



Modelling and Parameter Determination of an Induction Servo-Motor

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Authors' contributions

This work was carried out in collaboration with author JDJ, who is one of my PhD research supervisors. Both authors read and approved the final manuscript.

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ABSTRACT

This paper presents the modelling and parameter determination of an induction motor. The dynamic induction motor model was derived in relatively simple terms by using the concept of space vectors in d-q variables based on two-axis theory equations and the space phasor notation. A synchronous reference frame in which rotor flux lies on the d-axis was chosen with simplified dynamic equations and torque expressions. This research work presents these models with typical results and provides guidelines for their use for the dynamic simulation of small power induction motor based on mathematical modelling. An on-line dynamic simulation experiment was carried out to determine the induction motor parameters using MATLAB/Simulink program. The results obtained showed that the induction motor performs better under no-load. For satisfactory and better performance under load condition, controller will have to be introduced.

Keywords: Dynamic induction motor; d-q reference frame; dynamic simulation; modeling; space vectors; steady and dynamic states.

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1. INTRODUCTION

In recent years the control of high performance induction motor drives for general industrial applications and production automation has received widespread research interests. Induction machine modeling has continuously attracted the attention of researchers not only because such machines are made and used in large numbers but also due to their varied modes of operation both under steady and dynamic states. In an electric drive system the machine is a part of the control system elements. To be able to control the dynamic of the drive system, dynamic behavior of the machine need to be considered. The dynamic behavior of induction motor can be described using dynamic model of induction machine, which considers the instantaneous effects of varying voltages/currents, stator frequency and torque disturbance.

The practice of modeling and simulation saves time, and reduces the cost of building a prototype, and most importantly it ensures that the requirements are being achieved. Also a simple per phase equivalent circuit model of an induction motor is of great interest in the analysis and performance prediction at steady-state conditions. The steady-state induction motor model is therefore an equivalent circuit with respect to the stator and can easily be established from the short-circuited transformer-equivalent circuit [1]. So the dynamic d-q model of the induction motor based on the Park's transformation is being considered for this research work.

Furthermore, simulation-based design plays an important role in understanding and evaluating induction motor drives. In order to visualize clearly the relationship between internal parameters and system performances, all of the differential equations will be embedded into the derived model of the induction motor.

The development of accurate system models is fundamental to each stage in the design, analysis and control of all electrical machines. The level of precision required of these models depends entirely on the design stage under consideration. In particular, the mathematical description used in machine design requires very strict tolerance as stated by [2]. However, in the development of suitable models for control purpose, it is possible to make certain assumptions that considerably simplify the resulting machine model. Nonetheless, these

models must incorporate the essential element of both electromagnetic and the mechanic system for both steady state and transient operating conditions [3]. Additionally, since modern electric machines are variably fed from switching power conversion stages, the developed motor models should be valid for arbitrary applied voltage and current waveforms. This work presents suitable models for use in current control of the induction motors. In addition, the limits of the validity of these models are summarized and, in some cases, the models are extended to account for some non-idealities of the machine.

Along with variable frequency AC converters, induction motors are used in many adjustable speed applications which do not require fast dynamic response. The concept of vector control has opened up a new possibility that induction motors can be controlled to achieve dynamic performance as good as that of a DC or brushless DC motors. In order to understand and analyze vector control, the dynamic model of the induction motor is necessary. It has been found that the dynamic model equations developed on a rotating reference frame is easier to describe the characteristics of induction motors. The objective of this research work is to derive and explain induction motor model in relatively simple terms by using the concept of space vectors in d – q variables. It will be shown that when a synchronous reference frame in which rotor flux lies on the d-axis is chosen, dynamic equations of the induction motor is simplified and analogous to a DC motor.

2. CONCEPT OF SPACE VECTORS

In designing control systems generally, the designer must be able to model the dynamics of the systems and analyze the dynamics characteristics. Mathematical models have to be implemented for induction machine in order to analyze its operation both dynamically and in steady – state. The first step in the mathematical modeling of an induction motor is by describing it as coupled stator and rotor three-phase circuits using phase variables. The induction motor electrical parameters are expressed in terms of a resistance matrix, R , and inductance matrix, L , in which the magnetic mutual coupling elements are function of position, θ .

The next step is to transform the original stator and rotor abc frames of reference into a d-q frame in which the new variables for voltages, current and fluxes can be viewed as space vectors so that currents are now defined as

$I_s = [I_{ds} I_{qs}]$ and $I_r = [I_{dr} I_{qr}]$. In the d-q frame, the inductance parameters become constant, independent of position. There are four possible choices of d-q frames which are as follows; (a) Stator frame where $\omega_k = 0$; (b) Rotor frame where $\omega_k = \omega_m$; (c) Synchronous frame which is associated with the frequency ω_s (possibly time varying); and (d) Rotor flux frame in which the d-axis lines up with the direction of the rotor flux vector. Because it uses space vectors, the d-q model of the machine provides a powerful physical interpretation of the interactions taking place in the production of voltages and torques, and more importantly it leads to the ready adaptation of positional- or speed-control strategies such as vector control and direct torque control.

