CHAPTER 3

CONSTRUCTION AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR

3.1 INTRODUCTION

In this chapter the construction and speed control methods of induction motor are discussed. Three phase induction motor has a stator and a rotor. The stator carries a three phase stator winding and rotor may be having short circuited copper bars or rotor three phase winding. Only the stator winding is fed from 3-phase supply. The rotor winding derives its voltage and power from the externally energized stator winding through electromagnetic induction and hence the name.

Advantages

(i) It has simple and rugged construction.

(ii) It is relatively cheap.

(iii) It requires little maintenance.

(iv) It has high efficiency and reasonably good power factor.

(v) It has self-starting torque.
Disadvantages

(i) It is essentially a constant speed motor and its speed cannot be changed easily.

(ii) Its starting torque is inferior to D.C Shunt motor.

3.2 CONSTRUCTION OF INDUCTION MOTOR

A 3-phase induction motor has two main parts (i) Stator and (ii) Rotor. The rotor is separated from the stator by a small air-gap which ranges from 0.4 mm to 4 mm.

3.2.1 Stator

Stator consists of a steel frame which encloses a hollow, cylindrical core made up of thin laminations of silicon steel to reduce hysteresis and eddy current losses. A number of evenly spaced slots are provided on the inner periphery of the laminations. Stator laminations are shown in Figure 3.1.

![Figure 3.1 Stator lamination](image)
The 3-phase stator winding is wound for a definite number of poles as per requirement of speed. The greater the number of poles, lesser is the speed of the motor and vice-versa. When 3-phase supply is given to the stator winding, a rotating magnetic field of constant magnitude is produced. This rotating field induces currents in the rotor by electromagnetic induction.

3.2.2 Rotor

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:

i) Squirrel cage type

(ii) Wound type

i) Squirrel cage rotor

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 ring. 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. The squirrel cage rotor is shown in Figure 3.2.
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 enables the users 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.

ii) Wound rotor

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. Wound rotor is shown in Figure 3.3.
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. 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 the 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.

3.3 WORKING PRINCIPLE

When the rated AC supply is applied to the stator windings, it generates a magnetic flux of constant magnitude, rotating at synchronous speed. The flux passes through the air gap, sweeps past the rotor surface and through the stationary rotor conductors. An electromotive force (EMF) is induced in the rotor conductors due to the relative speed difference between the rotating flux and stationary conductors. The frequency of the induced
EMF is the same as the supply frequency. Its magnitude is proportional to the relative velocity between the flux and the conductors. Since the rotor bars are shorted at the ends, the EMF induced produces a current in the rotor conductors. The direction of the rotor current opposes the relative velocity between rotating flux produced by the stator and stationary rotor conductors. To reduce the relative speed, the rotor starts rotating in the same direction as that of flux and tries to catch up with the rotating flux. But in practice, the rotor never succeeds in catching up to the stator field. So, the rotor runs slower than the speed of the stator field. This difference in speed is called slip speed. This slip speed depends upon the mechanical load on the motor shaft. The frequency and speed of the motor, with respect to the input supply, are called the synchronous frequency and synchronous speed.

3.4 SPEED CONTROL

Synchronous speed is directly proportional to the ratio of supply frequency and number of poles in the motor. Synchronous speed of an induction motor is given in the Equation (3.1).

\[ N_s = \frac{120}{p} f \]  \hspace{1cm} (3.1)

Where \( f \) = rated frequency of the motor \( p \) = number of poles in the motor

Synchronous speed is the speed at which the stator flux rotates. Rotor flux rotates slower than synchronous speed by the slip speed. This speed is called the base speed. The speed listed on the motor nameplate is the base speed. Some manufacturers also provide the slip as a percentage of synchronous speed there are two basic ways of speed control, namely

(i) Slip-control for fixed synchronous speed. (ii) Control of synchronous speed.
A stricter sorting reveals the following methods

