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Approach to Couple MATLAB Simscape and Simulink Blocks for Dynamic Analysis of Multiphase Drive Systems

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Abstract. Multiphase machine models can be accurately designed and represented by means of MATLAB Simulink. This is because the dq-axis flux linkages and the torque response of the multiphase machines can be accurately expressed and described by means of lookup tables-based finite element method (FEM) simulations. However, the power electronic converters are easily implemented using MATLAB Simscape. Hence, the two MATLAB blocks should be connected together to provide the whole drive system. However, there will be a problem to easily connect the two MATLAB blocks directly. Consequently, this paper introduces a detailed description of the proposed interconnector that can be used to interface the two MATLAB blocks. A five-phase induction motor Simulink model connected to a five-phase voltage source inverter Simscape model will be presented to analyze and describe the implementation of the proposed interconnector. Finally, the simulation result of the five-phase squirrel cage induction motor, the five-phase voltage source inverter and the proposed interconnector are displayed.

INTRODUCTION

Multiphase drive systems have revealed excessive features over the conventional three-phase drive system such as higher torque, higher efficiency, lower torque ripple and better fault tolerant [1]. Hence, multiphase drive systems are recently get involved in many industrial applications e.g. aerospace and military applications. There are two main components in the drive system e.g. the motor and the converter. The performance of the whole drive system should be tested using MATLAB simulation before manufacturing and the real time operation. The power converter controls the transfer of the power from the supply to the motor. The power transformation requires control of MOSFETs, IGBTs and other power electronic devices in the system. Designing an automated controller with simulation can help ensure stability, enhance control quality, dynamic performance enhancement, and fault conditions handling. Simulation of power electronics converter gives understanding or a prediction into the communication of the automated control algorithms, control semiconductors, and the adjustment of the electrical system before the equipment testing starts. Besides, power electronics simulation with MATLAB Simulink gives researchers a chance to display complex topologies with multiple switching devices utilizing standard circuit parts. Designers can run quick simulations with normal models or ideal switching behavior, or utilize detailed nonlinear switching models for detailed design [2].

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The medium to high power drives application has an extraordinary improvement after introducing multiphase motor drives. The multiphase induction motor, with a phase number greater than three phases, finds a request in a critical and special areas where a high reliability is necessitated for example in high power application, locomotive traction, Hybrid Electric vehicles and aerospace applications. A multiphase drive system generally consists of a multiphase converter and the multiphase induction motor [2–5]. Preparing a simulation model for this system requires two block modelling, the first block is converter modelling and the second block contains five-phase motor modelling [6, 7]. In this paper, the possibility of constructing a non-standard motor model together with a standard converter model using Simulink and Simscape blocks is demonstrated. Researchers usually design the converter as a Simscape model due to its simplicity in design and control. But, there is no Simscape model for multiphase induction motor in MATLAB software package. As a result, a Simulink model for the multiphase induction motor is designed but there is a problem in the connection between the Simscape model and the Simulink model. This paper gives a solution for the interconnection between a MATLAB Simscape model of the five-phase voltage inverter block and a MATLAB Simulink five-phase motor block. The dynamic model is carried out to study the behavior of the system with the interconnection.

SIMULINK MODEL FOR FIVE-PHASES-INDUCTIONS MOTOR

In this model, a five-phase squirrel-cage induction motor characterized in a d-q synchronous reference frame is utilized. This higher phase number outperforms the conventional three-phase drives. It offers superior torque density and fault tolerance operation with a fatal at one or two phases. In this motor, the winding magnetic axes are 72 degrees apart electrically. A uniform air gap and sinusoidally distributed windings are suggested in this study besides ignoring core losses and magnetic saturation. The voltage equations shown below in the synchronous reference frame can be used to model a five-phase squirrel cage induction machine [8, 9].

$$V_{qs} = R_s I_{qs} + \frac{d\,\psi_{qs}}{dt} + \omega_e \psi_{ds} \tag{1}$$

$$V_{ds} = R_s I_{ds} + \frac{d\,\psi_{ds}}{dt} - \omega_e \psi_{qs} \tag{2}$$

$$0 = R_r I_{qr} + \frac{d\,\psi_{qr}}{dt} + (\omega_e - \omega_r)\psi_{dr} \tag{3}$$

$$0 = R_r I_{dr} + \frac{d\,\psi_{dr}}{dt} - (\omega_e - \omega_r)\psi_{qr} \tag{4}$$

