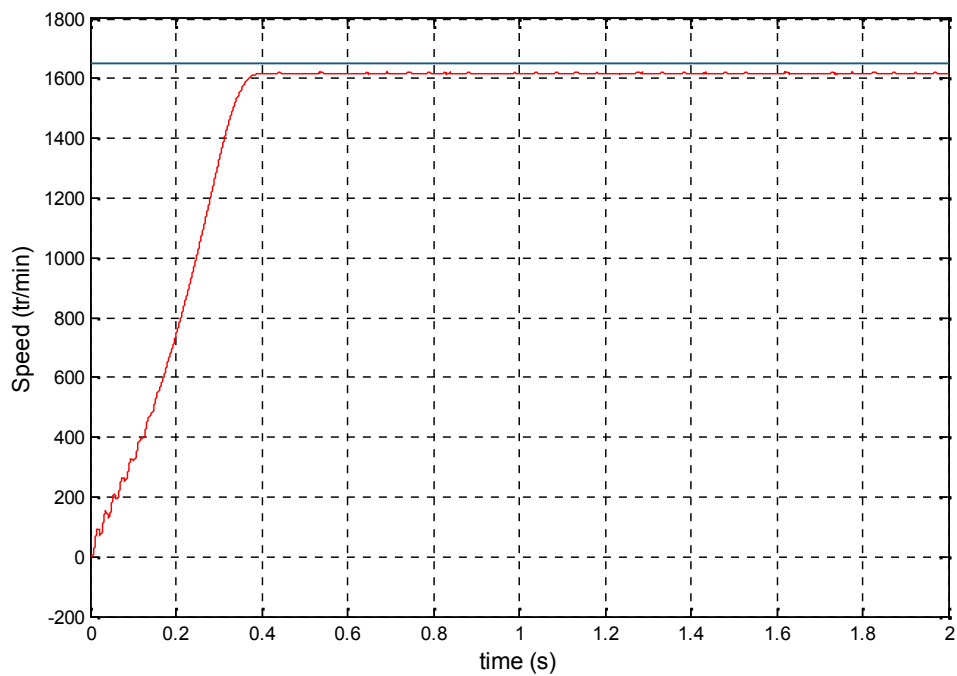


Figure 6.3. speed of motor and reference speed

The figure (6.3) represents the reference voltage

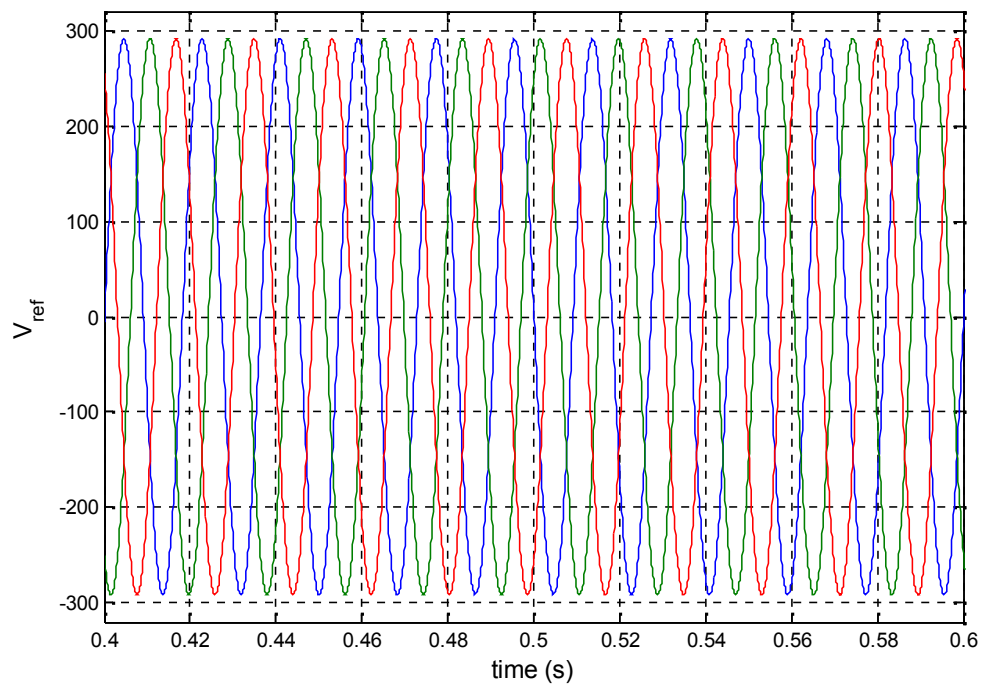


Figure 6.4. reference voltages versus time

The figure (6.5) represents the motor speed when more than once is changed at different speeds besides the reference speed

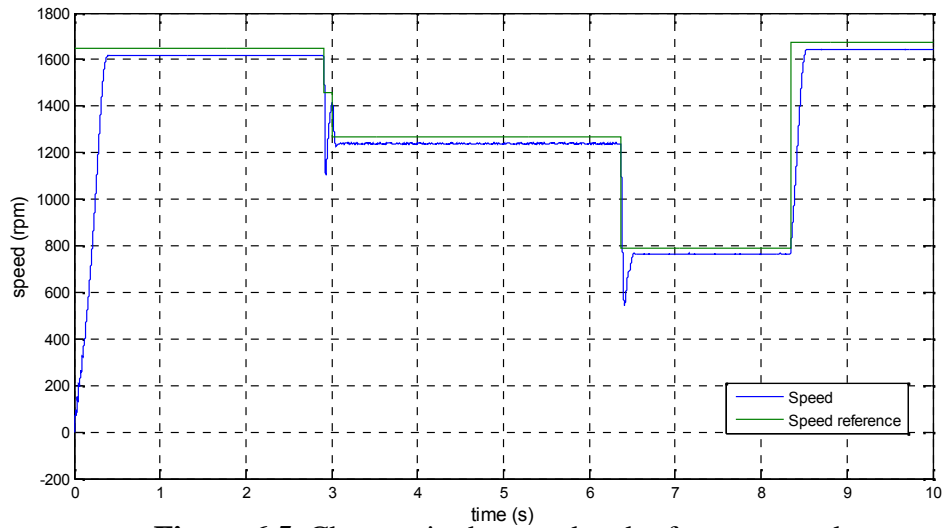


Figure 6.5. Changes in the speed and reference speed

The figure (6.6) represents the stator current when changing motor speed more than once and at different speeds

