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## Volume - 1

**Electronics**
**Electrical Power**
**Information Technology**
**Engineering Physics**

Sedona Hotel, Yangon, Myanmar
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# ELECTRICAL POWER ENGINEERING

# Steady-State Performance and Three- phase to Two-phase Transformation of Induction Motor

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***Abstract*— This paper is proposed the simulation of steady -state performance of three phase induction motor and the derivation of three-phase to two-phase transformation which may be used in dynamic modelling of induction motor. The dynamic simulation is one of the king steps in the validation of the design process of the motor drives systems and it is needed for eliminating inadvertent design mistakes and the resulting error in the prototype construction and testing. This paper demonstrates the simulation of steady state performance and the derivation of three-phase to two-phase transformation with one reference frame model of induction motor.**

***Keywords*— squirrel-cage induction motor, torque, speed, efficiency, steady-state performance, dq axis**

## I. INTRODUCTION

An induction motor is one which alternating current is supplied to the stator directly and to the rotor by induction or transformer action from the stator. When excited from the three-phase source, it will produce a magnetic field in the air gap rotating at synchronous speed as determined by the number of poles and the applied stator frequency.

The equivalent circuit of the induction motor is very similar to that for a transformer. Although the rotor currents are at slip frequency, the rotor is incorporated into the circuit in sample way. Three-phase induction motor is the most commonly used motor in industrial application for its simple design, reliable operation, rugged construction, low initial cost, easy operation and simple maintenance, high efficiency and having sample control gear for starting and speed control. Induction motors are available with torque characteristics suitable for a wide variety of applications. [1]

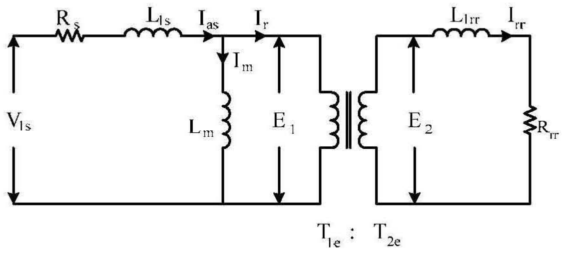


Fig. 1 Elementary equivalent circuit of induction motor

## II. GENERAL CONSTRUCTION OF INDUCTIO MOTOR

The induction motor is the simplest and most ruggedly constructed of the various types of electric motors and finds more expensive application in industry than any other type. It is made in two principal forms, the squirrel-cage and the wound rotor, the difference being wholly in the construction of the rotor. [1]

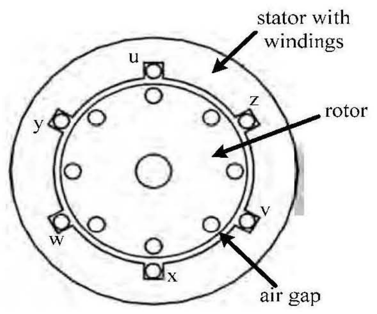


Fig. 2 Induction machine design

## III. STATOR

The stator frame consists of a symmetrical and substantial casting, having feet cast integral with it. The stator core, consisting of high grade, low loss electrical sheet-steel stampings, is assembled in the frame under hydraulic pressure. The thickness of stampings is usually from 0.35 to 0.6 mm. The stator laminations are punched in one piece for small induction motor. In induction machines of large size the stator core is assembled from a large number of segmental laminations.

The slots are enclosed slots in order to reduce the effective length of air gap. The stator windings are given the utmost care to make them mechanically and electrically sound, so as to ensure long life and high efficiency. After the winding is in position it through dried out whilst still hot and is completely immersed in a high grade synthetic resin varnish. It is then acid, alkali, moisture and oil proof. [2]

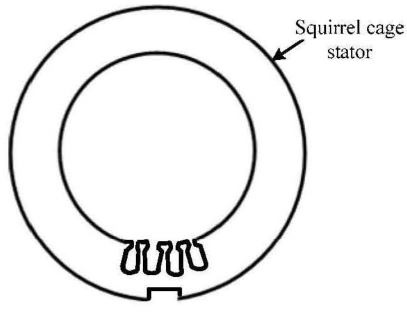


Fig. 3 Stator stamping

## IV. ROTOR

Induction machines are either equipped with squirrel-cage or wound rotors. Both types of rotors have slotted stampings.