For the stationary reference frame $\omega_e = 0$, yields:

$$V_{qs} = R_s i_{qs} + \frac{d\,\psi_{qs}}{dt} \tag{5}$$

$$V_{ds} = R_s i_{ds} + \frac{d\,\psi_{ds}}{dt} \tag{6}$$

$$0 = R_r i_{qr} + \frac{d\,\psi_{qr}}{dt} - \omega_r \psi_{dr} \tag{7}$$

$$0 = R_r i_{dr} + \frac{d\,\psi_{dr}}{dt} + \omega_r \psi_{qr} \tag{8}$$

$$\psi_{qs} = (L_{ls} + L_m) i_{qs} + L_m i_{qr} \tag{9}$$

$$\psi_{ds} = (L_{ls} + L_m) i_{ds} + L_m i_{dr} \tag{10}$$

$$\psi_{qr} = (L_{lr} + L_m)i_{qr} + L_m i_{qs} \tag{11}$$

$$\psi_{dr} = (L_{lr} + L_m)i_{dr} + L_m i_{ds} \tag{12}$$

The developed torque is given by:

$$T_e = \frac{5}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right) \tag{13}$$

$$T_e - T_L = J\frac{d\omega_r}{dt} + B\,\omega \tag{14}$$

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{xs} \\ V_{ys} \\ V_{os} \end{bmatrix} = \frac{2}{5}\begin{bmatrix} 1 & cos\alpha & cos2\alpha & cos3\alpha & cos4\alpha \\ 0 & -sin\alpha & -sin2\alpha & -sin3\alpha & -sin4\alpha \\ 1 & cos3\alpha & cos6\alpha & cos9\alpha & cos12\alpha \\ 0 & -sin3\alpha & -sin6\alpha & -sin9\alpha & -sin12\alpha \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \end{bmatrix}\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ds} \\ V_{es} \end{bmatrix} \tag{15}$$

$$\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i_{ds} \\ i_{es} \end{bmatrix} = \sqrt{\frac{2}{5}}\begin{bmatrix} 1 & 0 & 1 & 0 & 1 \\ cos\alpha & sin\alpha & cos2\alpha & sin2\alpha & 1 \\ cos2\alpha & sin2\alpha & cos4\alpha & sin4\alpha & 1 \\ cos3\alpha & sin3\alpha & cos6\alpha & sin6\alpha & 1 \\ cos4\alpha & sin4\alpha & cos8\alpha & sin8\alpha & 1 \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{xs} \\ i_{ys} \\ i_{os} \end{bmatrix} \tag{16}$$

Where V_{qs},V_{ds}, ψ_{qs}, ψ_{ds} are the q and d components of stator voltage and flux. R_s and R_r are the stator phase resistance and rotor resistance referred to stator respectively. ω_e, ω_r are the stator field speed and the speed of the rotor in elec rad/s respectively. L_{lr} is the rotor leakage inductance, $L_{ls}$and L_m are the stator leakage and mutual inductance. P is the motor poles number, J is the motor inertia kg.m^2, B is the motor coefficient of friction N.m.s/rad.

The previously presented transformation matrices, torque, voltage and flux equations are utilized to apply the concept of a five-phase squirrel cage induction motor in the MATLAB Simulink model as seen in Fig. 1.

Simscape Model for Five-Phase Inverter

Space vector control is used to control the five-phase inverter. The switches of inverter in Fig. 2 (a) can have only thirty-two allowed operating states, to sidestep short-circuit on the DC link side and also to sidestep open-circuit on the inductive load side. These operating states are divided into thirty active vectors $V_1 - V_{30}$ and two zero vectors V_0. The active vectors are classified into three levels large, medium and small vectors. As seen in Fig. 2 (b), the duty cycles d_α and d_β of active vectors V_α and V_β respectively decagon can be calculated [10–12]. In this study, the small vectors are not used to minimize the number of operating switching of inverter switches.

