Mathematical Modeling of Five-Phase and Three-Phase Induction Motor and their Result Comparison

Veldandi Vamshi Saikumar¹, B Sathyavani² and J Suresh³

¹ PG Scholar, S R Engineering College, Warangal, Telangana, India. Pin: 506371.
² Department of Electrical and Electronics Engineering, S R University, Warangal, Telangana, India. Pin: 506371.
³ Department of Electrical and Electronics Engineering, Sumathi Reddy Institute of Technology, Warangal, Telangana, India. Pin: 506371

Email: Saikumar.vamshi@hotmail.com

Abstract: In this paper, the mathematical model of three-phase and five-phase induction motors has been developed using PARK’S Transformation and implemented in MATLAB SIMULINK. This Mathematical modelling plays a key role in analyzing the system and its algorithms. Both the models have been tested under loaded and No load condition to find a comparative analysis. The main focus of this paper is to determine the increased capability of motor in switching from three phase to five phase.

Index Terms - mathematical modeling, five-phase, three-phase, induction motor

1. INTRODUCTION

With Rapid spike in industrialization, there has been a huge demand for heavy and robust equipment. Mostly in industries, the rating of induction motor required is very high. As the structure of induction motors have been rugged and most suitable for rough environments, several research has been done on them leading to buildout of multi-phase induction motors such as five-phase and six-phase induction motors. And one of the main reason for developing multi-phase induction motors is, notably in varying speed electrical drives the interlinking circuit between supply side and motor is inverter. As such increasing of the number of limbs in inverter is not restricted technically, and thus any number of phases can be acquired from an inverter. So this has paved path for improvement of multi-phase induction motors and their drive systems. The various applications of five phase induction motors is rolling mills, ship propulsion, Electric vehicles, Hybrid electric vehicles [1], Wind energy systems, Traction. The main reason for switching from three-phase induction motor to five-phase induction motor is because of the following advantages.
a) Reliability of the overall system is much higher.
b) Significant reduction in total power per phase.
c) Less acoustic noises.
d) Lesser vibrations.
e) Higher fault tolerance [2].
f) Reduced torque pulsation [3].
g) Better power distribution per phase.
h) The excitation waveform is less susceptible to time harmonic components.

Mathematical model is the very fundamental and vital step to get an efficient and reliable electrical machine. More the accurate mathematical model, more the efficiency and reliability. Despite the fact that mathematical modeling of induction motor has very old history and there is still lot of work needed to be done, to get a better replica of induction motor. Different models has been proposed for different applications such as for prediction of behaviour of system, analysis of the system, fault analysis, flux level control. A reliable motor depends on its accurate design and perfect parameter estimation.

2. MATHEMATICAL MODELING OF FIVE PHASE INDUCTION MOTOR

The mathematical machine modeling in state space form is significant for transient analysis. Despite the fact that rotating frame model is typically opted, but the model of stationary frame has been using now extensively. The parameters in the model can be selected as currents, fluxes, or a concoction of both. Given below the derived state space equations for motor in rotating frame with flux linkages as the primary variables. The five phase voltages are assumed as

\[ V_{as} = V_m \sin(\omega_e t) \]  
\[ V_{bs} = V_m \sin\left(\omega_e t - \frac{2\pi}{5}\right) \]  
\[ V_{cs} = V_m \sin\left(\omega_e t - \frac{4\pi}{5}\right) \]  
\[ V_{ds} = V_m \sin\left(\omega_e t - \frac{6\pi}{5}\right) \]  
\[ V_{es} = V_m \sin\left(\omega_e t - \frac{8\pi}{5}\right) \]  

Where, \( V_m \) is the peak value of terminal voltage \( \omega_e \) is the supply frequency in radians per second

These stationary reference frame variables is converted into two phase stationary reference frame variables using decoupling transformation matrix [4]. The decoupling transformation matrix is given below.

