Int. J. Elect. Enging. Educ., Vol. 36, pp. 163–172. Manchester U.P., 1999. Printed in Great Britain

MODELLING AND SIMULATION OF THE THREE-PHASE INDUCTION MOTOR USING SIMULINK

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ABSTRACT This paper describes a generalized model of the three-phase induction motor and its computer simulation using MATLAB/SIMULINK. Constructional details of various sub-models for the induction motor are given and their implementation in SIMULINK is outlined. Direct-on-line starting of a 7.5-kW induction motor is studied using the simulation model developed.

KEYWORDS MATLAB; modelling; simulation; SIMULINK; three-phase induction motor

LIST OF SYMBOLS

L_s	stator inductance
L_m	mutual inductance
L_r	rotor inductance
R_s	stator resistance
R_r	rotor resistance
R_c	cable resistance
ω_0	rotor speed
P	pole number
V_{ds}, V_{qs}	d-axis and q-axis components of the stator voltage vector V_s
V_{dr}, V_{qr}	d-axis and q-axis components of the rotor voltage vector V_r
i_{ds}, i_{qs}	d-axis and q-axis components of the stator current vectors i_s
i_{dr}, i_{qr}	d-axis and q-axis components of the rotor current vectors i_r
J	moment of inertia of rotor
J_L	moment of inertia of load

1 INTRODUCTION

Simulation of the three-phase induction machine is well documented in the literature and a digital computer solution can be performed using various methods, such as numeric programming, symbolic programming and the electromagnetic transient program (EMTP)[1,2]. With the rapid development in computer hardware and software, new simulation packages which are faster and more user friendly are now available. This paper discusses the use of one such product, the SIMULINK software of MATLAB, in the dynamic modelling of the induction motor. The main advantage of SIMULINK over other programming softwares is that, instead of compilation of program code, the simulation model is built up systematically by means of basic function blocks. Through a convenient graphical user interface (GUI), the function blocks can be created, linked and edited easily using menu commands, the keyboard and an appropriate pointing device (such as the mouse). A set of machine differential equations can thus be modelled by interconnection of appropriate function blocks, each of which performing a specific mathematical operation. Programming efforts are drastically reduced and the debugging of errors is easy. Since SIMULINK is a model operation programmer, the simulation model can be easily developed by addition of new sub-models to cater for various control functions. As a sub-model the induction motor could be incorporated in a complete electric motor drive system[3–5].

2 INDUCTION MOTOR MODEL CONSTRUCTED USING SIMULINK

A generalized dynamic model of the induction motor consists of an electrical sub-model to implement the three-phase to two-axis (3/2) transformation of stator voltage and current calculation, a torque sub-model to calculate the developed electromagnetic torque, and a mechanical sub-model to yield the rotor speed. In addition, a stator current output sub-model is needed for calculating the voltage drop across the supply cables.

2.1 *Electrical sub-model of the induction motor*

The three-phase to two-axis voltage transformation is achieved using the following equation[6]:

$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}}_{[A]} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \tag{1}$$

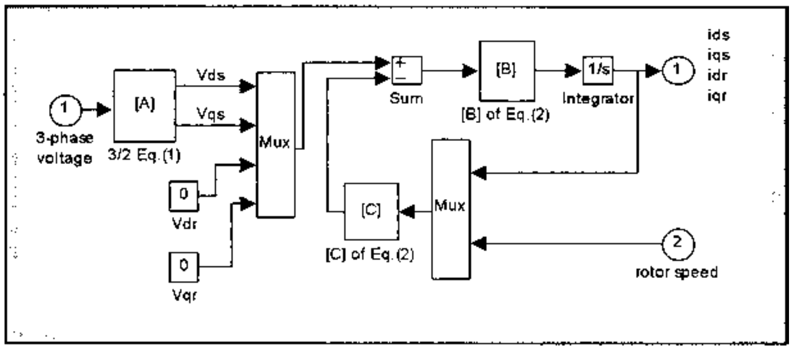

FIG. 1 Electrical model of an induction motor in SIMULINK.

where V_{as}, V_{bs}, and V_{cs} are the three-phase stator voltages, while V_{ds} and V_{qs} are the two-axis components of the stator voltage vector V_s.