The analysis of this type of machine is essentially the same for a three – phase, two – phase or single – phase machine. An accurate and dynamic model is necessary for the proper understanding and analysis of vector control operation. This model has to be suitable for the analysis of both the steady – state and dynamical operation of the system. Starting from the reference frame theory, with voltages, currents and fluxes referred to a two – axis quadrature co – ordinates system, a general model is developed according to [4,5] it is pertinent here to mention here, that, in contrast with the three phase induction machine, where two approaches are valid, (d-q axis and space vector theory), the single – phase type is completely described only by a two – axis quadrature axis.

The first mathematical model for the dynamic analysis of the induction machine was based on the two real axis reference frame, developed initially by [6] for the synchronous machine. Some researchers [7] have elaborated the space complex and obtained a model for the steady - state analysis of the machine by using the induction machine symmetric configuration. Both theories are being considered in the modeling of a three – phase induction machine used for this research work.

In the control of any power electronics drive system (say a motor, as in this case), it is normally required to start with a mathematical model of the plant. This is important as the designer will require it to design any type of appropriate controller to control the process of the plant. The induction motor model is derived using a rotating (d, q) field reference (without

saturation) concept. Some researchers [8] and [5] made some assumption which is valid for this research work, and the assumptions are as follows:

- Geometrical and electrical machine configurations are symmetrical.
- Space harmonics of the stator and rotor magnetic flux are negligible.
- Infinitely permeable iron;
- Stator and rotor windings are sinusoidally distributed in space and replaced by an equivalent concentrated winding;
- Saliency effects, the slotting effects are neglected or negligible.
- Magnetic saturation, anisotropy effect, core loss and skin effect are negligible.
- Windings resistance and reactance do not vary with the temperature.
- Currents and voltages are sinusoidal terms.
- End and fringing effects are neglected.

All these assumption do not alter in a serious way the final result for a wide range of induction machines.

The real model of a typical three – phase induction machine with three stator windings and three rotor windings are shown in Fig. 1

3. MODELING OF INDUCTION SERVO MOTOR

The suitability of the induction motor drive to a given application is characterized by its steady state and dynamic behaviour. In order to analytically predict the motor drive performance, it is essential to develop a mathematical model of the drive under required operating conditions, using reasonable assumptions.

The generalized equivalent circuit on an arbitrarily rotating frame are as shown in Fig. 2a (open circuit) and 2b (short circuit). Now, depending on a specific choice of ω_a , many forms of dynamic equivalent can be established. Among them, the synchronous frame form can be obtained by choosing $\omega_a = \omega_s$. this form is very useful in describing the concept of vector control of induction motor because at this rotating frame, space vector is not rotating, but fixed and have a constant magnitude in steady-state. Since space vectors in the synchronous frame will be used frequently, they are denoted without any superscript, thus indicating the type of frame.

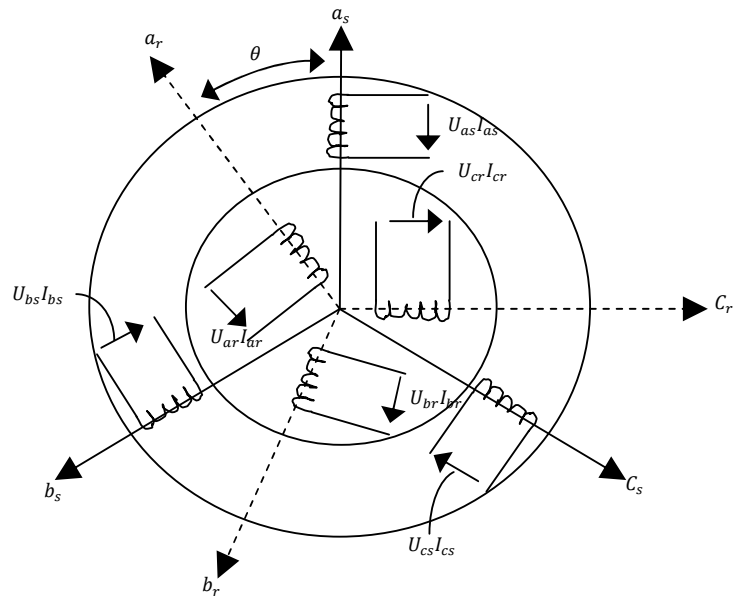
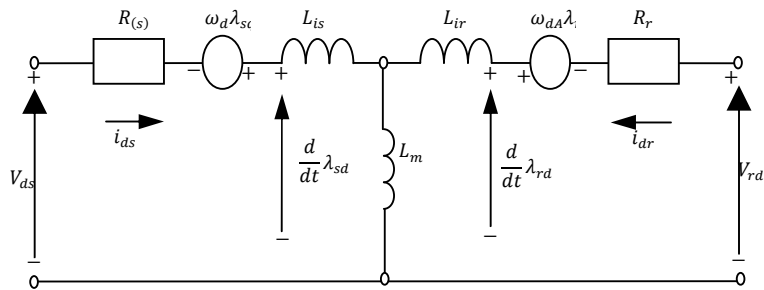
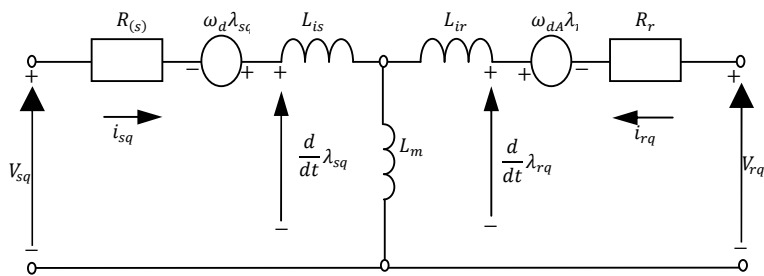


