Chapter – II

CHAPTER 2

MULTIPHASE INDUCTION MOTORS

2.1. INTRODUCTION

Three phase motors have been in use more frequently for last century. However, there has been a growing interest in multiphase motors in application areas where high power, high torque and reliability is a prime target. Development of application areas like traction, aerospace, hybrid electric vehicles, ship propulsion have provided the motivation for research in multiphase motors [1, 20]. In this section multiphase induction motors are discussed in detail with equivalent circuit of six phase induction motor.

2.1.1 Multiphase Induction motor

In traditional electric machine applications a three-phase stator winding is selected, since the three-phase supply is readily available. However, when an AC machine is supplied from an inverter, the need for a predefined number of phases on stator, such as three, disappears and other phase numbers can be chosen. [51]

Probably the first proposal of a multiphase variable speed electric drive dates back to 1969 [20]. While [12, 33] proposed a five phase induction motor drive, a six-phase (double star) induction machine supplied from a six-phase inverter was examined in [28, 29]. The early interest in multiphase machines was caused by the possibility of reducing the torque ripple in inverter fed drives, when compared to the three-phase case. Another advantage of a multiphase motor drive over a three-phase motor drive is an improved reliability due to fault tolerance features, this being one of the main reasons behind the application of six-phase (double-star) and nine-phase (triple-star) induction motor drives in locomotives [48]. The other main reason is that for a given motor rating, an increase of the number of phases enables reduction of the power per phase, which translates into a reduction of the power per inverter leg (that is, a semiconductor rating). Multiphase machines are therefore often considered for and applied in high power applications [1, 5, 7]. Other advantages of multiphase machines over their three-phase counterparts include an improvement in the noise characteristics and a possibility of reduction in the stator copper loss, leading to an improvement in the efficiency. Vector control principles can be extended from a three-phase to a multiphase motor in a simple manner when the machine torque is produced by the fundamental stator current component only. For example, vector control of a five-phase induction motor is elaborated in [12]. In principle, there is not any difference with regard to the vector control scheme between a three-phase and an m-phase machine.

Multiphase motor drives have been proposed for different applications where some specific advantages (lower torque pulsations, less DC link current harmonics, higher overall system reliability, etc) can be better exploited justifying the higher complexity in contrast to the three-phase solution [2]. Some of the most suitable applications are the high current ones (ship propulsion, aircraft applications, locomotive traction, electrical vehicles), where the main advantage of multi-phase drives is the splitting of the controlled power (current) on more inverter legs, reducing the single switch current stress compared to the three-phase converters. Since the power switches rated current is reduced proportionally with the phase number, the increased number of power switches does not represent an additional cost; on the contrary, in some cases the cost is reduced by the "non-linearity" of the component prices. However, the system cost (and complexity) is penalized by the increased number of the current sensors, gate drive circuits, additional circuitry power supply, etc. Among the different multi-phase induction drives solutions, the dual-3-phase induction machine having two stator winding sets spatially shifted by 30 electrical degrees with separated neutral has important advantages [3-4]:

1. The current stress of each semiconductor power device is reduced by one half compared with the same power 3-phase machine counterpart.

2. The dual-3-phase solution can benefit of the wide availability of components dedicated to 3-phase systems.

3. These electrical machines are convenient in high power and/or high current applications, such as ship propulsion, aerospace applications, and electric/hybrid vehicles (EV). In applications like EV, often the low available DC-link voltage imposes high phase current for a 3-phase machine. In this case, the dual-3-phase induction machine is an interesting alternative to the conventional 3-phase counterpart.

2.1.1 (A) Split Phase Induction Motors

Split-phase electrical machines consist of two similar stator windings sharing the same magnetic circuit. Such a construction made it possible to extend the power range of solid-state based drives by sharing the total power between two drives [8]. Usually a split-phase machine is built by splitting the phase belt of a conventional three-phase machine into two equal parts with spatial phase separation of 30 electrical degrees. By using this arrangement, for the same air gap flux, the inverter dc bus voltage can be reduced by approximately a half, compared to a three-phase system, since the number of turns per phase is reduced [29]. Such structure has a disadvantage of the need for two or more inverters to drive the machine.