In the two-axis stator reference frame, the current equation of an induction motor can be written as[5,6]:

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} = \int_{\tau=0}^{t} \left\{ \underbrace{\begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix}^{-1}}_{[B]} \right.$$

$$\left. \times \left(\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} - \underbrace{\begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & \frac{P}{2}\omega_0 L_m & R_r & \frac{P}{2}\omega_0 L_r \\ -\frac{P}{2}\omega_0 L_m & 0 & -\frac{P}{2}\omega_0 L_r & R_r \end{bmatrix}}_{[C]} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \right) \right\} d\tau \qquad (2)$$

As shown in Fig. 1, Matrix [A] in Equation (1) and matrix [B] in Equation (2) can be implemented by the 'Matrix Gain' block of SIMULINK[7], while matrix [C] in Equation (2) can be implemented by four 'Fcn' blocks of SIMULINK whose detail is illustrated in Fig. 2.

In the electrical model, the three-phase voltage $[V_{as}, V_{bs}, V_{cs}]$ is the input and the current vector $[i_{ds}, i_{qs}, i_{dr}, i_{qr}]$ is the output vector. The rotor voltage vector

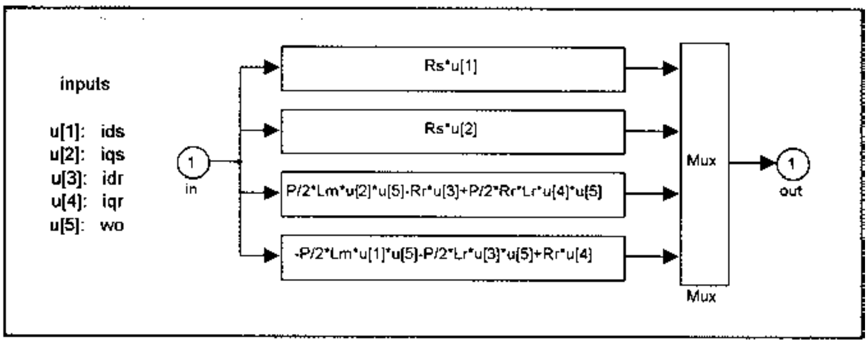

FIG. 2 Matrix [C] implemented using four Fcn blocks of SIMULINK.

is normally zero because of the short-circuited cage rotor winding, i.e. $V_{dr} = 0$ and $V_{qr} = 0$.

2.2 *Torque sub-model of induction motor*

In the two-axis stator reference frame, the electromagnetic T is given by[6]:

$$T = \frac{PL_m}{3}(i_{dr}i_{qs} - i_{qr}i_{ds}) \tag{3}$$

Fig. 3 shows how the torque sub-model is realized in SIMULINK.

2.3 *Mechanical sub-model of induction motor*

From the torque balance equations and neglecting viscous friction, the rotor speed ω_0 may be obtained as follows[8]:

$$\omega_0 = \int_{\tau=0}^{t} \frac{T - T_L}{J} \, d\tau \tag{4}$$

where J is the moment of inertia of the rotor and load and T_L is the load torque.

Fig. 4 shows the implementation of the mechanical sub-model.

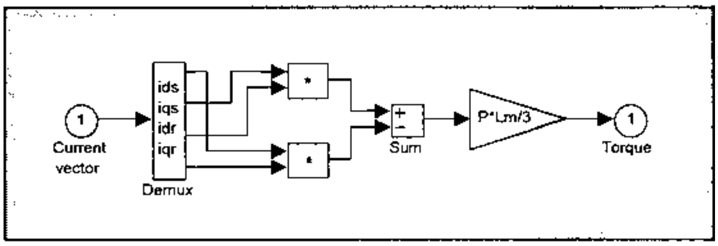

FIG. 3 Torque sub-model.

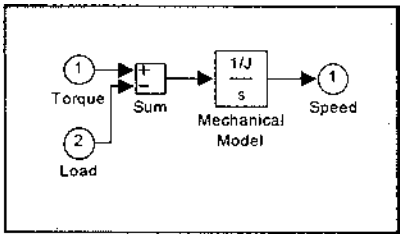

FIG. 4 Mechanical sub-model.

2.4 *Stator current output sub-model*

The stator current output sub-model is used to calculate the stator current amplitude according to the following equation[6]:

$$|i_s| = \frac{2}{3}\sqrt{(i_{ds}^e)^2 + (i_{qs}^e)^2} \tag{5}$$

A SIMULINK 'Fcn' block is used to implement the above equation.