Fig. 1. Real model of a three – phase induction machine



(a) d - axis



(b) q -axis

Fig. 2. D – Q Equivalent circuit of induction servo motor on a synchronous frame (Open circuit)

The model of Fig. 2 (above) was used to estimate the voltage required to drive the torque and flux to the required values within a fixed time period. By using KVL and assuming linear magnetic circuit iron losses, the dynamic model voltages of the three – phase induction servo

motor can be expressed in the d – q synchronously reference rotating frame as: For the stator circuit.

$$V_{ds} + W_d \lambda_{qs} = R_s i_{ds} + \frac{d}{dt} \lambda_{ds} \tag{1}$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt} \lambda_{ds} - W_d \lambda_{qs} \quad (2)$$

Similarly,

$$V_{qs} = R_s i_{qs} + \frac{d}{dt} \lambda_{qs} + W_d \lambda_{ds} \quad (3)$$

While for the rotor circuit we have

$$V_{dr} = R_r i_{dr} + \frac{d}{dt} \lambda_{dr} - W_{dA} \lambda_{qr} \quad (4)$$

and

$$V_{qr} = R_r i_{qr} + \frac{d}{dt} \lambda_{qr} + W_{dA} \lambda_{dr} \quad (5)$$

These voltages obtained can be synthesized using the space vector modulation.

The models with currents space vectors state - space variable is being used. As complex state variables, the currents space vectors $X = [i_{qs}, i_{ds}, i_{qr}, i_{dr}]$ are usually assumed. The stator current space vector was considered generally as the right choice because it corresponds to directly measurable quantities. This model is readily available from voltages and flux linkages per second equations which can be expressed in matrix form.

According to some researchers such as [1,9-11], the stator and Rotor flux linkage – current relations are as follows; on the d – axis:

$$\lambda_{ds} = L_{is} i_{ds} + L_m (i_{ds} + i_{dr}) = (L_{is} + L_m) i_{ds} + L_m i_{dr} \quad (6)$$

$$\lambda_{dr} = L_{ir} i_{dr} + L_m (i_{ds} + i_{dr}) = (L_{ir} + L_m) i_{dr} + L_m i_{ds} \quad (7)$$

For the q – axis circuit

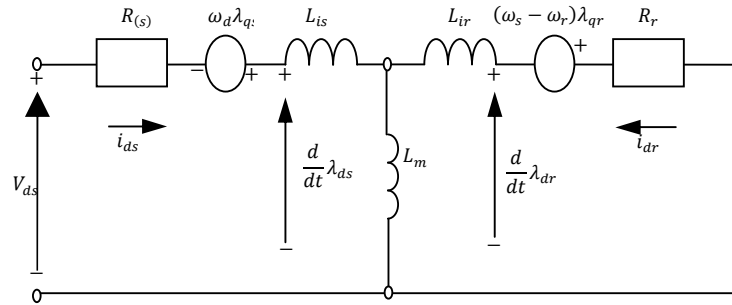
$$\lambda_{qs} = L_{is} i_{qs} + L_m (i_{qs} + i_{qr}) = (L_{is} + L_m) i_{qs} + L_m i_{qr} \quad (8)$$

$$\lambda_{qr} = L_{ir} i_{qr} + L_m (i_{qs} + i_{qr}) = (L_{ir} + L_m) i_{qr} + L_m i_{qs} \quad (9)$$