Another advantage of using this kind of winding arrangement is harmonic cancellation. The sixth harmonic torque pulsation, which is common in a six-step three-phase drive, can be eliminated by using split-phase arrangement.

As in split-phase machines, the dual-stator machines consist basically of two independent stator windings sharing the same magnetic frame. Differently, a dual stator machine does not necessarily have similar winding groups. For example, a 6 different voltage rating or a different number of phases could be used for each winding group.

For instance, two independent stator windings may be used for an induction generator system [30]. One set of windings may be responsible for the electromechanical power conversion (i.e. driving the load) while the second one is used for excitation purposes. This eliminates the need of a converter rated to full load power in a vector controlled induction generator [30, 35]. The same idea can be used for power factor correction in induction motors. One of the two different sets of three-phase windings may be connected to the main power and carry the active power responsible for the torque production while the second winding carries the reactive power.

2.1.1 (B) Dual Stator Motor

Using a dual-stator machine which is a particular case of a multi-phase machine, the power ratings may be extended without the need to use multi-level converters. Instead of increasing the power rating of a three-phase converter using multi levels for the converter, additional phases are added and the current is shared by additional inverter legs.

The six-phase machine is a particular case of split-phase or dual-stator machine. It can be built by splitting a three-phase winding into two groups. These three-phase groups are shifted by thirty electrical degrees from each other. This composes an asymmetrical six-phase machine since the angular distance between phases is not the same. Figure 2.1 shows the representation of the machine stator windings for Y connection and a simplified construction diagram for a concentrated-winding, a method which is similar to that of a three-phase machine can be adopted in analyzing a six-phase induction machine.