\[
\begin{bmatrix}
V_{dS}^s \\
V_{qS}^s \\
V_{xS}^s \\
V_{yS}^s \\
V_{0S}^s
\end{bmatrix}
= \frac{2}{5}
\begin{bmatrix}
1 & \cos\alpha & \cos2\alpha & \cos3\alpha & \cos4\alpha \\
0 & -\sin\alpha & -\sin2\alpha & -\sin3\alpha & -\sin4\alpha \\
1 & \cos3\alpha & \cos6\alpha & \cos9\alpha & \cos12\alpha \\
0 & -\sin3\alpha & -\sin6\alpha & -\sin9\alpha & -\sin12\alpha \\
0.5 & 0.5 & 0.5 & 0.5 & 0.5
\end{bmatrix}
\begin{bmatrix}
V_{as} \\
V_{bs} \\
V_{cs} \\
V_{ds} \\
V_{es}
\end{bmatrix}
\]  

Where \( \alpha = \frac{2\pi}{5} \)

\( V_{dS}^s \) and \( V_{qS}^s \) are the \( d^s \) and \( q^s \) axis stator fundamental voltages. \( V_{xS}, V_{yS}, V_{0S} \) are the extra components of stator considered so as it will be useful during inverse transformation from dq to abc.
These two phase stationary reference frame variables are transformed into synchronously rotating reference frame, ignoring the zero sequence components as shown below [5].

\[
V_{qs} = V_{qs}^s \cos \theta_e - V_{ds}^s \sin \theta_e
\]  
\[
V_{ds} = V_{qs}^s \sin \theta_e + V_{ds}^s \cos \theta_e
\]

Where, $V_{ds}$ and $V_{qs}$ are the $d$ and $q$ axis synchronously rotating voltages, which rotate at synchronous speed $\omega_e$ with respect to $d^s$ and $q^s$ axis and the angle $\theta_e = \omega_e t$.

The block diagram for this conversion is shown in Figure 1.

The stator circuit equations are defined as

\[
V_{qs} = R_s i_{qs} + \frac{d}{dt} \psi_{qs} + \omega_e \psi_{ds}
\]
\[
V_{ds} = R_s i_{ds} + \frac{d}{dt} \psi_{ds} - \omega_e \psi_{qs}
\]

The last terms in above equations is defined as speed emf due to rotation of the axes, that is, when $\omega_e = 0$, the equations reverse back to stationary form.

Similarly the rotor circuit equations are defined as,

\[
V_{qr} = R_r i_{qr} + \frac{d}{dt} \psi_{qr} + (\omega_e - \omega_r) \psi_{dr}
\]
\[
V_{dr} = R_r i_{dr} + \frac{d}{dt} \psi_{dr} - (\omega_e - \omega_r) \psi_{qr}
\]
The flux linkage expressions in terms of currents can be written as

\[ \psi_{qs} = L_l i_{qs} + L_m (i_{qs} + i_{qr}) \]  
\[ \psi_{qr} = L_t i_{qr} + L_m (i_{qs} + i_{qr}) \]  
\[ \psi_{qm} = L_m (i_{qs} + i_{qr}) \]  
\[ \psi_{ds} = L_l i_{ds} + L_m (i_{ds} + i_{dr}) \]  
\[ \psi_{dr} = L_t i_{dr} + L_m (i_{ds} + i_{dr}) \]  
\[ \psi_{dm} = L_m (i_{ds} + i_{dr}) \]

The flux linkages variables are defined as

\[ F_{qs} = \omega_b \psi_{qs} \]  
\[ F_{qr} = \omega_b \psi_{qr} \]  
\[ F_{ds} = \omega_b \psi_{ds} \]  
\[ F_{dr} = \omega_b \psi_{dr} \]

Where, \(\omega_b\) is the base frequency of the machine. Substituting Equations (19) to (22) in equations (9) to (12), We get,

\[ V_{qs} = R_s i_{qs} + \frac{1}{\omega_b} \frac{dF_{qs}}{dt} + \frac{\omega_e}{\omega_b} F_{ds} \]  
\[ V_{ds} = R_s i_{ds} + \frac{1}{\omega_b} \frac{dF_{ds}}{dt} - \frac{\omega_e}{\omega_b} F_{qs} \]  
\[ 0 = R_r i_{qr} + \frac{1}{\omega_b} \frac{dF_{qr}}{dt} + \frac{(\omega_e - \omega_r)}{\omega_b} F_{dr} \]  
\[ 0 = R_r i_{dr} + \frac{1}{\omega_b} \frac{dF_{dr}}{dt} - \frac{(\omega_e - \omega_r)}{\omega_b} F_{qr} \]