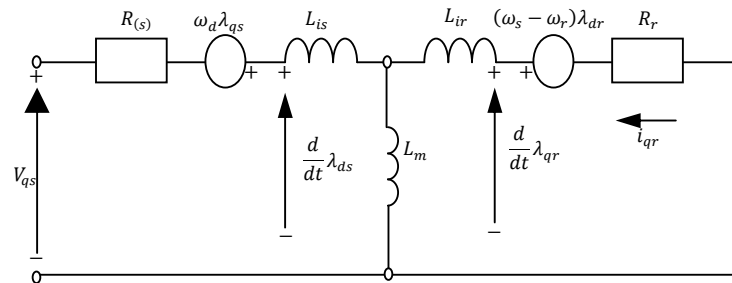
Where $L_s = L_{is} + L_m$

and $L_r = L_{ir} + L_m$

Where L_s and L_r where the stator and rotor inductances, and L_m as the mutual inductance under ideal situation, the voltage for the rotor circuit can be rewritten as:



(a) d – axis circuit



(b) q – axis circuit

Fig. 3. D – Q Equivalent circuit of induction servo motor on a synchronous frame (Short circuit)

The quantities of the d – q equivalent circuits are as follows;

$$R_s, R_r, L_s, L_r, L_m$$

$\lambda_{ds}, \lambda_{qs}$ -d – axis and q – axis stator flux respectively.

$\lambda_{dr}, \lambda_{qr}$ -d – axis and q – axis rotor flux respectively.

i_{ds}, i_{qs} -d – axis and q – axis stator current respectively.

i_{dr}, i_{qr} -d – axis and q – axis rotor current respectively.

V_{ds}, V_{qs} -d – axis and q – axis stator voltage respectively.

The equivalent circuits of Fig.3 assume zero initial motor speed, thus $V_{dr} = V_{qr} = 0$

By applying circuit analysis to Fig.3, we have the following equations;

$$V_{ds} = R_s i_{ds} + \frac{d}{dt} \lambda_{ds} - \omega_s \lambda_{qs} \quad (10)$$

$$V_{qs} = R_s i_{qs} + \frac{d}{dt} \lambda_{qs} + \omega_s \lambda_{ds} \quad (11)$$

$$0 = R_r i_{dr} + \frac{d}{dt} \lambda_{dr} - \omega_{dA} \lambda_{qr} \quad (12)$$

$$0 = R_r i_{qr} + \frac{d}{dt} \lambda_{qr} + \omega_{dA} \lambda_{dr} \quad (13)$$

From eqns. 7 and 9 the rotor currents can be obtained as follows;

$$i_{dr} = \frac{1}{L_r} \lambda_{dr} - \alpha \cdot i_{ds} \quad (14)$$

Similarly,

$$i_{qr} = \frac{1}{L_r} \lambda_{qr} - \alpha \cdot i_{qs} \quad (15)$$

Where $\alpha = \frac{L_m}{L_r}$

From eqns. (6) and (14) we deduce as follows;

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} = L_s i_{ds} + L_m \left(\frac{1}{L_r} \lambda_{dr} - \alpha \cdot i_{ds} \right) \quad (16)$$

While from eqns. (8) and (9) we have,

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} = L_s i_{qs} + L_m \left(\frac{1}{L_r} \lambda_{qr} - \alpha \cdot i_{qs} \right) \quad (17)$$

Thus eqn. (16) can be rewritten as;

$$\lambda_{ds} = L_1 i_{ds} + \frac{L_m}{L_r} \lambda_{dr} - L_m \alpha i_{ds} \quad (18)$$

And eqn. (17) becomes;

$$\lambda_{qs} = L_1 i_{qs} + \frac{L_m}{L_r} \lambda_{qr} - L_m \alpha i_{qs} \quad (19)$$

Simplifying eqns. (18) and (19) we have;

$$\lambda_{ds} = L_1 i_{ds} + \alpha \lambda_{dr} \quad (20)$$

$$\lambda_{qs} = L_1 i_{qs} + \alpha \lambda_{qr} \quad (21)$$

Where $L_1 = L_s - \alpha L_m$ and $\alpha = \frac{L_m}{L_r}$

Also from eqns. (10) and (11)

$$\frac{d}{dt} \lambda_{dr} = -R_r i_{dr} + \omega_{dA} \lambda_{qr} \quad (22)$$

And

$$\frac{d}{dt} \lambda_{qr} = -(R_r i_{qr} + \omega_{dA} \lambda_{dr}) \quad (23)$$

By substituting for the values of i_{dr} and i_{qr} in eqns. (20) and (21), and letting $\omega_{dA} = \omega_m$ we have,

$$\frac{d}{dt} \lambda_{dr} = -\frac{R_r}{L_r} \lambda_{dr} + \alpha R_r \cdot i_{ds} + \omega_m \lambda_{qr} \quad (24)$$

$$\frac{d}{dt} \lambda_{qr} = -\frac{R_r}{L_r} \lambda_{qr} + \alpha R_r \cdot i_{qs} - \omega_m \lambda_{dr} \quad (25)$$