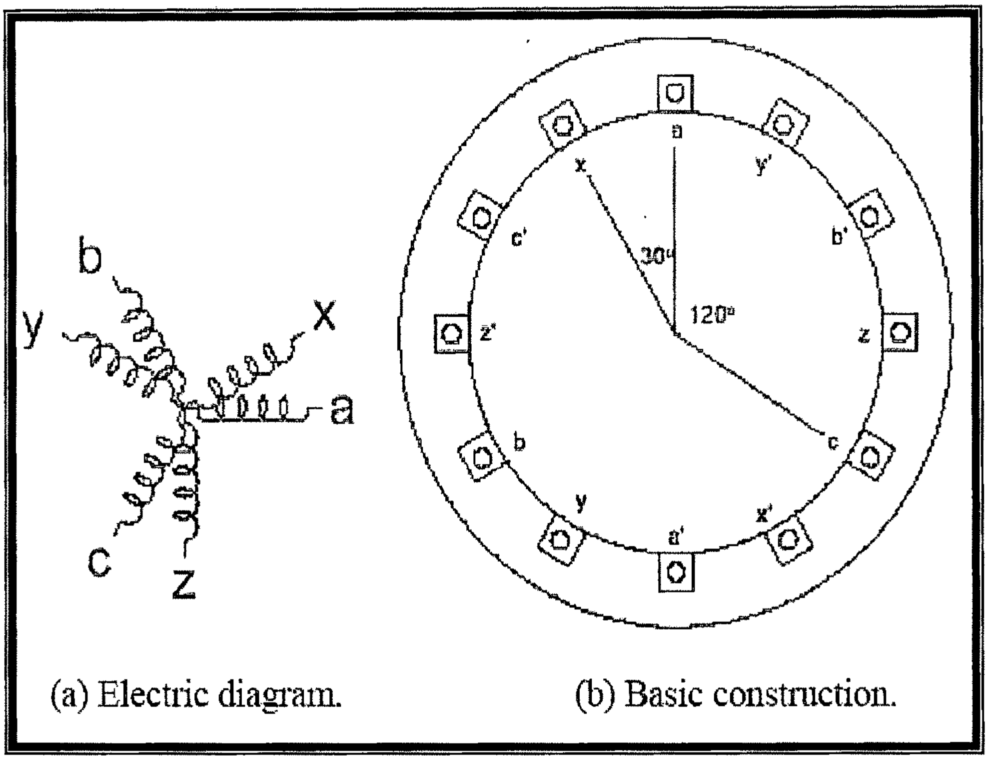


Figure 2.1 Six phase Machine

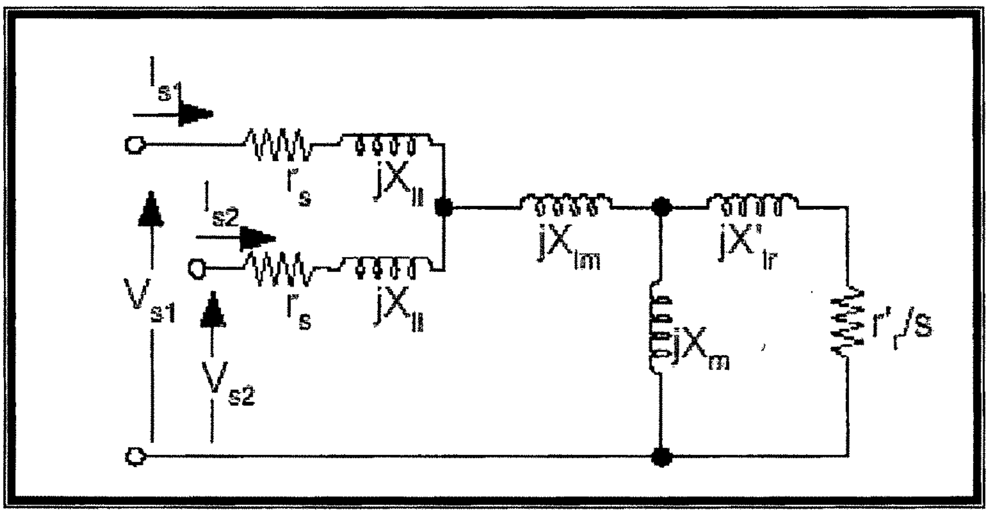
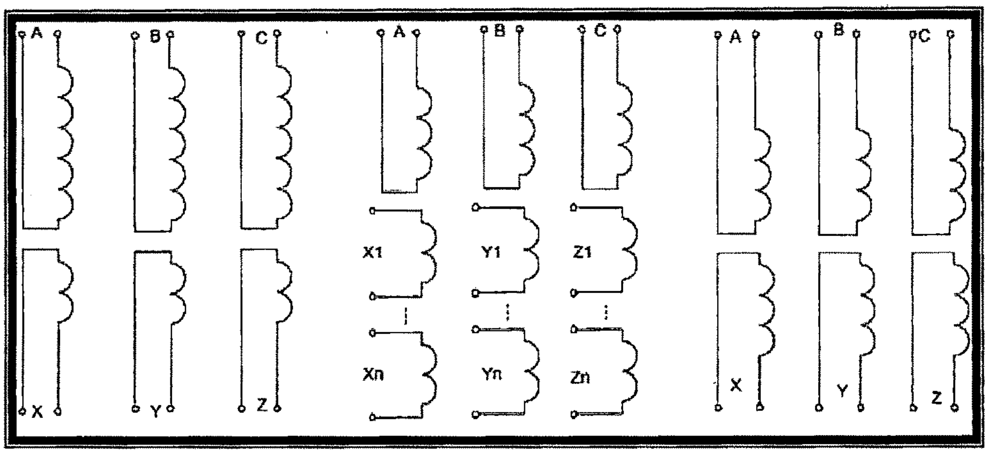


Figure 2.2 Equivalent Circuit of Six phase IM for sinusoidal steady state

In Figure 2.2, the steady-state equivalent circuit for sinusoidal excitation which is similar to the one of a conventional three-phase machine with the addition of an extra stator circuit is shown. When compared to three phase induction motor equivalent circuit, the six phase motor has two stator currents as shown, i.e. I_{S1} and I_{S2} . Also voltages across stator 1 and 2 are V_{S1} and V_{S2} respectively. Two stators are identical so that I_{S1} = I_{S2} and $V_{S1} = V_{S2}$. Similarly stator resistance and reactance for both the stators are same. Thus six phase induction motor can be considered as, two identical three phase motors sharing same magnetic circuit, electrically separate and common shaft.