### *A. Squirrel-cage Rotor*

The squirrel-cage rotor is made up of stampings which are keyed directly to the shaft. The slots are partially closed and the winding consists of embedded copper bars to which the short-circuited rings are brazed. The squirrel cage rotor is so robust that it is almost indestructible.

The great majority of present day induction motors are manufactured with squirrel-cage rotors, a common practice being to employ winding of cast aluminium. In this construction the assembled rotor laminations are placed in a mould after which molten aluminium is forced in, under pressure, to form bars, is known as die cast rotor and has become very popular as there are no joints and thus there is no possibility of high contact resistance.

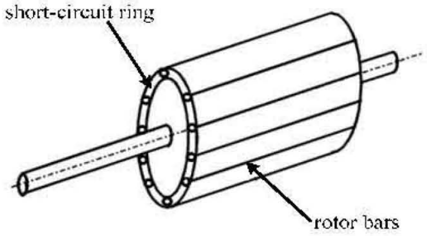


Fig. 4 Squirrel-cage rotor

### *B. Wound Rotor*

The wound rotor has also slotted stampings and the windings are former wound. The wound rotor construction is employed for induction motors requiring speed control or external high values of starting torque. The wound rotor has completely insulted copper windings very much like stator windings. The windings can be connected in star or delta and the three ends are brought out at the three slip rings.

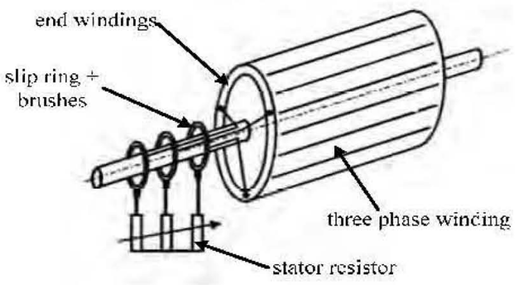


Fig. 5 Wound rotor

The current is collected from their slip rings with carbon brushes for which it is led to the resistances for starting purposes. When the motor is running, the slip rings are short-circuited by means of a collar, which is pushed along the shaft and connects all the slip rings together on the inside. Usually the brushes are provided with a device for lifting them from the slip rings when the motor has started up, thus reducing the wear and the frictional losses. [2]

## V. SLIP

The difference between the synchronous speed and the rotor speed is known as slip. It is usually expressed as a friction of the synchronous speed.

$$s = \frac{N_s - N}{N_s}$$

where $N_s$ = synchronous speed (r.p.m)
N = motor speed (r.p.m)

## VI. MEASUREMENT OF MOTOR PARAMETERS

### *A. Stator Resistance*

With the rotor at standstill, the stator phase resistance is measured by applying a dc voltage and the resulting current. While this procedure gives only the dc resistance at a certain temperature, the ac resistance has to be calculated by considering the wire size, the stator frequency and the operating temperature.

### *B. No-load Test*

The induction motor is driven at synchronous speed by another motor, preferably a dc motor. Then the stator is energized by applying rated voltage at rated frequency. The input power per phase is measured.

### *C. Locked-Rotor Test*

The rotor of the induction motor is locked to keep it at standstill and a set of low three phase voltages is applied to calculate rated stator currents. The input power per phase is measured along with the input voltage and stator current. The slip is unity for the locked-rotor condition and hence the circuit resembles that of a secondary-shorted transformer. [3]

## VII. STEADY-STATE PERFORMANCE CALCULATION OF INDUCTION MOTOR

The required parameters for steady-state performance calculation of induction motor are received from laboratory test results. Torque slip characteristic, power slip characteristic, efficiency slip characteristic of induction motor and magnitude of rotor and stator currents are shown in this paper.