(i) Pole changing.
(ii) Stator voltage control.
(iii) Supply frequency control.
(iv) Eddy-current coupling.
(v) Rotor resistance control.
(vi) Slip power recovery

3.4.1 Vector Control

The vector control was formulated at the beginning of 1970s. The stator current is split into two orthogonal components. One component is in the direction of flux linkage that represents magnetizing current or flux component of the current. The second component is perpendicular to the flux linkage representing the torque component of the current. By varying both the components independently, the induction motor can be treated as separately excited DC motors. The implementation of vector control requires information regarding the magnitude and position of the flux vector. Depending upon the method of acquisition of flux information, the vector control or field oriented control method can be termed as direct or indirect. In the direct method the position of the flux to which orientation is desired strictly measured with the help of sensors, or estimated from the machine terminal variables such as speed and stator current / voltage signals (Takahashi et al 1986). The measured or estimated flux is used in the feedback loop, thus the machine parameters have minimal effect on the overall drive performance. But the measurement of flux using flux sensors necessitates a special manufacturing process or modifications in the existing
magnets. Also, direct field orientation method has its inherent problem at low speed where the voltage drops due to resistances are dominant, and pure integration is difficult to achieve. The indirect vector control was originally proposed in, eliminates the direct measurement or computation of the rotor flux from the machine terminal variables, but controls its instantaneous flux position by summing the rotor position signal with a commanded slip position signal. The direction of rotor position needs an accurate rotor speed information and the commanded slip position is calculated from the model of the induction motor, that again involves machine parameters which may vary with temperature, frequency and magnetic saturation. To get ideal decoupling, the controller should track the machine parameters and for this various adaptation methods have been proposed. However, it has been reported that the controller performance is adequate within normal operating temperatures for most of the high performance applications, and the parameter adaptations methods may be essential only in the case of critical applications. In contrast to direct method, the indirect method controls the flux in an open loop manner. The field orientation scheme can be implemented with reference to any of the three flux vectors: stator flux, air gap flux and rotor flux. It has been shown that out of the three orientations with respect to the rotor flux alone gives a natural decoupling between flux and torque. It also gives the fast torque response and better stability (Bose 2007).

3.4.2 Scalar Control

The scalar control takes into account the magnitude variation of control variance only. A variable voltage, variable frequency power source is needed for the control of an induction motor. Constant voltage by frequency control became simple, cheap after the advent of voltage source inverter. So it is one of the popular methods for speed control of induction motor. This aims at maintaining the same terminal voltage to frequency ratio so as to give a
nearly constant flux over a wide range of speed variation. Since flux is kept constant the full load torque capability are maintained constant under steady state condition except low speed (When an additional voltage boost is needed to compensate for stator winding voltage drop). In this control scheme, the performance of the machine improves in the steady state only, but the transient response is poor. More over constant V/f control keeps the stator flux linkage constant in steady state without maintaining decoupling between the flux and torque (Marcelo Suetake et al 2011). So due to inherent coupling effect the dynamic response of the drive is poor. To avoid open loop speed fluctuation due to variation in load torque and supply voltage, a closed loop V/f speed control scheme with slip regulation is normally used for stable operation of the drive under steady state. Scalar control drives were widely used in the industry, because it is simple to implement.