Basically, the six-phase induction motor was introduced with two objectives. First, the opportunity to divide the output power into two three-phase groups allows the increase in the drive system power ratings. Secondly, for use with six step inverters, the pulsating torque in a six-phase machine is lower than in a three phase machine. Another reason for using six-phase systems is reliability. When a failure happens in one of the phases, in the machine or in the power converter, the system can still operate at a lower power rating since each three-phase group can be made independent from each other. In the case of losing one phase, the six-phase machine can be operated as a five-phase machine as described in [41].



(a) Split Phase (b) Dual Stator (c) Six Phase

Figure 2.3 Illustration of Six phase windings

Dual-stator machines are similar to split-phase machines with the difference that the stator groups are not necessarily equal. As a particular case of split-phase or dual-stator machine, the six-phase machine can be built by splitting a three-phase winding into two groups. Usually these three-phase groups are displaced by thirty electrical degrees from each other. This arrangement composes an asymmetrical six-phase machine since the angular distance between phases is not all the same [41].

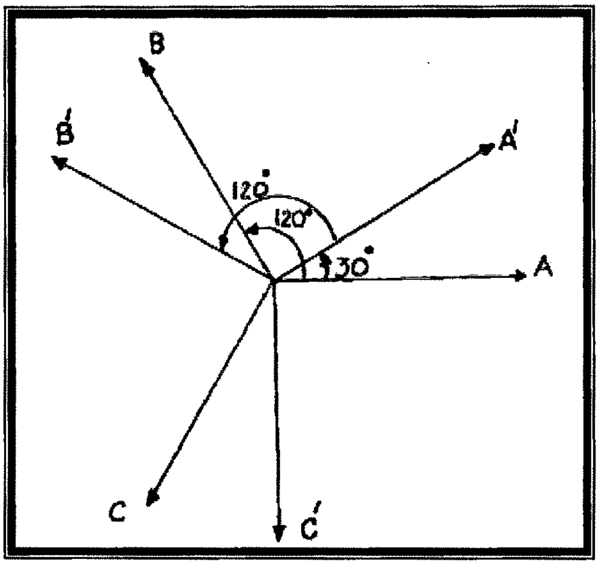


Figure 2.4 Phasor diagram for split phase IM

The split-phase motor configuration is achieved by splitting the phase belt of a conventional three-phase motor into two equal halves with a phase separation of **30”** between the two (Fig. 2.4). The split phase groups, namely *ABC* and *A'B'C'* (Fig. 2.5) are controlled by two inverters with a dc link voltage of V_{DC} / (2 cosl5) each. In figure 2.5, the n sets of three-phase windings are spatially phase shifted by 60^0/n electrical degrees.