Assuming \(V_{qr} = V_{dr} = 0\)

Multiplying equations (13) to (18) with \(\omega_b\) on both sides we get,

\[ F_{qs} = \omega_b \psi_{qs} = X_l i_{qs} + X_m (i_{qs} + i_{qr}) \]  
\[ F_{qr} = \omega_b \psi_{qr} = X_t i_{qr} + X_m (i_{qs} + i_{qr}) \]  
\[ F_{qm} = \omega_b \psi_{qm} = L_m (i_{qs} + i_{qr}) \]  
\[ F_{ds} = \omega_b \psi_{ds} = X_l i_{ds} + X_m (i_{ds} + i_{dr}) \]  
\[ F_{dr} = \omega_b \psi_{dr} = X_t i_{dr} + X_m (i_{ds} + i_{dr}) \]  
\[ F_{dm} = \omega_b \psi_{dm} = L_m (i_{ds} + i_{dr}) \]
Where, $X_{ls} = \omega_b L_{ls}$, $X_{lr} = \omega_b L_{lr}$ and $X_m = \omega_b L_m$

From equation (27) and (29), we get,

$$i_{qs} = \frac{F_{qs} - F_{qm}}{X_{ls}} \tag{33}$$

Similarly,

$$i_{qr} = \frac{F_{qr} - F_{qm}}{X_{lr}} \tag{34}$$

$$i_{ds} = \frac{F_{ds} - F_{dm}}{X_{ls}} \tag{35}$$

$$i_{dr} = \frac{F_{dr} - F_{dm}}{X_{lr}} \tag{36}$$

Solving above equations for $F_{qm}$, we get

$$F_{qm} = X_m \left[ \frac{F_{qs} - F_{qm}}{X_{ls}} + \frac{F_{qr} - F_{qm}}{X_{lr}} \right] \tag{37}$$

$$F_{qm} = \frac{X_m}{X_{ls}} F_{qs} + \frac{X_m}{X_{lr}} F_{qr} \tag{38}$$

\textbf{Figure 2.} Block diagram of $F_{qm}$

Similarly,

$$F_{dm} = \frac{X_m}{X_{ls}} F_{ds} + \frac{X_m}{X_{lr}} F_{dr} \tag{39}$$

\textbf{Figure 3.} Block diagram of $F_{dm}$
Where,

\[ X^*_m = \frac{1}{\frac{1}{X_m} + \frac{1}{X_{ls}} + \frac{1}{X_{lr}}} \]  

(40)

Substituting equations (33) to (36) in equations (23) to (26)

\[ V_{qs} = \frac{R_s}{X_{ls}} (F_{qs} - F_{qm}) + \frac{1}{\omega_b} \frac{df_{qs}}{dt} + \frac{\omega_e}{\omega_b} F_{ds} \]  

(41)

\[ V_{ds} = \frac{R_s}{X_{ls}} (F_{ds} - F_{dm}) + \frac{1}{\omega_b} \frac{df_{ds}}{dt} - \frac{\omega_e}{\omega_b} F_{qs} \]  

(42)

\[ 0 = \frac{R_r}{X_{lr}} (F_{qr} - F_{qm}) + \frac{1}{\omega_b} \frac{df_{qr}}{dt} + \frac{(\omega_e - \omega_r)}{\omega_b} F_{dr} \]  

(43)

\[ 0 = \frac{R_r}{X_{lr}} (F_{dr} - F_{dm}) + \frac{1}{\omega_b} \frac{df_{dr}}{dt} - \frac{(\omega_e - \omega_r)}{\omega_b} F_{qr} \]  

(44)

Which can be expressed in state space form as

\[ \frac{df_{qs}}{dt} = \omega_b \left[ V_{qs} - \frac{\omega_e}{\omega_b} F_{ds} - \frac{R_s}{X_{ls}} (F_{qs} - F_{qm}) \right] \]  

(45)

\[ \frac{df_{ds}}{dt} = \omega_b \left[ V_{ds} + \frac{\omega_e}{\omega_b} F_{qs} - \frac{R_s}{X_{ls}} (F_{ds} - F_{dm}) \right] \]  

(46)