The electrical sub-model in Fig. 1, the torque sub-model in Fig. 3, the mechanical sub-model in Fig. 4, and the stator current output sub-model are grouped together to form the induction motor model as shown in Fig. 5.

3 SIMULATION SYSTEM OF INDUCTION MOTOR

The complete simulation system of the induction motor includes the induction motor model in Fig. 5 and a power supply sub-model.

3.1 *Power supply sub-model*

The voltage supply block consists of a three-phase sinusoidal voltage generator and a terminal-voltage calculation block which accounts for the voltage drop in the supply cable.

The three-phase sinusoidal voltage generator is based on Equation (6) and one of the three phase voltages is modelled as shown in Fig. 6.

$$\begin{cases} V_{as} = |V|\cos(\omega t + \theta) \\ V_{bs} = |V|\cos(\omega t - 2\pi/3 + \theta) \\ V_{cs} = |V|\cos(\omega t + 2\pi/3 + \theta) \end{cases} \tag{6}$$

where $|V|$ is the amplitude of the terminal voltage, ω is the supply frequency, and θ is the initial phase angle.

Due to the voltage drop in the supply cable, the terminal voltage is given by Equation (7):

$$|V| = E - R_c|i_s| \tag{7}$$

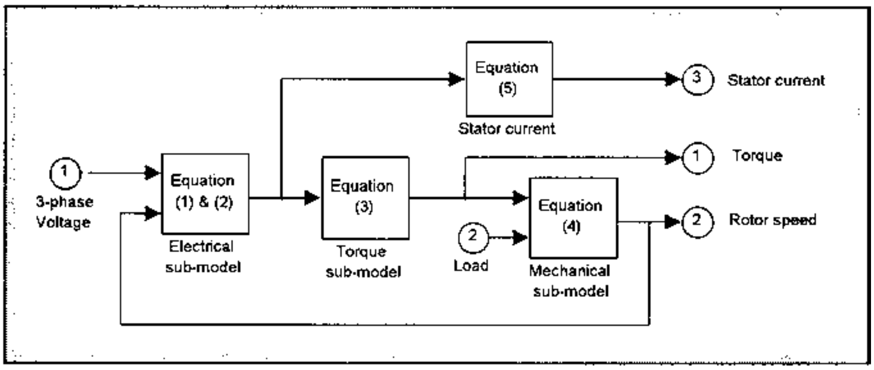

FIG. 5 Induction motor model in SIMULINK.

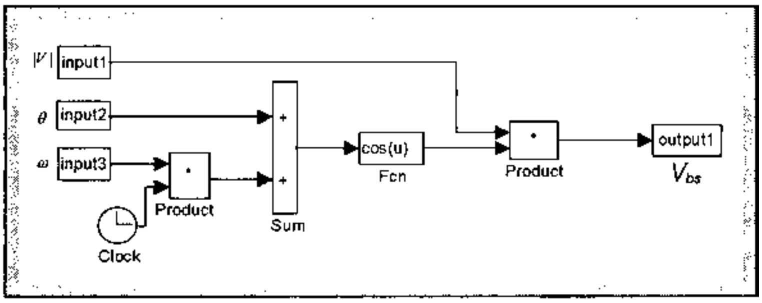

FIG. 6 Modelling one supply phase in SIMULINK.

where E is the supply voltage and R_c is the cable resistance. Fig. 7 shows how the equation is modelled in SIMULINK.

Grouping the voltage generator block of Fig. 6 and terminal-voltage calculation block of Fig. 7, the power supply block is formed as shown in Fig. 8.

3.2 *Simulation model of the induction motor*

The induction motor model in Fig. 5 and the power supply sub-model in Fig. 8 are grouped together to form the complete induction motor simulation model as shown in Fig. 9. The XY-graph block[7] is used to display the dynamic torque/speed characteristic of the induction motor, while the scope block enables the speed, stator current, and stator voltage of the motor to be observed.

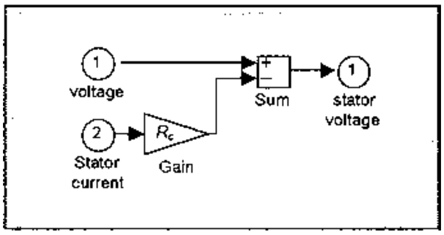

FIG. 7 Terminal-voltage calculation block.