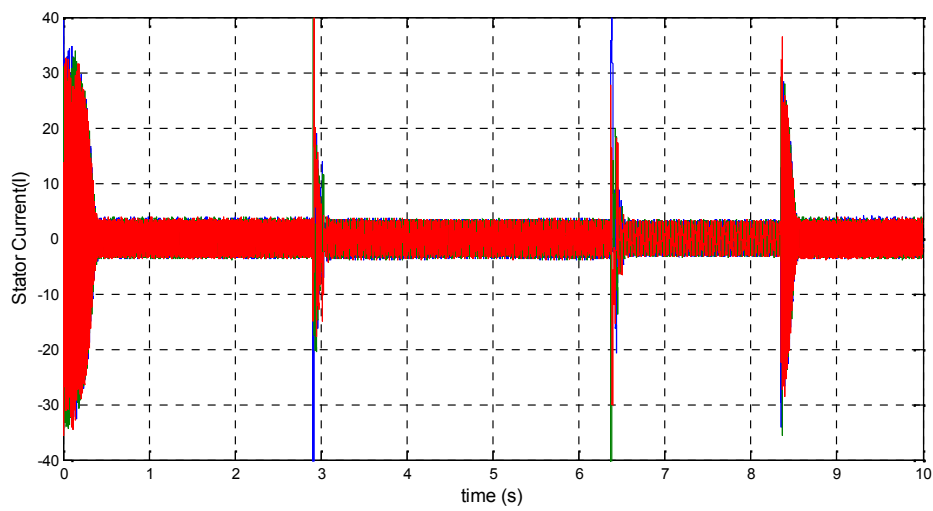


Figure 6.6. stator current at different speeds

The figure (6.7) represents the reference voltage when changing motor speed

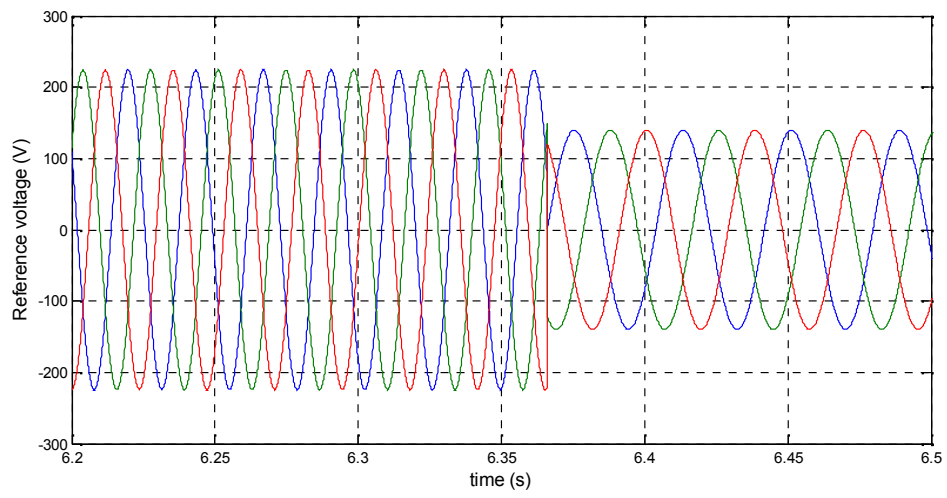


Figure 6.6. reference voltages when changing motor speed

CONCLUSION

PWM Inverters, both 1- and 3- were modeled and studied. The PWM signals were generated by comparing either a triangular waveform with a sinusoidal waveform using relational operators. These PWM signals were then applied to the gates of forced-commutation devices like IGBT's so as trigger them in a specific sequence to be able to convert the DC supply voltage to an AC output voltage. The DC supply could either be from a battery, a fuel cell, or from a rectifier which receives AC supply from the mains.

A 3- PWM Inverter was also fashioned using the Simulink Library blocks PWM Generator and Universal Bridge. In all cases, successful Inverter action was obtained.

An Induction Motor was run with the help of a PWM Inverter without implementing any kind of speed control mechanisms and the various characteristic curves were obtained. It was observed that there were a lot of transient currents in the stator and rotor at the time of starting and they took some time to settle down to their steady-state values. The lower the stator resistance, the quicker the transients died down and hence, the stator resistance should be kept very low. In an uncontrolled Induction Motor, torque was observed to rise to a maximum value and then settle at the base value, while rotor speed was observed to rise to its rated value and remain constant there.

Open-loop V/f Control was implemented using MATLAB and it was observed that by varying the supply frequency and terminal voltage such that the V/f ratio remains the same, the flux produced by the stator remained constant. As a result, the maximum torque of the motor remained constant across the speed range.

The development of the algorithm to perform the PWM operation using Matlab Simulink, and implementation to actual model using the Matlab/Real time workshop to control the speed of induction motor was successfully discussed. The acceleration and deceleration ramps as well as rotational direction switching functions were also functioning, proven by both Matlab simulation and implementation to the actual model. This method provides a means to control speed of induction motor remotely using a host PC, which may be connected through local area network or wireless network connection of the actual motor, IGBTs and keypad to the host PC.

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