Making $T_r = \frac{L_r}{R_r}$ in eqns. (24) and (25), the rotor flux equations can be obtained as;

$$\frac{d}{dt} \lambda_{dr} = -\frac{1}{T_r} \lambda_{dr} + \alpha R_r i_{ds} + \omega_m \lambda_{qr} \quad (26)$$

$$\frac{d}{dt} \lambda_{qr} = -\frac{1}{T_r} \lambda_{qr} + \alpha R_r i_{qs} - \omega_m \lambda_{dr} \quad (27)$$

By differentiating eqns. (20) and (21) we have

$$\frac{d}{dt} \lambda_{ds} = \frac{L_1 di_{ds}}{dt} + \alpha \frac{d\lambda_{dr}}{dt} \quad (28)$$

$$\frac{d}{dt} \lambda_{qs} = \frac{L_1 di_{qs}}{dt} + \alpha \frac{d\lambda_{qr}}{dt} \quad (29)$$

Substituting for $\frac{d\lambda_{dr}}{dt}$ and $\frac{d\lambda_{qr}}{dt}$ from eqns. (24) and (25) we have;

$$\frac{d}{dt} \lambda_{ds} = \frac{L_1 di_{ds}}{dt} - \frac{\alpha}{T_r} \lambda_{dr} + \alpha^2 R_r i_{ds} + \alpha \omega_r \lambda_{qr} \quad (30)$$

$$\frac{d}{dt} \lambda_{qs} = \frac{L_1 di_{qs}}{dt} - \frac{\alpha}{T_r} \lambda_{qr} + \alpha^2 R_r i_{qs} - \alpha \omega_r \lambda_{dr} \quad (31)$$

From Eqns. (2) and (3)

$$\frac{d}{dt} \lambda_{ds} = R_s i_{ds} + \omega_s \lambda_{qs} + V_{ds} \quad (32)$$

And

$$\frac{d}{dt} \lambda_{qs} = R_s i_{qs} + \omega_s \lambda_{ds} + V_{qs} \quad (33)$$

Equating these eqns. (32) and (33) to eqns. (30) and (31) we have

$$\frac{L_1 d i_{ds}}{dt} = (R_s + \alpha^2 R_r) i_{ds} + \frac{\alpha}{T_r} \lambda_{ds} + \omega_s \lambda_{qs} - \omega_r \lambda_{qr} + V_{ds} \quad (34)$$

$$\begin{aligned} \frac{d i_{ds}}{dt} &= \frac{(R_s + \alpha^2 R_r)}{L_1} i_{ds} + \frac{\alpha}{L_1 T_r} \lambda_{ds} + \frac{\omega_s}{L_1} \lambda_{qs} - \alpha \frac{\omega_r}{L_1} \lambda_{qr} + \frac{V_{ds}}{L_1} \\ &= \frac{\alpha}{L_1 T_r} \lambda_{ds} + \frac{\omega_s}{L_1} \lambda_{qs} + \alpha \frac{\omega_r}{L_1} \lambda_{qr} - \frac{1}{T_r} i_{ds} + \frac{1}{L_1} V_{ds} \end{aligned} \quad (35)$$

So also

$$\begin{aligned} \frac{L_1 d i_{qs}}{dt} &= -R_s i_{ds} + \omega_s \lambda_{ds} + V_{qs} + \frac{\alpha}{T_r} \lambda_{qs} + \alpha^2 R_r i_{qs} \\ &\quad + \alpha \omega_r \lambda_{dr} \end{aligned} \quad (36)$$

$$\begin{aligned} \frac{d i_{qs}}{dt} &= \frac{-(R_s + \alpha^2 R_r)}{L_1} i_{qs} + \frac{\alpha}{L_1 T_r} \lambda_{qs} - \frac{\omega_s}{L_1} \lambda_{ds} \\ &\quad - \alpha \frac{\omega_r}{L_1} V_r + \frac{V_{qs}}{L_1} \\ &= \frac{\alpha}{L_1} \lambda_{qs} + \frac{\omega_s}{L_1 T_r} \lambda_s - \frac{\omega_r}{L_1} \lambda_{dr} - \alpha \frac{\omega_r}{L_1} V_r \\ &\quad - \frac{1}{T_r} i_{qs} + \frac{1}{L_1} V_{qs} \end{aligned} \quad (37)$$