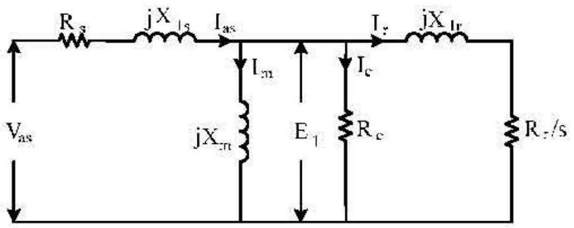


Fig. 6 Equivalent circuit with the rotor at stator frequency

TABLE I
INPUT PARMETERS OF INDUCTION MOTOR

| No. | Input parameters | | |
|---|---|---|---|
| | Symbol | Quantity | Input value |
| 1 | - | Phase | 3 |
| 2 | p | Number of pole | 4 |
| 3 | f | Frequency | 50 Hz |
| 4 | $v_{ll}$ | Line to line voltage | 380 V |
| 5 | $R_s$ | Stator resistance | 3.5Ω |
| 6 | $R_r$ | Rotor resistance | 3.8Ω |
| 7 | $R_c$ | Resistance to account for core losses | 700 Ω |
| 8 | $X_m$ | Magnetizing reactance | 80Ω |
| 9 | $X_{ls}$ | Stator magnetizing leakage reactance | 5Ω |
| 10 | $X_{lm}$ | Rotor magnetizing leakage reactance | 5Ω |

*A. Torque-slip Characteristic of Induction Motor*

$$T = 3I_r^2 R_r \frac{(1-s)}{s\omega_m}$$

where s is full load slip of motor

Rotor angular speed, $\omega_m = \frac{\omega_r}{p/2} = \frac{\omega_s(1-s)}{p/2}$

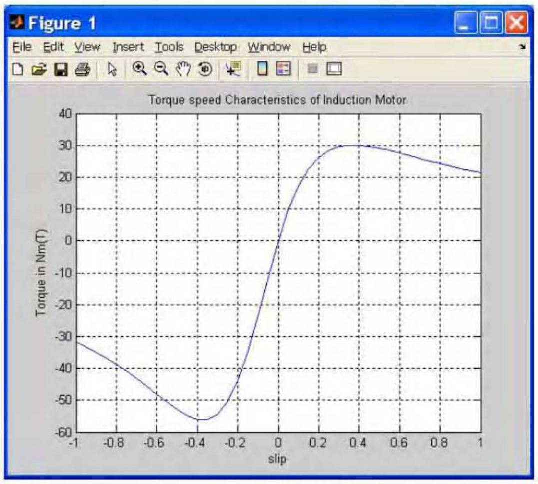


Fig. 7 Torque-slip characteristic of induction motor

The slip is chosen in place of rotor speed because it is nondimensional and so it is applicable to any motor frequency. Near the synchronous speed, at low slips, the torque is linear and is proportional to slip; beyond the maximum torque, the torque is approximately inversely proportional to slip. [4]

The torque -slip characteristics are shown from point -1 to 1. The maximum torque for induction motor is 0.4 slip position and the lowest value of torque is occurred at -0.4 slip point, as shown in Fig. 7.

*B. Efficiency of Induction Motor*

In an induction motor, copper losses, core losses and friction and windage losses are occurred. There are copper losses and core losses in the stator, and copper losses and frictional losses in the rotor. Actually there are some core losses in the rotor.

Under operating conditions, however, the rotor frequency is so low that it may logically be assumed that all core losses occur in the stator only. The efficiency of induction motor can be determined by loading the motor and measuring the input and output directly.

$$\eta = \text{Poutput/Pinput}$$

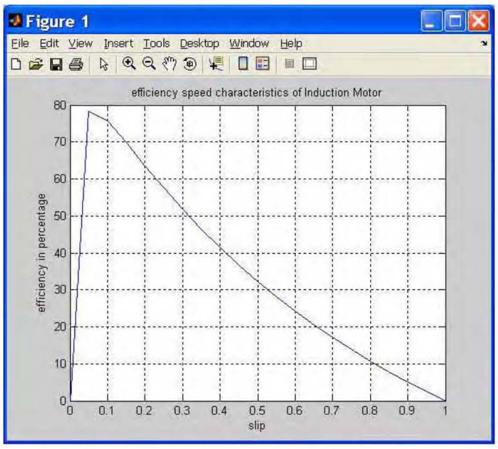


Fig. 8 Efficiency-slip characteristic of induction motor

The maximum efficiency of induction motor occurs at 0.05 slip position.

*C. Magnitude of Stator Current in Induction Motor*

Stator current, $I_s = \frac{V_{as}}{Z_{im}}$

The magnitude of stator current - slip characteristics are shown from slip point 0 to 1.