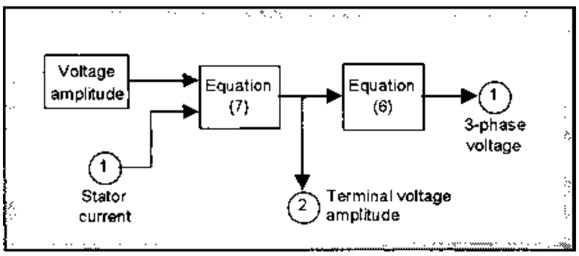

FIG. 8 Power supply block.

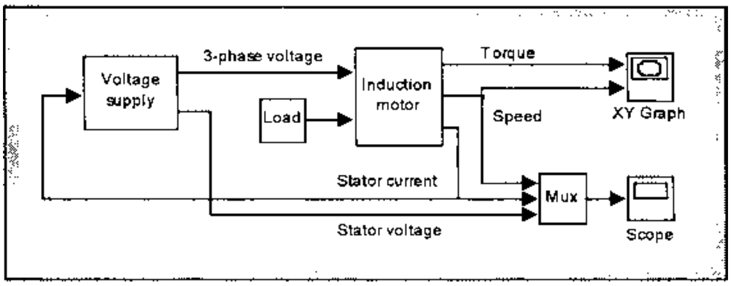

FIG. 9 Simulation system of an induction motor in SIMULINK.

4 SIMULATION RESULTS

The induction motor chosen for the simulation studies has the following parameters:

Type: three-phase, 7.5 kW, 6-pole, wye-connected, squirrel-cage induction motor

$R_s = 0.288\ \Omega$/ph $\quad R_r = 0.158\ \Omega$/ph

$L_s = 0.0425\ \Omega$/ph $\quad L_m = 0.0412\ \Omega$/ph

$L_r = 0.0418\ \Omega$/ph $\quad J = 0.4$ kg m^2

$J_L = 0.4$ kg m^2

To illustrate the transient operation of the induction motor, a simulation study of direct-on-line starting is demonstrated. At $t = 0$, the motor, previously de-energized and at standstill, is connected to a 220 V, 60 Hz three-phase supply through a cable. The load torque, T_L, is constant at 20 N.m. Figs. 10 to 15 show the results of computer simulation using the SIMULINK model. The results are similar to those obtained using the traditional simulation method involving differential equations. It is noticed that when the supply cable has a large resistance, the torque oscillations in the torque/speed charac-

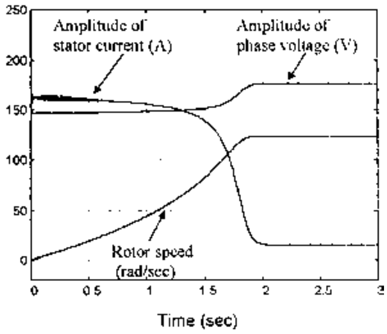

FIG. 10 Simulation results with cable resistance $R_c = 0.2\ \Omega$.

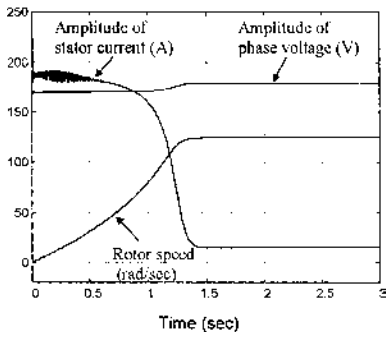

FIG. 11 Simulation results with cable resistance $R_c = 0.05\ \Omega$.

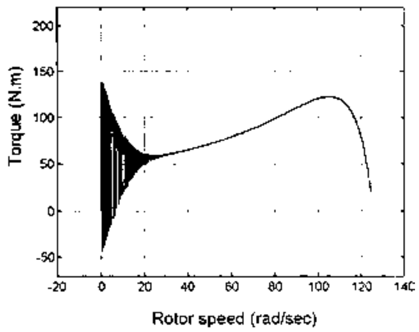

FIG. 12 Torque/speed characteristic with cable resistance $R_c = 0.2\ \Omega$.

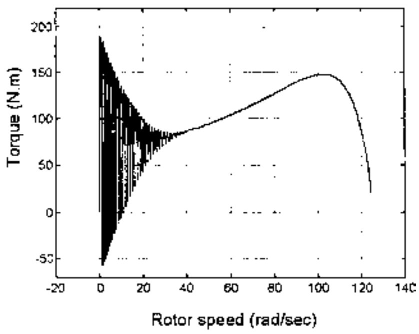

FIG. 13 Torque/speed characteristic with cable resistance $R_c = 0.05\ \Omega$.

teristic are reduced and decay more rapidly, but the run up time of the motor is longer.