**Figure 4.** Block diagram of $F_{qs}$
\[
\frac{dF_{ar}}{dt} = -\omega_b \left[ \frac{\omega_e - \omega_r}{\omega_b} F_{dr} + \frac{R_r}{X_{lr}} (F_{qr} - F_{qm}) \right]
\]

(47)

\[
\frac{dF_{dr}}{dt} = -\omega_b \left[ -\frac{\omega_e - \omega_r}{\omega_b} F_{dr} + \frac{R_r}{X_{lr}} (F_{dr} - F_{dm}) \right]
\]

(48)
Development of torque by interaction of airgap flux and rotor mmf is expressed in generalized form as,

\[ T_e = \frac{n}{2} \left( \frac{p}{2} \right) \bar{\psi}_m \times \bar{I}_r \]  \hspace{1cm} (49)

Where, \( n \) = number of phases. Resolving it into five phase system, we get

\[ T_e = \frac{5}{2} \left( \frac{p}{2} \right) (\psi_{ds}i_{qs} - \psi_{qs}i_{ds}) \]  \hspace{1cm} (50)

\[ T_e = \frac{5}{2} \left( \frac{p}{2} \right) \left( \frac{1}{\omega_b} \right) (F_{ds}i_{qs} - F_{qs}i_{ds}) \]  \hspace{1cm} (51)

Figure 8. Block diagram of \( T_e \)

The speed \( \omega_r \) can be related to the torque as

\[ T_e = T_L + \frac{2}{P} \int \frac{d\omega_r}{dt} \]  \hspace{1cm} (52)

Where, \( T_L \) = Load torque, \( J \) = rotor inertia, \( P \) = no of poles

Figure 9. Block diagram of \( \omega_r \)

Using equations (33) to (36), those synchronously rotating reference frame currents are converted into stationary frame two phase variables

\[ i_d = i_{qs}cos\theta_e + i_{ds}sin\theta_e \]  \hspace{1cm} (53)

\[ i_q = i_{ds}cos\theta_e - i_{qs}sin\theta_e \]  \hspace{1cm} (54)
These stationary two phase variables are converted into five phase variables using the below conversion technique.

\[
\begin{bmatrix}
    i_a \\
    i_b \\
    i_c \\
    i_d \\
    i_e
\end{bmatrix}
= \sqrt{\frac{2}{5}} \times
\begin{bmatrix}
    1 & 0 & 1 & 0 & 1 \\
    \cos \alpha & \sin \alpha & \cos 2\alpha & \sin 2\alpha & 1 \\
    \cos 2\alpha & \sin 2\alpha & \cos 4\alpha & \sin 4\alpha & 1 \\
    \cos 3\alpha & \sin 3\alpha & \cos 6\alpha & \sin 6\alpha & 1 \\
    \cos 4\alpha & \sin 4\alpha & \cos 8\alpha & \sin 8\alpha & 1
\end{bmatrix}
\begin{bmatrix}
    i_d \\
    i_q \\
    i_x \\
    i_y \\
    i_0
\end{bmatrix}
\] (55)

3. SIMULATION MODEL

The simulation model of five phase induction motor designed is shown in Fig.11

![Figure 10. Block diagram of stator currents](image)

![Figure 11. Simulation model of induction motor](image)
4. MATHEMATICAL MODEL OF THREE PHASE INDUCTION MOTOR

The three phase voltages are assumed as

\[ V_{as} = V_m \sin(\omega_e t) \]  
(56)

\[ V_{bs} = V_m \sin \left( \omega_e t - \frac{2\pi}{3} \right) \]  
(57)

\[ V_{cs} = V_m \sin \left( \omega_e t - \frac{4\pi}{3} \right) \]  
(58)

Where, \( V_m \) is the peak value of terminal voltage \( \omega_e \) is the supply frequency in radians per second.

These stationary reference frame variables is converted into two phase stationary reference frame variables using decoupling transformation matrix. The decoupling transformation matrix is given below.

\[
\begin{bmatrix}
V_{ds} \\
V_{qs} \\
V_{ns}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & \cos \alpha & \cos2\alpha \\
0 & -\sin \alpha & -\sin2\alpha \\
0.5 & 0.5 & 0.5
\end{bmatrix} \begin{bmatrix}
V_{as} \\
V_{bs} \\
V_{cs}
\end{bmatrix}
\]  
(59)

Where \( \alpha = \frac{2\pi}{3} \)

\( V_{ds}^s \) and \( V_{qs}^s \) are the \( d^s \) and \( q^s \) axis stator fundamental voltages. \( V_{ns} \) is the zero sequence component of stator.