Therefore the state equations of the induction servo motor, as derived in eqns. (26) to (37) are as follows

$$\begin{aligned} \frac{d i_{ds}}{dt} &= \frac{\alpha}{L_1 T_r} \lambda_{dr} + \frac{\omega_s}{L_1} \lambda_{ds} - \alpha \frac{\omega_r}{L_1} \lambda_{qr} - \frac{1}{T_r} i_{ds} \\ &\quad + \frac{1}{L_1} V_{ds} \end{aligned} \quad (38)$$

$$\begin{aligned} \frac{d i_{qs}}{dt} &= \frac{\alpha}{L_1 T_r} \lambda_{qs} + \frac{\omega_s}{L_1} \lambda_{ds} - \alpha \frac{\omega_r}{L_1} \lambda_{dr} - \frac{1}{T_r} i_{qs} \\ &\quad + \frac{1}{L_1} V_{qs} \end{aligned} \quad (39)$$

$$\frac{d}{dt} \lambda_{dr} = -\frac{1}{T_r} \lambda_{dr} + \frac{L_m}{T_r} i_{ds} + \omega_r \lambda_{qr} \quad (40)$$

$$\frac{d}{dt} \omega = \frac{1}{j} (T_e - T_L - F_w) \quad (41)$$

The system equations shown in eqns. (38) – (41), fully describe the induction motor and can now be controlled using the field – oriented

control. So, it is necessary to adopt the decoupling relationship and means of proper selection of State Co-ordinates under the simplifying hypothesis that the rotor flux is kept constant [12].

Since the decoupling condition of the feedback linearization method always holds, the parameters of the induction motor must be precisely known and accurate information on the rotor flux was required. The reason for adopting field oriented control is that the dynamic behavior of the induction motor under the field oriented or feedback linearization control techniques is quite similar to that of a separately excited DC motor, and the control effort is simplified. However, the performance will be degraded due to the motor parameter variations or unknown external disturbances.

In order to prepare the induction motor for field oriented control, the rotor flux quadrature component will be equal to zero, that is;

$$\dot{\lambda}_{qr} = 0 \text{ or } \frac{d}{dt} \lambda_{qr} = 0, \text{ with } \lambda_{qr}(0) = 0 \quad (42)$$

Thus, eqn. (27) can be written as

$$\omega_m = \frac{L_m}{\tau_r \lambda_{dr}} i_{qs} \quad (43)$$

But $\omega_m = \omega_s - \omega_r$

Therefore

$$\omega_s = \omega_r + \frac{L_m}{\tau_r \lambda_{dr}} i_{qs} \quad (44)$$

Then the equation of states for the induction motor become;

$$\frac{d i_{ds}}{dt} = \frac{\alpha}{L_1 T_r} \lambda_{dr} + \frac{\omega_s}{L_1} \lambda_{ds} - \frac{1}{T_r} i_{ds} + \frac{1}{L_1} V_{ds} \quad (45)$$

$$\frac{d i_{qs}}{dt} = \frac{\omega_s}{L_1} \lambda_{ds} - \alpha \frac{\omega_r}{L_1} \lambda_{dr} - \frac{1}{T_r} i_{qs} + \frac{1}{L_1} V_{qs} \quad (46)$$

$$\frac{d}{dt} \lambda_{dr} = -\frac{1}{T_r} \lambda_{dr} + \frac{L_m}{T_r} i_{ds} \quad (47)$$

$$\frac{d}{dt} \omega = \frac{1}{j} (T_e - T_L - F_w) \quad (48)$$

4. SIMULATION RESULTS AND DISCUSSION

The parameters of equivalent circuit of Induction Machines are crucial when considering advanced control techniques (i.e. Vector Control). The control methods for induction motor drive system require an accurate determination of machine

parameters. Accidentally these parameters are also uncertain when the machine is released from production. The most common ways, to manually determine induction motor Parameters are to test the motor under no-load and locked rotor conditions. Typically, five parameters need to be determined and they are as follows;

- R_s, R_r – the stator and rotor resistances
- L_s, L_r – the stator and rotor leakage inductances
- L_m – the magnetizing inductance.

The following tests were carried out to obtain these parameters;

4.1 Dc Test

This is performed to enable us compute the stator winding resistance, R_s .

$$R_s = \frac{V_{dc}}{2I_{dc}} = 0.5 \frac{V_{dc}}{I_{dc}} \quad (49)$$

It should be noted, however, that V_{dc} in eqn. (49) is the average value and as such the stator resistance obtained from this dc test is an approximate value. The actual value of ac resistance can be obtained by considering the wire size, the stator frequency and the operating temperature.

4.2 NO-Load Test

This is like the open circuit test on a transformer and it gives information about exciting current and rotational losses. The stator is energized by applying rated voltage at rated frequency.

4.3 Locked Rotor Test

The locked rotor test, like short circuit test on a transformer, provides the information about leakage impedances and rotor resistance.