3.4.3 Speed-Torque Characteristics of Induction Motors

Figure 3.4 shows the typical speed-torque characteristics of an induction motor (Casadei 2002). The X axis shows speed and slip. The Y axis shows the torque and current. The characteristics are drawn with rated voltage and frequency supplied to the stator. During start-up, the motor typically draws up to seven times the rated current. This high current is a result of stator and rotor flux, the losses in the stator and rotor windings, and losses in the bearings due to friction. This high starting current overcomes these components and produces the momentum to rotate the rotor. At start-up, the motor delivers 1.5 times the rated torque of the motor. This starting torque is also called locked rotor torque (LRT). As the speed increases, the current drawn by the motor reduces slightly.
The current drops significantly when the motor speed approaches 80% of the rated speed. At base speed, the motor draws the rated current and delivers the rated torque. At base speed, if the load on the motor shaft is increased beyond its rated torque, the speed starts dropping and slip increases. When the motor is running at approximately 80% of the synchronous speed, the load can increase up to 2.5 times the rated torque. This torque is called breakdown torque. If the load on the motor is increased further, it will not be able to take any further load and the motor will stall (Mohamadian 2003). In addition, when the load is increased beyond the rated load, the load current increases following the current characteristic path. Due to this higher current flow in the windings, inherent losses in the windings increase as well. This leads to a higher temperature in the motor windings. Motor windings can withstand different temperatures, based on the class of insulation used in the windings and cooling system used in the motor. Some motor manufacturers provide the data on overload capacity and load over duty cycle. If the motor is overloaded for longer than recommended, then the motor may burn out. As
seen in the speed-torque characteristics, torque is highly nonlinear as the speed varies. In many applications, the speed needs to be varied, which makes the torque vary.

3.4.4 V/f Control Theory

In the v/f control which being a scalar control technique, only the magnitudes of the variables (Voltage and frequency) are varied. Scalar control, though easier to implement than vector control, provides inferior dynamic performance. The former cannot operate at peak performance under dynamically varying loads. In variable-speed applications in which a small variation of motor speed with loading is permissible, scalar control scheme can produce satisfactory performance. However, if precision control is required, then using the vector control system is essential. In scalar control, very little knowledge of the motor is required for frequency control. Consequently, this control is in wide use. Nevertheless, the loophole lies in the point that the torque developed is load dependent since it is not controlled directly. Besides, the transient response of such a control is sluggish due to the predefined switching configuration of the inverter. From the torque-speed characteristic curves, it can be seen that the same torque at the same value of slip speed will be obtained if we operate at a constant air gap flux. This, in fact is the basis for constant V/f control of an induction motor (Yashaevi & Basawaraj Amarapur 2012). This type of control may be executed either in open loop or in closed loop. Several real-life motor control applications do not demand a high dynamic performance, as long as the speed can be efficiently changed in the full range. This allows usage of a sinusoidal steady state model of the induction motor, in which the magnitude of the stator flux is proportional to the ratio between the magnitude and the frequency of the stator voltage. As long as this ratio is kept constant, the stator flux will remain constant, and as a result the motor torque will solely depend on the slip
frequency. Figure 3.5 shows the speed-torque characteristics of induction motor draws the rated current and delivers the rated torque at the base speed. When the load is increased speed will decrease. From earlier section it is understood that, the motor can take up to 2.5 times the rated torque with around 20% drop in the speed. Any further increase of load on the shaft can stall the motor. The torque developed by the motor is directly proportional to the magnetic field produced by the stator, the voltage applied to the stator is directly proportional to the product of stator flux and angular velocity (Marcelo Suetake 2011).

![Graph](image)