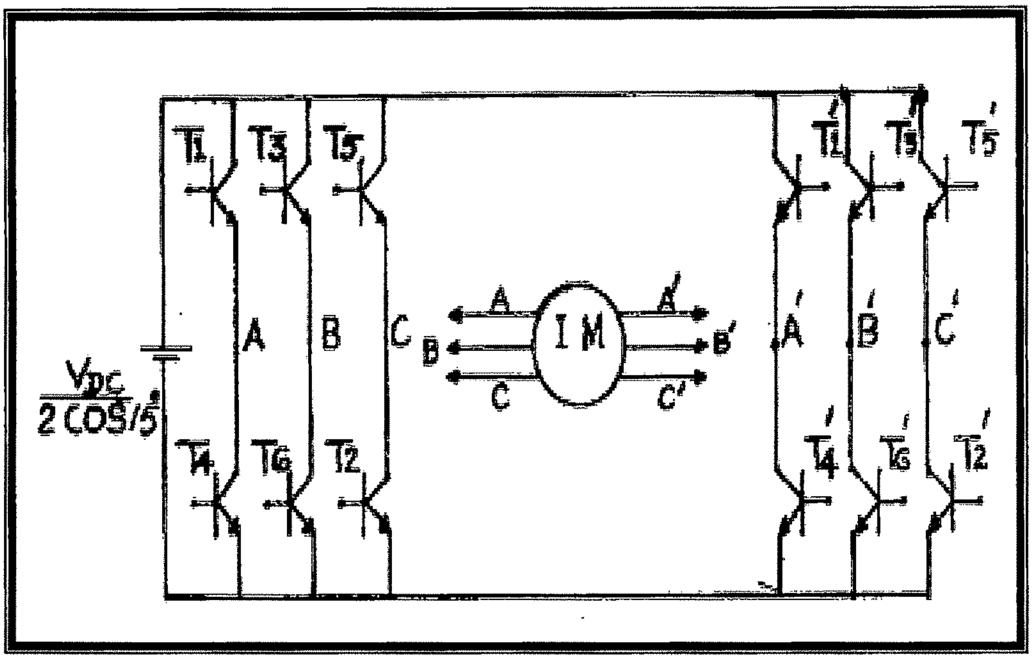


Figure 2.5 Split Phase Induction motor drive

2.2. MODELING OF SIX PHASE INDUCTION MOTOR

The dual three-phase induction machine is a six dimensional system. Therefore, modeling and control of this machine in the original reference frame would be very difficult. For this reason, it is necessary to obtain a simplified model to control it. To derive this model, some assumptions must be made like the sinusoidal distribution of the stator and rotor windings.

Moreover, the magnetic saturation, the mutual leakage inductances and the core losses must be neglected. If so, the voltage equations in the original phase coordinates can be expressed as:

$$[V_s] = [R_s][i_s] + p[\lambda_s]$$
$$= [R_s].[i_s] + p([L_{ss}].[i_s] + [L_{sr}(\delta_r)].[i_r]) \qquad [2.1]$$

$$[\theta] = [R_r].[i_r] + p[\lambda_r]$$
$$= [R_r].[i_r] + p([L_{rr}].[i_r] + [L_{rs}(\delta_r)].[i_s]) \qquad [2.2]$$

Where **θ** is the rotor angular position and *p=d/dt*

For analysis and control purposes, the original six dimensional machine systems can be decomposed into three two-dimensional orthogonal subspaces (α, β),

(μ_1 , μ_2) and (z_1, z_2) by using the transformation matrix T6

$$\mathbf{T_6} = \mathbf{K} \begin{bmatrix} 1 & -1/2 & -1/2 & \sqrt{3}/2 & -\sqrt{3}/2 & 0 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 & 1/2 & -1/2 & -1 \\ 1 & -1/2 & -1/2 & -\sqrt{3}/2 & \sqrt{3}/2 & 0 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 & 1/2 & 1/2 & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \qquad \mathbf{[2.3]}$$

, K =1/3

Thus, applying the matrix (2.3) to the voltage equations (2.1), (2.2) yields:

As shown in [6]-[7], the machine model can be divided into three sets of decoupled equations, corresponding to the three subspaces (α, β), (μ_1, μ_2) and (z_1, z_2).

$$[T_6] = [T_6].[R_s].[T_6^{-1}].[T_6].[i_s] + p.\begin{pmatrix}[T_6].[L_{ss}].[T_6^{-1}].[T_6].[i_s] \\ + [T_6][L_{ss}][T_6^{-1}][T_6][i_r]\end{pmatrix} \quad \textbf{[2.4]}$$

$$[\theta] = [T_6][R_s][T_6^{-1}][T_6][i_r] + p.\begin{pmatrix}[T_6].[L_{rr}].[T_6^{-1}].[T_6].[i_r] \\ + [T_6].[L_{rs}].[T_6^{-1}].[T_6].[i_s]\end{pmatrix} \quad \textbf{[2.5]}$$

$$\begin{bmatrix} Vs\alpha \\ Vs\beta \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Rs + Ls.p & 0 & M.p & 0 \\ 0 & Rs + Ls.p & 0 & M.p \\ M.p & \omega r.M & Rr + Lr.p & \omega r.Lr \\ -\omega r.M & M.p & -\omega r.Lr & Rr + Lr.p \end{bmatrix} .[\mathbf{i_{s\alpha}}\ \mathbf{i_{s\beta}}\ \mathbf{i_{r\alpha}}\ \mathbf{i_{r\beta}}]^t$$