At the completion of these three tests, equivalent circuit parameters can be calculated easily. In a situation whereby the motor classification is not

known, [13] and [14] showed that the leakage reactance can be assumed as;

$$X_1 = X_2 = 0.5 X_{br} \quad (50)$$

Thus making it possible to obtain the magnetization reactance, X_m , using the expression;

$$X_m = |Z_{br}| - X_1 \quad (51)$$

Furthermore, a better approximation is needed for the value of the rotor resistance since it has a more significant effect on the performance of the motor when compared with other circuit parameters. According to [15], the following expression achieves the desired approximation;

$$R_r = (R_{br} - R_1) \left[\frac{X_2 - X_m}{X_m} \right]^2 \quad (52)$$

From the on-line experiments (i.e., dc, no-load and blocked rotor tests), the induction motor equivalent circuit parameters results obtained are as shown in table 1.

$$V_{dc} = 120V$$

$$I_{dc} = 71.69A$$

From the data the induction motor parameters were estimated as follows;

Stator resistance,

$$R_s = 0.5 \frac{V_{dc}}{I_{dc}} = 0.5 X \frac{120}{71.69} = 0.837 \Omega$$

And from no-load test,

$$|Z_{br}| = X_1 + X_m = \frac{V_a}{I_{per\ phase}} = \frac{120}{9.23} = 13\Omega$$

Also from the blocked rotor test,

$$R_{br} = \frac{P_a}{I_\phi^2} = \frac{247.1}{25.74^2} = 0.373 \Omega$$

$$\text{And } Z_{br} = \frac{V_a}{I_\phi} = \frac{100}{25.74} = 3.885 \Omega$$

$$\text{Thus } X_{br} = \sqrt{|Z_{br}|^2 - R_{br}^2} = \sqrt{3.885^2 - 0.373^2} = \sqrt{15.09 - 0.13913} = 3.87 \Omega$$

$$X_{br} = X_1 + X_2$$

$$\text{Using } X_1 = X_2 = 0.5X_{br} = 0.5 \times 3.87 = 1.935$$

$$\text{And } X_m = |Z_{br}| - X_1 = 13 - 1.935 = 11.07,$$

$$L_1 = L_2 = \frac{X_1}{2\pi f} = \frac{1.935}{100\pi} = 0.00622 H$$

$$L_m = \frac{X_m}{2\pi f} = \frac{11.07}{100\pi} = 0.03525 H$$

The rotor resistance can also be estimated by using;

$$\begin{aligned}
 R_r &= (R_{br} - R_s) \left[\frac{X_2 + X_m}{X_m} \right]^2 \\
 &= (0.373 - 0.837) \left[\frac{1.935 + 11.07}{11.07} \right]^2 \\
 &= -0.464 \times 1.1748^2 \\
 &= 0.64\Omega
 \end{aligned}$$

These values of the induction motor parameters were used to obtain a MATLAB/Simulink model shown in Fig. 4

Figs. 5 and 6 show the responses obtained from the MATLAB/Simulink model of the induction motor for different values of torque T_m . Fig. 5) Shows a no-load condition, in which the three phase's currents quickly settle to almost the same value (i.e. 0 Ampere.). The speed was set at 160 rad/s. The electromagnetic torque generated, though initially high during the transient periods, reached the steady state value in less than 0.5 second. Hence the magnitude of the rotor currents was also high during the

transient (starting) periods The stator currents also showed high starting values of $\pm 90 A$ and later settled down to $\pm 25 A$. It can be inferred from this results that at lower speeds, the flux required to develop the suitable torque is high which leads to a high starting currents, but once the motor reaches the set speed, it requires a nominal current to drive the induction motor.

Fig. 6 shows a situation where a load disturbance of 1 Nm is applied. It was observed that both the red and blue phases' currents quickly settled at the same value with the speed still at 160 rad/s while the yellow phase current assumed a new value. At the transient periods, the magnitude of the stator currents, rotor currents, and electromagnetic torque exhibit high values, but come to nominal values as the rotor speed achieves the set value. The stator voltages remain constant all the time. On further investigation, it was observed that when more torque was added and at the same speed of 160 rad/s, though the phase's currents quickly settled down, they assumed different values. This will make the motor control a little difficult and challenging.

Table 1. Experimental results for no-load and block-rotor tests

Test type	Ia (A)	Ib (A)	Ic (A)	Va (V)	Pa (W)
No-load test	9.229	9.231	9.227	120	34.9
Blocked-rotor test	25.75	25.74	25.73	100	247.1