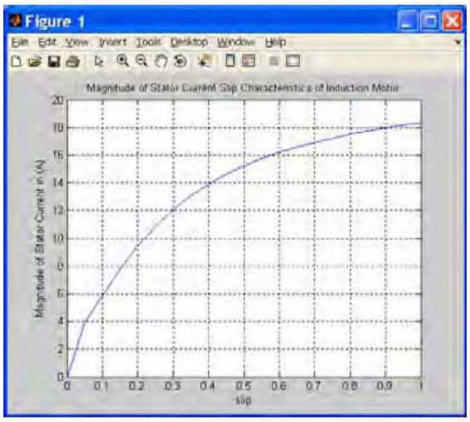


Fig. 9 Magnitude of stator current-slip characteristic of induction motor

### *D. Power-slip Characteristic of Induction Motor*

Power, $P = T\omega_m$

The power - slip characteristics are shown from slip point 0 to 1.

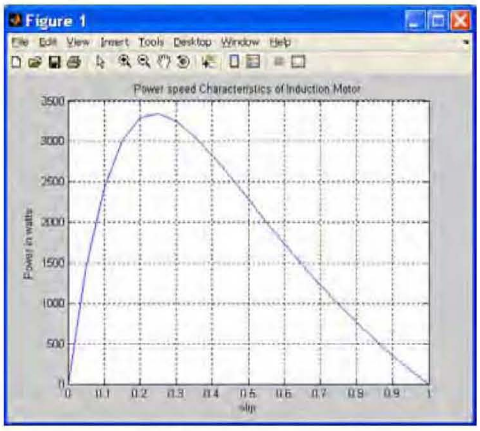


Fig. 10 Power-slip characteristic of induction motor

### *E. Magnitude of Rotor Current in Induction Motor*

Rotor current, $I_r = \frac{Z_{eq}}{Z_{im}} I_s$

The magnitude of rotor current - slip characteristics are shown from slip point 0 to 1.

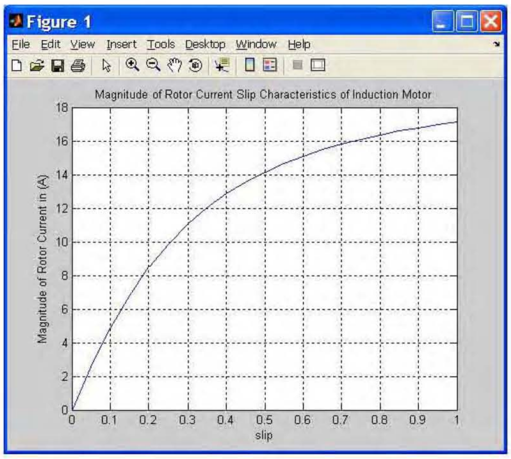


Fig. 11 Magnitude of rotor current-slip characteristic of induction motor

## VIII. INTRODUCTION TO DYNAMIC MODELING OF INDUCTION MOTOR

The dynamic model of induction motor is derived by using a two-phase motor in direct and quadrature axes. The equivalent between the three-phase and two-phase machine model is derived from simple observation and this approach is suitable for extending it to model n phase machine by means of two-phase machine.

The transformation to obtain constant inductances is achieved by replacing the actual with a fictitious rotor on the q and d axes, as shown in Fig.12. In this process, the fictitious rotor will have the same number of turns for each phase as the actual rotor phase windings and should produce the same mmf.

The fictitious rotor current $i_{qrr}$ and $i_{drr}$ are equal to the sum of the projections of $i_\alpha$ and $i_\beta$ on the q and d axis respectively, as

$$\begin{bmatrix} i_{drr} \\ i_{qrr} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ \sin\theta_r & -\cos\theta_r \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

$$i_{dqrr} = [T_{\alpha\beta}]\, i_{\alpha\beta}$$

where, $i_{dqrr} = [i_{drr} \quad i_{qrr}]^t$

$$i_{\alpha\beta} = [i_\alpha \quad i_\beta]^t$$

$$T_{\alpha\beta} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ \sin\theta_r & -\cos\theta_r \end{bmatrix}$$