**Figure 3.5 Speed-torque characteristics under rated current and rated torque at the base speed**

This makes the flux produced by the stator proportional to the ratio of applied voltage and frequency of supply. By varying the frequency, the speed of the motor can be varied. Therefore, by varying the voltage and frequency by the same ratio, flux and hence, the torque can be kept constant throughout the speed range. This makes constant V/f the most common speed control of an induction motor (Soni & Anil Gupta 2013). Figure 3.5 shows the
relation between the voltage and torque versus frequency. Figure 3.5 demonstrates voltage and frequency being increased up to the base speed. At base speed, the voltage and frequency reach the rated values as listed on the nameplate. The motor can be driven beyond the base speed by increasing the frequency further. However, the voltage applied cannot be increased beyond the rated voltage. Therefore, only the frequency can be increased, which results in the field weakening and the torque reduction. Above base speed, the factors governing torque become complex, since friction and windage losses increase significantly at higher speeds. Hence, the torque curve becomes nonlinear with respect to speed or frequency. Speed control is one of the various application imposed constraints for the choice of a motor. Hence, in the last few years, it has been studied by many, and various methods for the same have been developed. Out of all the speed control mechanisms, the V/f control scheme is very popular because it provides a wide range of speed control with good running and transient performance. This control mechanism is referred to as scalar control mode. Here both the input and output commands are speed, unlike the Vector control mode where it is torque/flux and reference current, respectively (Amiri 2013). Even though vector control drives provide excellent performance in terms of dynamic speed regulation, implementation of the same is tedious owing to on-line coordinate transformations that convert line currents into two axis representation and vice versa. The field of power electronics has contributed immensely in the form of voltage-frequency converters which has made it possible to vary the speed over a wide range. However, the highly non-linear nature of the induction motor control dynamics demands strenuous control algorithms for the control of speed. The conventional controller types that are used for the aforementioned purpose are may be numeric or neural or fuzzy. The controller types that are regularly used are: Proportional Integral (PI), Proportional Derivative (PD), Proportional Integral Derivative (PID), Fuzzy Logic Controller (FLC) or a blend between them. The PID controller offers a
very efficient solution to numerous control problems in the real time
applications. If PID controllers are tuned properly, they can provide a robust
and reliable control. This very feature has made PID controllers exceedingly
popular in industrial applications. The only problem associated with the use of
conventional PI, PD and PID controllers in speed control of induction motors
is the complexity in design arising due to the non-linearity of Induction Motor
dynamics (Kumar 2013). The conventional controllers have to linearize the
non-linear systems in order to calculate the parameters. To obtain a perfect
non-linear model is almost impossible and hence the values of the parameters
that are obtained from it are thereby approximate. Again, Variable Speed
Drives (VSD) for Induction Motor (IM) require a wide operating speed range
along with a fast torque response, irrespective of the variations in load,
thereby leading us towards more advanced methods of control so as to meet
the real demand. The conventional control methods possess the following
difficulties:

1. Dependence on the exactness of the mathematical model of
   the system.

2. Expected performance not being met due to the load
disturbance, motor saturation and thermal deviations.

3. Decent performance exhibited only at one operating speed
   when classical linear control is employed.

4. Adopting the right coefficients for acceptable results.

From the above, it can be deduced that in order to implement
conventional control methodologies, it is necessary to have knowledge of the
system’s model that is to be controlled. The usual method of computation of
mathematical model of the induction motor is difficult, due to the non-
linearity of motor dynamics. Whenever a variation in the system or ambient
parameters arises, the system’s behavior becomes non-pleasing. The conventional controllers designed to provide high performance increase the design complexity along with the cost. Of late, soft computation techniques are being used widely in induction motor drives.

3.5 PULSE WIDTH MODULATION

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 (Kadri et al 2010). In the past, when only partial power was needed (such as for a sewing machine motor), a rheostat (located in the sewing machine’s foot pedal) connected in series with the motor adjusted the amount of current flowing through the motor, but also wasted power as heat in the resistor element. Though it was an inefficient scheme, it was tolerable because the total power was low. This was one of several methods of controlling power. There were others some still in use such as variable auto transformers, including the trademarked Autrastat for theatrical lighting; and the Variac, for general AC power adjustment. These were quite efficient, but also relatively costly. For about a century, some variable-speed electric motors have had decent efficiency, but they were somewhat more complex than constant-speed motors, and sometimes required external electrical apparatus, such as a bank of variable power resistors. However, there is a great need for applying partial power in other devices, such as electric stoves, lamp dimmers, and robotic servos. Basically, a PWM variable-power scheme switches the power quickly between fully on and fully off. In any event, the switching rate is much faster than what would affect the load, which is to say the device that uses the power. In practice, applying full power for part of the time does not cause any problems; PWM is very
practical (Arulmozhiyal 2009). The term duty cycle describes the proportion of on time to the regular interval or period of time; a low duty cycle corresponds to low power, because the power is off for most of the time. Duty cycle is expressed in percent, 100% being fully on. PWM works well with digital controls, which, because of their on/off nature, can easily set the needed duty cycle. PWM of a signal or power source involves the modulation of the PWM duty cycle is effected to either convey information over a communications channel or control the amount of power sent to a load.