5 CONCLUSION

SIMULINK is a powerful software package for the study of dynamic and nonlinear systems. Using SIMULINK, the simulation model can be built up

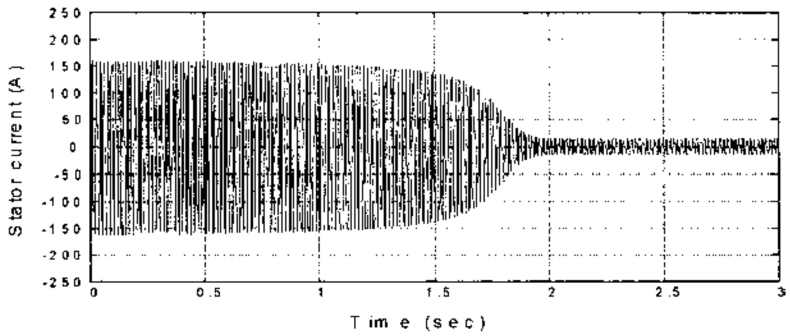

FIG. 14 Stator phase current with cable resistance $R_c = 0.2\ \Omega$.

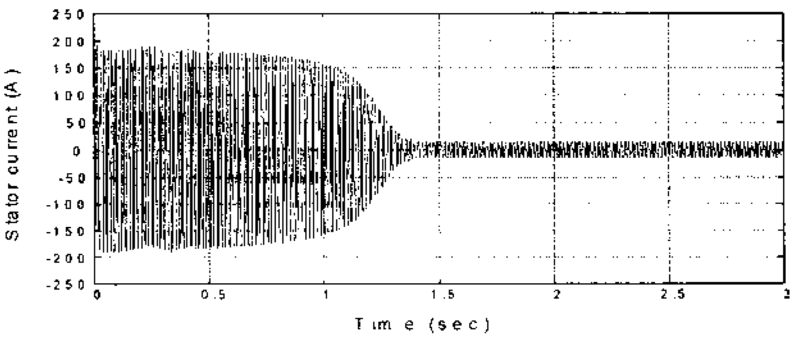

FIG. 15 Stator phase current with cable resistance $R_c = 0.05\ \Omega$.

systematically starting from simple sub-models. The induction motor model developed may be used alone, as in the direct-on-line starting example presented, or it can be incorporated in an advanced motor drive system, e.g. field-oriented control. The authors believe that SIMULINK will soon become an indispensable tool for the teaching and research of electrical machine drives.

ACKNOWLEDGEMENT

The work reported in this paper was funded by the Hong Kong Polytechnic University research grant V157.

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ABSTRACTS – FRENCH, GERMAN, SPANISH

Modélisation et simulation d'un moteur triphasé à induction utilisant SIMULINK
Cet article décrit un modèle généralisé d'un moteur triphasé à induction et sa simulation informatique utilisant MATLAB/SIMULINK. Les détails constructifs de différents sous-modèles du moteur à induction sont donnés et leur implémentation par SIMULINK est esquissée. Le démarrage direct d'un moteur de 7.5 kW est étudié en utilisant le modèle de simulation développé.

Modellieren und Simulieren der Drehstrominduktionsmotor mit SIMULINK
Dieser Beitrag beschreibt ein verallgemeinertes Modell der Drehstrominduktionsmaschine und ihrer Computersimulierung mit MATLAB/SIMULINK. Konstruktive Einzelheiten verschiedener Untermodelle für die Induktionsmaschine werden angegeben und ihre Durchführung in SIMULINK wird umrissen. Mit dem entwickelten Simulationsmodell wird direktes on-line Starten einer Induktionsmaschine von 7,5 kW studiert.

Modelación y simulación de un motor de inducción de tres fases empleando SIMULINK
Este artículo describe un modelo generalizado de un motor de inducción de tres fases y su simulación por computador empleando MATLAB/SIMULINK. Se muestran detalles constructivos de varios submodelos del motor de inducción y se destaca su implantación en SIMULINK. Se estudia la puesta en marcha de un motor de inducción de 7,5 kW empleando el modelo de simulación desarrollado.