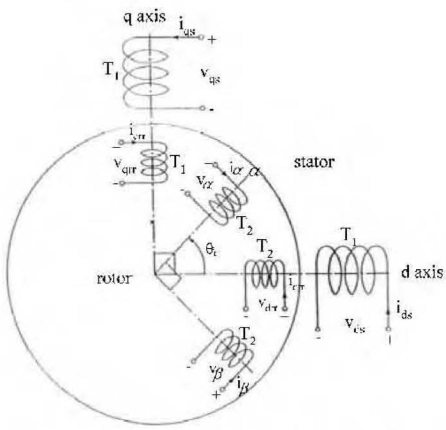


Fig. 12 Transformation of actual to fictitious rotor variables

## IX.THREE-PHASE TO TWO-PHASE TRANSFORMATION

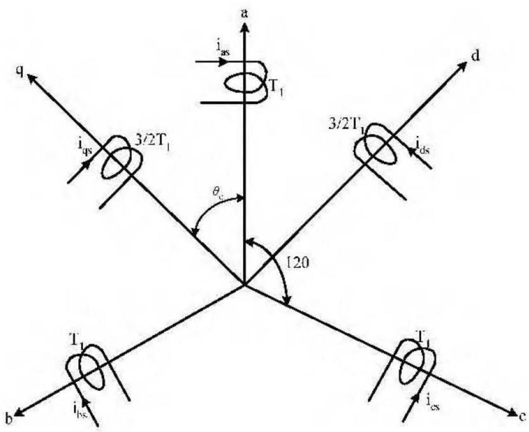


Fig. 13 Two-phase and three-phase stator windings

A dynamic model for three-phase induction machine can be derived from the two-phase machine if the equivalence between the three and two phases is established. The equivalence is based on the equality of the mmf produced in the two-phase and three-phase windings and equal current magnitudes. Fig.13. shows the three-phase to two-phase windings. Assuming that each of the three-phase windings has $T_1$ turns per phase and equal current magnitudes, the two-phase windings will have $3T_1/2$ turns per phase for mmf equality. The d and q axes mmf are found by resolving the mmfs of the three-phase along the d and q axes.

The q axes is assumed to be lagging the a axis by $\theta_c$. The relationship between dq0 and abc current is as follows:

$$\begin{bmatrix} i_{qs} \\ i_{ds} \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_c & \cos\left(\theta_c - \frac{2\pi}{3}\right) & \cos\left(\theta_c + \frac{2\pi}{3}\right) \\ \sin\theta_c & \sin\left(\theta_c - \frac{2\pi}{3}\right) & \sin\left(\theta_c + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{ds} \\ i_{cs} \end{bmatrix}$$

## X. GENERALIZED MODEL OF ARBITRARY REFERENCE FRAMES

In rotating reference frames, the system inductance matrix becomes independent of rotor position and leading to the simplification and compactness of the system equations. Instead of deriving the transformations for each and every particular reference frame, it is advantageous to derive the general transformation for an arbitrary rotating reference frame.

Reference frames rotating at an arbitrary speed are called arbitrary reference frames. The relationship between the stationary reference frames denoted by d and q axes and the arbitrary reference frames denoted by $d^c$ and $q^c$ axes are shown in Fig. 14.

The three-phase machine is assumed to have balanced windings and balanced inputs, and then the zero-sequence components are zero and eliminating the zero-sequence equations. The relationship between the currents are written as

$$i_{dqs} = [T^c] i^c_{dqs}$$

where, $$T^c = \begin{bmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{bmatrix}$$

The speed of arbitrary reference frames is $\dot{\theta}_c = \omega_c$. The terminal voltages equations of induction motor model in arbitrary reference frames are

$$\begin{bmatrix} v^c_{qs} \\ v^c_{ds} \\ v^c_{qr} \\ v^c_{dr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & \omega_c L_s & L_m p & \omega_c L_m \\ -\omega_c L_s & R_s + L_s p & -\omega_c L_m & L_m p \\ L_m p & (\omega_c - \omega_r) L_m & R_r + L_r p & (\omega_c - \omega_r) L_r \\ -(\omega_c - \omega_r) L_m & L_m p & -(\omega_c - \omega_r) L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i^c_{qs} \\ i^c_{ds} \\ i^c_{qr} \\ i^c_{dr} \end{bmatrix}$$