These two phase stationary reference frame variables are transformed into synchronously rotating reference frame, ignoring the zero sequence components as shown below.

\[ V_{qs} = V_{qs}^s \cos \theta_e - V_{ds}^s \sin \theta_e \]  
(60)

\[ V_{ds} = V_{qs}^s \sin \theta_e + V_{ds}^s \cos \theta_e \]  
(61)

Where, \( V_{ds} \) and \( V_{qs} \) are the \( d \) and \( q \) axis synchronously rotating voltages, which rotate at synchronous speed \( \omega_e \) with respect to \( d^s \) and \( q^s \) axis and the angle \( \theta_e = \omega_e t \).

The process will remain same as above until the torque equation. Where the final torque equation becomes [6-22].

\[ T_e = \frac{3}{2} \left( \frac{p}{2} \right) (\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \]  
(62)

\[ T_e = \frac{3}{2} \left( \frac{p}{2} \right) \left( \frac{1}{\omega_b} \right) (F_{ds} i_{qs} - F_{qs} i_{ds}) \]  
(63)

![Block diagram of three phase torque](image)
5. PARAMETERS

The parameters used for simulation are shown below in table 1.

| Parameter          | Value          |
|--------------------|----------------|
| Rotor resistance   | $R_r = 0.6$    |
| Stator resistance  | $R_s = 0.8$    |
| Rotor inductance   | $L_{lr} = 0.0026$ |
| Stator inductance  | $L_{ls} = 0.0026$ |
| Magnetizing Inductance | $L_m = 0.151$  |
| Base frequency     | $f_b = 100$    |
| Number of poles    | $P = 2$        |
| Moment of inertia  | $J = 0.047$    |
| Friction factor    | $F = 0.00572$  |

Table 1. Machine Parameters

Where,

\[ L_r = L_{lr} + L_m \]  \hspace{1cm} (64)

\[ T_r = \frac{L_r}{R_r} \]  \hspace{1cm} (65)

Base speed,

\[ w_b = 2 \pi f_b \]  \hspace{1cm} (66)

\[ X_{ls} = w_b L_{ls} \]  \hspace{1cm} (67)

\[ X_{lr} = w_b L_{lr} \]  \hspace{1cm} (68)

\[ X_m = w_b L_m \]  \hspace{1cm} (69)

\[ X_m^* = \frac{1}{\frac{1}{X_{lr}} + \frac{1}{X_{ls}} + \frac{1}{X_m}} \]  \hspace{1cm} (70)

6. RESULTS AND COMPARISON

The above created models are tested under various conditions with machine parameters as shown in table 1. Full load torque and speed of three phase induction motor thus simulated is shown in figure 13 and figure 14.

The stator currents of three phase induction motor is shown in figure 15.

Similarly for five phase induction motor as shown in figure 16, 17, and 18.
Figure 13. Full Load Torque of 3 phase Induction Motor

Figure 14. Full Load Speed of 3 phase Induction Motor

Figure 15. Stator currents of three phase IM
The torque and speed of both the machines are compared using simulation data inspector, shown in figures 19 and 20.
Figure 19. Torque comparison of three phase and five phase Induction Motor

Figure 20. Speed comparison of three phase and five phase Induction Motor

Figure 21. Speed Torque characteristics of three phase Induction Motor

Figure 22. Speed Torque characteristics of five phase Induction Motor
7. CONCLUSION

As it is evident from the simulation results that, under fully loaded condition five phase induction motor took around 1 second to reach the steady state value. Whereas the three phase induction motor took around 1.5 seconds to reach the steady state value. Under constant changing loads, this parameter plays a very important role in analyzing the system behaviour as well as it improves the reliability of the system. Also under same machine parameters, the maximum torque of machine increased by 67 times approximately with change in three phase to five phase. And we can say that per phase power distribution is improved.

The above model can be implemented for simulating multi-phase induction motors for higher number of phases.

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