3.5.1 Space Vector Pulse Width Modulation (SVPWM)

The Space Vector Pulse Width Modulation (SVPWM) method is an advanced, computation-intensive PWM method and possibly among the best. The inverter switching sequence is given in Table 3.1.

Table 3.1 Switching sequence

<table>
<thead>
<tr>
<th>Vector</th>
<th>A+</th>
<th>B+</th>
<th>C+</th>
<th>A-</th>
<th>B-</th>
<th>C-</th>
<th>VAB</th>
<th>VBC</th>
<th>VCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>V0={000}</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Zero Vector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V1={100}</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>+Vdc</td>
<td>0</td>
<td>-Vdc</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Active vector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V2={110}</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>0</td>
<td>+Vdc</td>
<td>-Vdc</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Active vector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V3={010}</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>-Vdc</td>
<td>+Vdc</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Active vector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V4={011}</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>-Vdc</td>
<td>0</td>
<td>+Vdc</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Active vector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V5={001}</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>0</td>
<td>-Vdc</td>
<td>+Vdc</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Active vector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V6={101}</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>+Vdc</td>
<td>-Vdc</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Active vector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V7={111}</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Zero vector</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
All the PWM techniques for variable frequency drive application. Because of its superior performance characteristics, it has found widespread application in recent years (Marcelo Suetake 2011). The PWM methods so far have considered only the implementation of half bridge operated independently, giving a satisfactory PWM performance. Space vector modulation (SVM) is an algorithm for the control of pulse width modulation (PWM) (Sujeet Kumar Soni et al 2013). It is used for the creation of alternating current (AC) waveforms most commonly it is employed to drive 3 phase AC powered motors at varying speeds from DC, using multiple class-D amplifiers. The various variations of SVM that result in different quality and computational requirements. One active area of development is in the reduction of total harmonic distortion (THD) created by the rapid switching inherent in those algorithms. A three phase inverter as shown to the right must be controlled so that at no time are both switches in the same leg turned on or else the DC supply would be shorted (Kadri et al 2010). This requirement may be met by the complementary operation of the switches within a leg. If A⁺ is on then A⁻ is off and vice versa. Basic active vectors and null vectors are shown in Figure 3.6.

![Figure 3.6 Basic active vectors and null vectors](image-url)
This leads to eight possible switching vectors for the inverter, $V_0$ through $V_7$ with six active switching vectors and two zero vectors. To implement space vector modulation a reference signal $V_{ref}$ is sampled with a frequency $f_s (T_s = 1/f_s)$. The reference signal may be generated from three separate phase references using the $\alpha\beta\gamma$ transform. The reference vector is then synthesized using a combination of the two adjacent active switching vectors and one or both of the zero vectors. Various strategies of selecting the order of the vectors and which zero vector(s) to use exist. Strategy selection will affect the harmonic content and the switching losses. All eight possible switching vectors for a three-leg inverter using space vector modulation. An example $V_{ref}$ is shown in the first sector. $V_{ref\_max}$ is the maximum amplitude of $V_{ref}$ before non-linear over modulation is reached. More complicated SVM strategies for the unbalanced operation of four-leg three-phase inverters do exist.

3.6 CONCLUSION

In this chapter the construction of three phase induction motors, speed torque characteristics and various speed control methods were discussed. In this research work SVPWM inverter based three phase squirrel cage induction motor V/f control is presented. So this chapter particularly, focuses on the squirrel cage induction motor, scalar control and SVPWM technique.