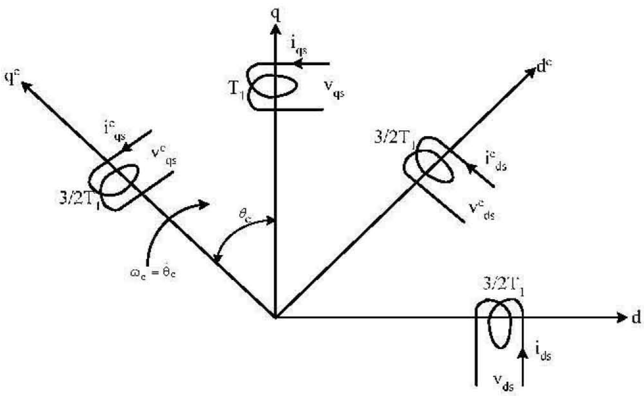


Fig. 14 Stationary and arbitrary reference frames

## XI. DERIVATION OF INDUCTION MOTOR MODEL

There are three particular cases of generalized model of the induction motor in arbitrary reference frames model. These are

(i) stator reference frames model
(ii) rotor reference frames model
(iii) synchronous reference frames model.

## XII. TRANSFORMATION OF THREE-PHASE TO TWO-PHASE WITH STATOR REFERENCE FRAME MODEL

In stator reference frame model, the speed of the reference frames frame is that of the stator, which is zero: hence $\omega_c = 0$. Then the resulting model is

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & L_m p & 0 \\ 0 & R_s + L_s p & 0 & L_m p \\ L_m p & -\omega_r L_m & R_r + L_r p & -\omega_r L_r \\ \omega_r L_m & L_m p & \omega_r L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}$$

This model is used when stator variables are required to be actual, i.e. the same as in the actual machine stator and rotor variables can be fictitious. This model allows elegant simulation of stator controlled induction motor drives, such as phase-controlled and inverter-controlled induction motor drives, because the input variables are well defined and could be used to find the stator q and d axes voltage through a set of simple algebraic equations.

$V_{as} = 310.3\sin\omega_s t$
$V_{bs} = 310.3\sin\omega_s t - 120°$
$V_{cs} = 310.3\sin\omega_s t + 120°$
$V_{qs} = V_{as} = 310.3\sin\omega_s t = 310.3V$
$V_{ds} = 310.3\angle 90° = j310.3V$
$p = j\omega_s = j\,2\pi f_s$
Consider at the rotor is locked:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + j\omega_s L_s & 0 & j\omega_s L_m & 0 \\ 0 & R_s + j\omega_s L_s & 0 & j\omega_s L_m \\ j\omega_s L_m & 0 & R_r + j\omega_s L_r & 0 \\ 0 & j\omega_s L_m & 0 & R_r + j\omega_s L_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}$$

By substitution the values;

$i_{qr} = 3.886\angle{-90.33}$
$i_{dr} = 3.886\angle{-0.33}$
$i_{qs} = 0.308\angle 52.79$
$i_{ds} = 0.308\angle 142.79$

The phase currents are

$$\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ 1/2 & -\sqrt{3}/2 & 1 \\ -1/2 & \sqrt{3}/2 & 1 \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{o} \end{bmatrix} = \begin{bmatrix} 0.186 + j0.245 \\ 0.3052 - j0.0386 \\ -0.3052 + j0.0386 \end{bmatrix}$$

Effective stator to rotor turn ratio is a= 3.

The various rotor currents are
$i_{qrr} = ai_{qr} = 11.658\angle{-90.33}$
$i_{drr} = ai_{dr} = 11.658\angle{-0.33}$

The $\alpha$ and $\beta$ currents , assuming $\theta_r = 0$;

$$\begin{bmatrix} i_{drr} \\ i_{qrr} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ \sin\theta_r & -\cos\theta_r \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix}$$

$$\begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 11.658\angle{-90.33} \\ 11.658\angle{-0.33} \end{bmatrix}$$

$$= \begin{bmatrix} 11.658\angle{-90.33} \\ -11.658\angle{-0.33} \end{bmatrix}$$

## XIII. CONCLUSION

A dynamic model for three-phase induction motor can be derived from the two-phase transformation. The dynamic model can also be driven from other two reference frames models. After transformation, model with flux linkage, per unit model derivation and finally stability analysis of induction motor can be achieved.

Three-phase induction motor has simple design and rugged construction. Induction motor is easy to operate and simple maintenance, and need simple gear for starting and speed control. Induction motor has low initial cost, high efficiency and reliable operation. Three-phase AC induction motors are widely used in industrial and commercial applications. Induction motors are very essential for industrial applications and their role is very important.

So, this paper is applicable for the motor operation with simple design and reliable operation.


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