$$V_o^* = d_{\alpha m}V_{\alpha m} + d_{\alpha l}V_{\alpha l} + d_{\beta m}V_{\beta m} + d_{\beta l}V_{\beta l} + d_z V_z \tag{17}$$

$$d_\alpha = \frac{T_\alpha}{T_s} = m_v.\sin\left(\frac{\pi}{5} - \theta_v\right) \tag{18}$$

$$d_\beta = \frac{T_\beta}{T_s} = m_v.\sin(\theta_v) \tag{19}$$

$$d_z = \frac{T_z}{T_s} = 1 - (\ \ d_\alpha + d_\beta) \tag{20}$$

$$d_{\beta m} = d_\beta \frac{V_m}{V_L + V_m} \tag{21}$$

$$d_{\beta L} = d_\beta \frac{V_l}{V_L + V_m} \tag{22}$$

$$d_{\alpha m} = d_\alpha \frac{V_m}{V_L + V_m} \tag{23}$$

$$d_{\alpha l} = d_\alpha \frac{V_l}{V_L + V_m} \tag{24}$$

In (17)–(24) T_α, T_β and T_z are the duration times of the vectors V_α, V_β and V_z .

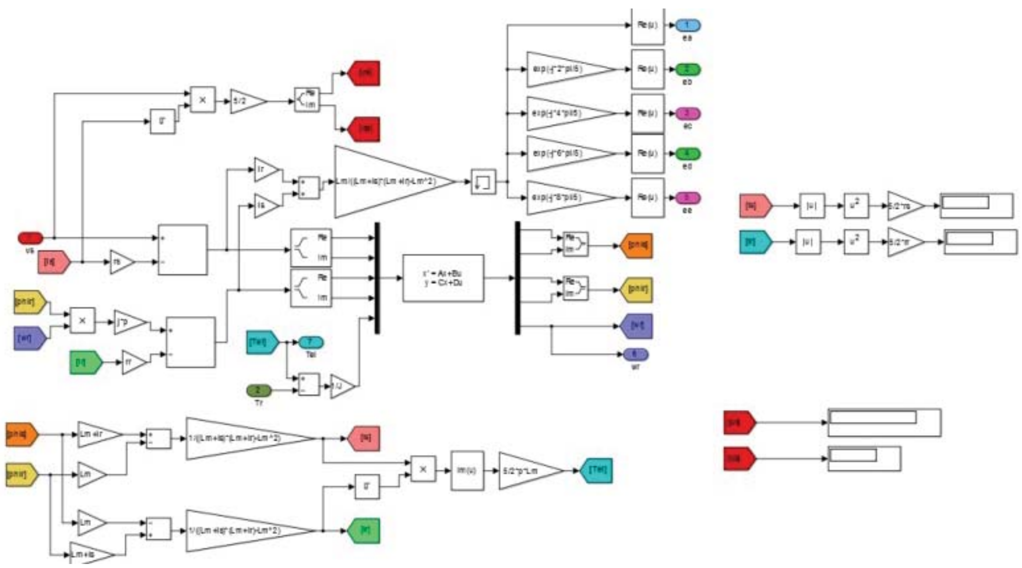
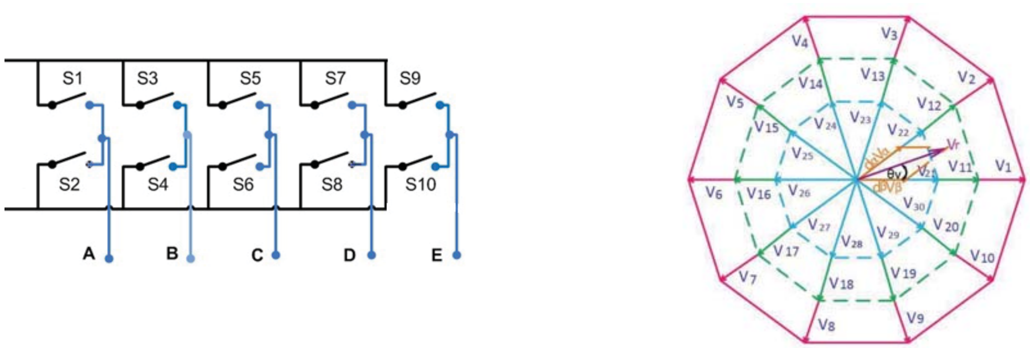