[2.6]

The (α, β) machine model is similar to the three-phase machine model in the stationary reference frame. Thus, equation (2.6) can be rewritten using the space vectors mapped in the (α, β) subspace.

$$\overline{v}_s = R_s \cdot \overline{i}_s + p \cdot \overline{\lambda}_s$$

$$0 = R_r \cdot \overline{i}_r + p \cdot \overline{\lambda}_r - j \cdot \omega_r \cdot \overline{\lambda}_r \qquad [2.7]$$

Where the flux linkage vectors are expressed as:

$$\overline{\lambda}_s = L_s \cdot \overline{i}_s + M \cdot \overline{i}_r$$

$$\overline{\lambda}_s = L_r \cdot \overline{i}_r + M \cdot \overline{i}_s \qquad [2.8]$$

The machine model in (μ_1 , μ_2) subspace can be expressed by equations (2.9), and in (z_1, z_2) subspace by equations (2.10).

$$\begin{bmatrix} v_{su1} \\ v_{su2} \end{bmatrix} = \begin{bmatrix} R_s + L_{ls} \cdot p & 0 \\ 0 & R_s + L_{ls} \cdot p \end{bmatrix} \cdot \begin{bmatrix} i_{su1} \\ i_{su2} \end{bmatrix}$$

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_r + L_{lr} \cdot p & 0 \\ 0 & R_r + L_{lr} \cdot p \end{bmatrix} \cdot \begin{bmatrix} i_{ru1} \\ i_{ru2} \end{bmatrix} \qquad [2.9]$$

$$\begin{bmatrix} v_{sz1} \\ v_{sz2} \end{bmatrix} = \begin{bmatrix} R_s + L_{ls} \cdot p & 0 \\ 0 & R_s + L_{ls} \cdot p \end{bmatrix} \cdot \begin{bmatrix} i_{sz1} \\ i_{sz2} \end{bmatrix}$$

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_r + L_{lr} \cdot p & 0 \\ 0 & R_r + L_{lr} \cdot p \end{bmatrix} \cdot \begin{bmatrix} i_{rz1} \\ i_{rz2} \end{bmatrix} \qquad [2.10]$$

The following can be noted:

1) The electromechanical energy conversion variables are mapped in the (α, β) subspace, while the non electromechanical energy conversion variables can be found in the two other subspaces.

2) The current components in the (μ_1, μ_2) and (z_1, z_2) subspaces do not contribute to the air-gap flux and are limited only by the stator resistance and stator leakage inductance, which is usually small. These currents will only produce losses and consequently should be controlled to be as small as possible.

3) The control of the dual three-phase machine is greatly simplified since it can be solved with the equivalent circuit in the (α, β) subspace, being similar to the equivalent circuit of a three-phase machine. Finally we get two phase equivalent of six phase.

2.3. ADVANTAGES OF SIX PHASE IM OVER THREE PHASE IM

Variable-speed AC motor drives with more than three phases (multi-phase drives) have several advantages when compared to the standard three-phase realizations [20, 21]: the current stress of the semiconductor devices decreases proportionally with the phase number, torque ripple is reduced, rotor harmonic currents are smaller, power per rms ampere ratio is higher for the same machine volume and harmonic content of the DC link current for VSI fed drives is reduced. Other advantages include an improvement in the noise characteristics [30, 39] and a reduction in the stator copper loss, leading to improved efficiency. Further advantages are related to the higher reliability at the system level, since a multi-phase drive can operate with an asymmetrical winding structure in the case of loss of one or more inverter legs/machine phases, the operation is maintained though at reduced rating. [41].

2.4. CONCLUSION

This chapter is devoted to theory of multiphase induction motor, modeling of six phase motor and its comparison with three phase motors. The advantages of six phase induction motor over three phase are discussed.

Applications of multi-phase induction motor drives are mainly related to the high-power/high-current applications, such as for example in electric ship propulsion in locomotive traction and in electric/hybrid electric vehicles.