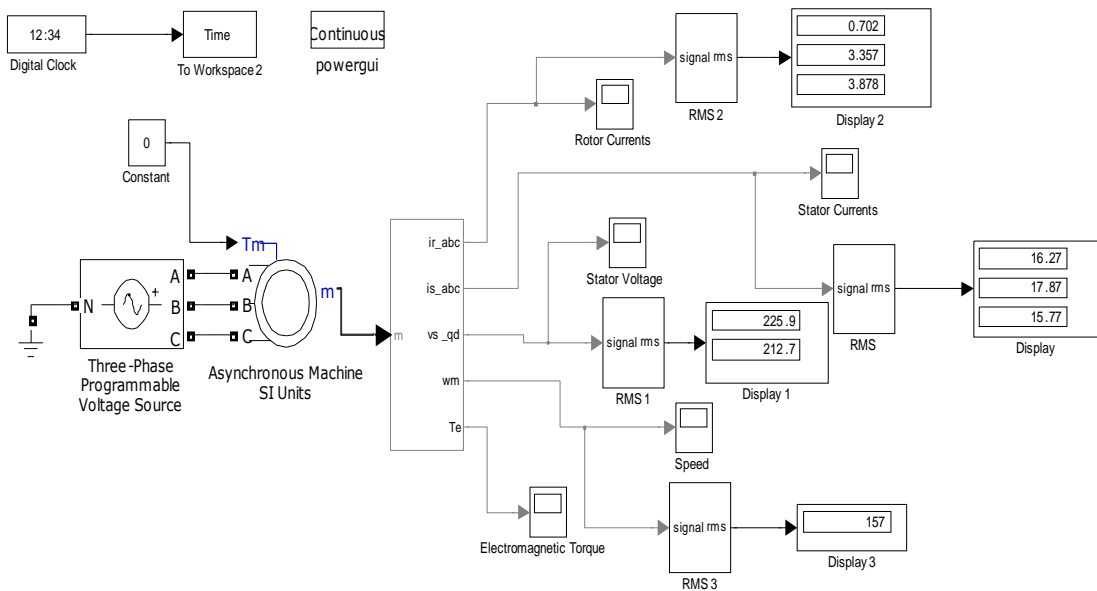


Fig. 4. MATLAB/ simulink model of the three phase induction motor

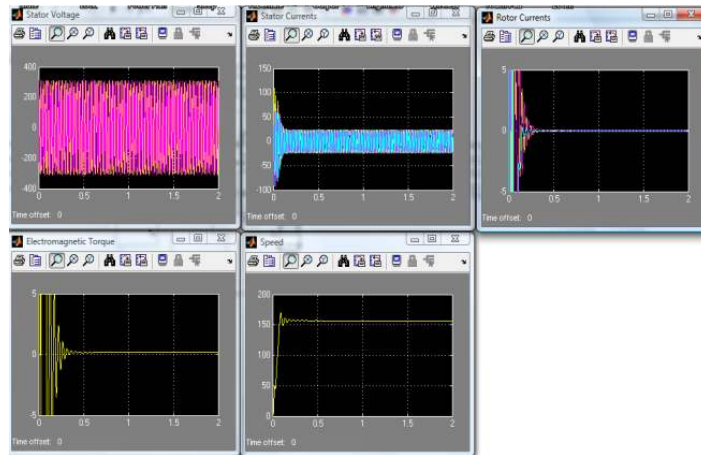


Fig. 5. Responses from the MATLAB simulations of Fig. 1.17 when $T_m = 0$

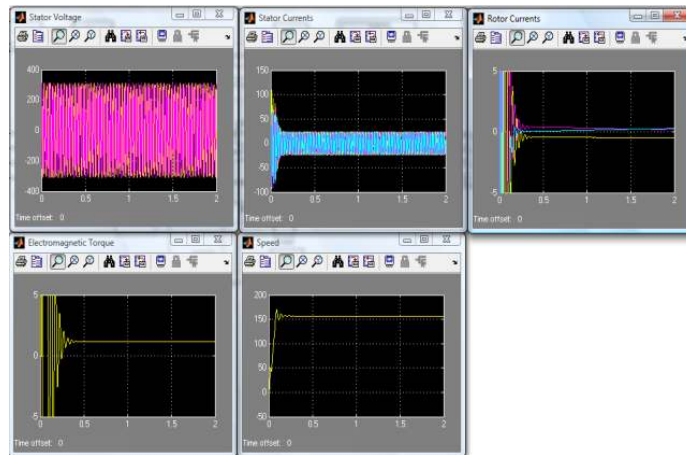


Fig. 6. Responses from the MATLAB simulations of Fig. 1.17 when $T_m = 1$

5. CONCLUSION

The work of modeling and parameter determination of an induction motor drive system has been presented in this paper. Generalized equations describing the behaviour of an induction motor under steady-state and transient conditions were established by considering it as an elementary two pole idealized machine. The model consists of current, flux and electromagnetic torque models. The flux and current models were used to solve the induction motor voltage equations, taking into account a stator reference frame. The d-q equivalent circuit was used, but time-varying parameters due to skin effect in rotor impedance, influence of temperature on stator, rotor resistance and rotor leakage inductance variations due to the slip were taken into consideration. With the help of d-q transformation of variables, basic equations for

induction motor were developed. An on-line simulation experiment was carried out to determine the induction motor parameters. The values obtained for these parameters were used to obtain a MATLAB/Simulink model for the induction motor. The results obtained from the MATLAB/Simulink showed that induction motor performs better under no-load condition but requires a specialized controller for stability when carrying load.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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