FIGURE 1. Five-phase induction motor Simulink modeling



(a) (b)

FIGURE 2. (a) Five-Phase Inverter, (b) Decagon of Inverter

INTERCONNECTOR MODELLING

The interconnection part consists of current measurement (I) blocks, voltage measurement (V) blocks, controlled voltage source blocks (CVS), summing points and some of R-L series branches. Figure 3 clarifies the structure of the block diagram for the proposed model in which the interconnection block is carried out. The interconnection block has five input signals for the five-phase output voltage from the Simscape model of inverter and one output

Simulink vector signal. The interconnection block is described in detail in Fig. 4, where Fig. 4, a displays the detailed model of the interconnection between voltages, currents measurement blocks. The value of the resistance and inductance in R-L series branches are equal to the resistance and inductance of the stator. Figure 4, b and Fig. 4, c describe in detail the connection of the two blocks found in the detailed model of the interconnection in Fig. 4, a.

SIMULATIONS AND DISCUSSIONS

The system is developed and simulated using MATLAB program. In the Appendix, motor parameters are itemized. The five-phase induction motor is supplied from a five-phase voltage source inverter with a proposed interconnection. Figure 5 introduces the analysis for the motor performance, where Fig. 5, a displays the rotor speed response of the motor which near the synchronous speed of 1500 rpm. Figure 5, b shows the transient and steady state response for the stator phase currents for the five-phases motor. Figure 5, c shows the developed torque from the simulated motor and Fig. 5, d shows the five-phase supply input voltages for the stator of the simulated motor.

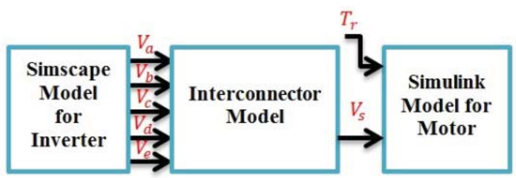


FIGURE 3. Block diagram representation for the proposed system with the interconnection part.

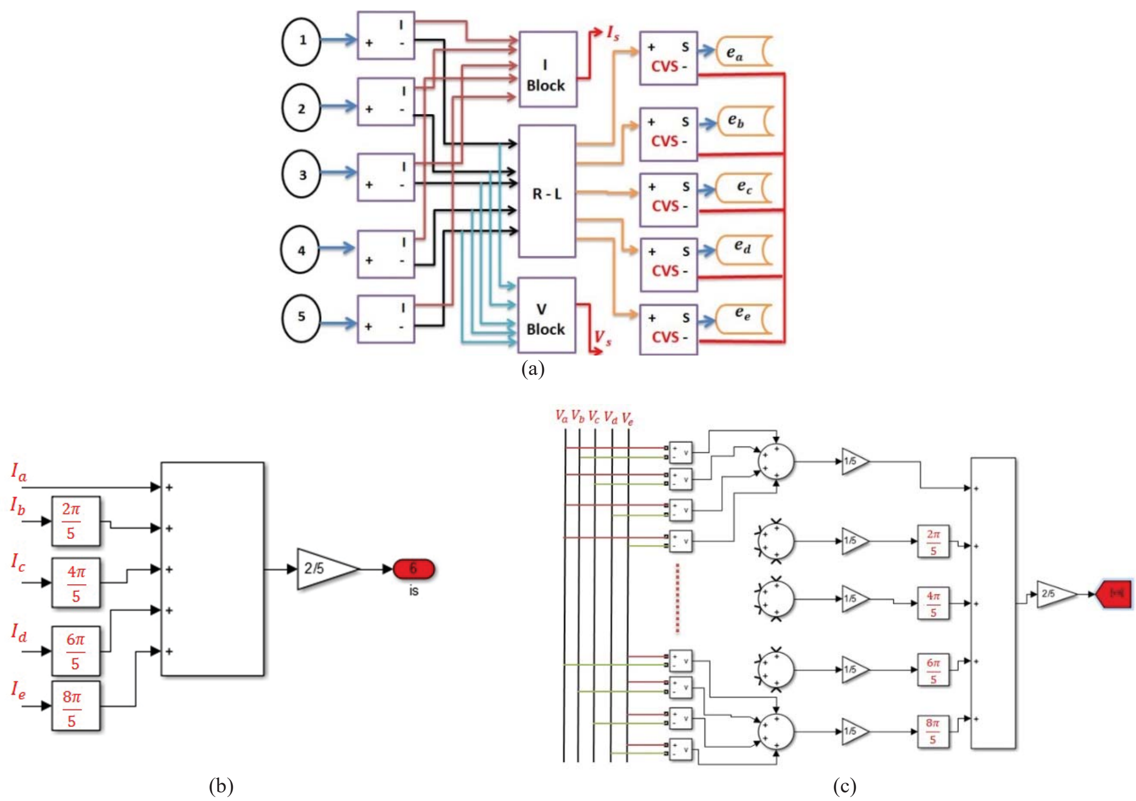
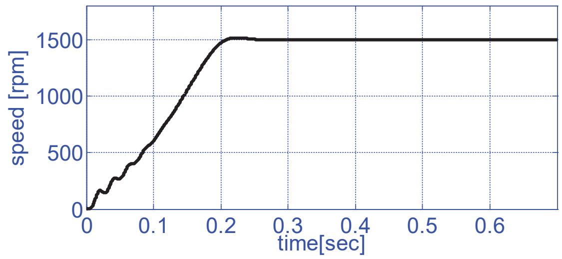
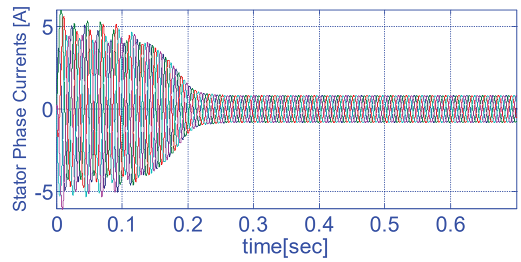


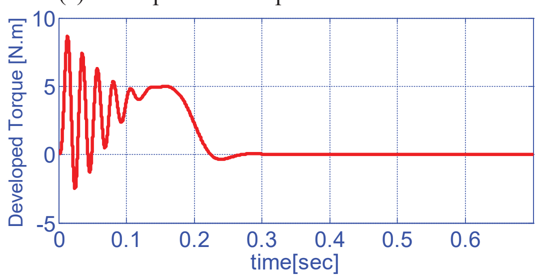
FIGURE 4. (a) Detailed model of the interconnector, (b) Current block, (c) Voltage block



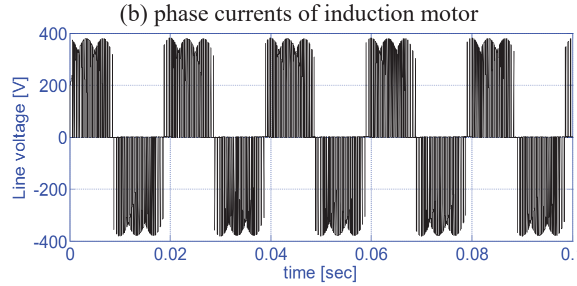
(a) rotor speed of five-phase induction motor



(b) phase currents of induction motor



(c) developed torque from five-phase induction motor



(d) output voltage from five-phase inverter

FIGURE 5. Simulation results for 50Hz frequency

CONCLUSION

In this article, a problem of the interconnection between MATLAB Simulink and simscape blocks has been solved. A Simulink model of a five-phase squirrel cage induction motor connected to a simscape model of five-phase voltage source inverter is carried out to analyze the implementation of the interconnection between the two blocks. Finally, the simulation results for the five-phase squirrel cage induction motor, a five-phase inverter and the proposed interconnector are displayed.

APPENDIX

TABLE 1. Motor parameter

Rating	**1.1 kW**
Rated line Voltage	380 V
frequency	50 Hz
Poles pairs	2
Stator phase resistance	7.48 Ω
Rotor resistance referred to stator	3.68 Ω
Leakage inductance of stator	0.0221 H
Leakage inductance of rotor referred to stator	0.0221 H
mutual inductance	0.4114 H
Motor inertia	0.02 $Kg.m^2$

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