# AC 2011-489: MODELING AND SIMULATION OF ELECTRIC MACHINERY FOR A SENIOR DESIGN PROJECT IN ELECTRICAL ENGINEERING PROGRAM

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# Modeling and Simulation of Electric Machinery for a Senior Design Project in Electrical Engineering Program

## Abstract

As modern technology advances rapidly, it becomes crucial to train and educate our young engineering students. From pedagogical point of view, computer simulation provides a hands-on tool for students to gain deep insights on the dynamic performance and interactions of electric machinery, which often are not easily mastered through studying theory. In order to well prepare engineering students for the challenges presented by advanced technologies in the 21st century, the author developed a series of Matlab/Simulink programs for modeling and simulation of electric machinery, which is used by the following project. In this paper, an intelligent control of induction motor simulation program is presented, which was used in a senior design project (Independent Study) in the electrical engineering program. This project includes the following modules: motor module, PWM module, abc-to-dq module, dq-to-abc module, three phase current generator module, intelligent velocity controller module, and current controller module. Among the above modules, there are several novel ones created by the author, which replaced those existing ones in Matlab/Simulink. For an instance, to clearly visualize the relationship between internal parameters and system performances, all of the referential differential equations were embedded into the models of electrical machines. The theoretical derivation, modeling work, and simulation results in the aforementioned project are provided in the paper.

## I. Introduction

In our current global market, it is urgent to enhance our young engineering students' competitiveness. In order to well educate, train, and prepare them, engineering higher education can take advantage of new technologies and tools available, so that our engineering graduates will successfully handle the challenges that lie ahead. While studying theory is very important, using computer simulation is a great aid in studying theory, since it can provide hands-on experience that is not easily obtained in a lecture or through reading textbooks. Hence computer simulation can aid our students to gain deep insights of certain theories.

In industry, modeling and simulation are widely used by engineers as a critical procedure to design an electric machinery drive so as to save the cost of building a system prototype. When all of the components for a simulation are correctly chosen, the simulation process is able to demonstrate both steady state and transient performance that would have been obtained if the drive was actually built. This practice thus saves time, reduces cost of building a prototype, and ensures that requirements are met beforehand. In industrial R&D, using Matlab/Simulink in modeling and simulation has played a major role, and become more and more popular.

In order to well prepare our engineering students for the challenges presented by advanced technologies in the 21st century, as educators in engineering higher education, we need to offer the opportunities for our young engineering students to get experience in using modern technology tools. Using Matlab/simulink to learn and design electric machinery drives in electrical engineering will open doors and career opportunities for young engineers, and makes them an asset in the future. Therefore, the author developed a series of Matlab/Simulink programs for modeling and simulation of electric machinery, which is used by the following project.

In the following sections, an intelligent control of induction motor simulation program is presented, which was used in a senior design project (Independent Study) in the electrical engineering program. The presented project includes the following modules: motor module, PWM module, abc-to-dq module, dq-to-abc module, three phase current generator module, intelligent velocity controller module, and current controller module. Among them, there are several novel modules created by the author, which replaced those existing ones in Matlab/Simulink. For an instance, to clearly visualize the relationship between internal parameters and system performances, all of the referential differential equations were embedded into the models of electrical machines.

The main parts of the design project will be discussed in the following section. Section II describes the principle of induction motor modeling with indirect vector current control. Section III presents main modules of the design project. Section IV shows the simulation results for the presented project. Finally, some discussions are given in section VI.

## II. Principle of Induction Motor Modeling with Indirect Vector Current Control

Given several assumptions[1, 2], the dynamical model of an induction motor in a fixed reference frame attached to the stator can be described as follows:

$$\frac{d\omega}{dt} = \frac{M}{JL_r}(\psi_a i_b - \psi_b i_a) - \frac{T_L}{J} \tag{1}$$

$$\frac{d\psi_a}{dt} = -\frac{R_r}{L_r}\psi_a - \omega\psi_b + \frac{R_r}{L_r}Mi_a \tag{2}$$

$$\frac{d\psi_b}{dt} = -\frac{R_r}{L_r}\psi_b + \omega\psi_a + \frac{R_r}{L_r}Mi_b \tag{3}$$

$$\begin{aligned}\frac{di_a}{dt} = {} & \frac{MR_r}{(L_rL_s - M^2)L_r}\psi_a + \frac{M}{L_rL_s - M^2}\omega\psi_b \\ & - \frac{M^2R_r + L_r^2R_s}{(L_rL_s - M^2)L_r}i_a + \frac{L_r}{L_rL_s - M^2}u_a\end{aligned} \tag{4}$$

$$\begin{aligned}\frac{di_b}{dt} = {} & \frac{MR_r}{(L_rL_s - M^2)L_r}\psi_b - \frac{M}{L_rL_s - M^2}\omega\psi_a \\ & - \frac{M^2R_r + L_r^2R_s}{(L_rL_s - M^2)L_r}i_b + \frac{L_r}{L_rL_s - M^2}u_b\end{aligned} \tag{5}$$

where rotor speed $\omega$, rotor fluxes $(\psi_a, \psi_b)$, and stator currents $(i_a, i_b)$ are state variables; rotor inertia $J$, stator and rotor inductances $(L_s, L_r)$, mutual inductance $M$, stator and rotor resistances $(R_s, R_r)$ are system parameters; control inputs are stator voltages $(u_a, u_b)$.

For the purpose of nonlinear decoupling of induction motor using the technique of indirect field-oriented control, the model of induction motor can be represented on *d*-*q* rotating axis, in which the *d*-axis is aligned with the rotor flux at all time and the *q*-axis is always $90^{\circ}$ ahead of the *d*-axis. Therefore, we take new variables similar to[3, 4] as follows

$$\begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} = \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} \psi_a \\ \psi_b \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} u_a \\ u_b \end{bmatrix} \tag{8}$$

in which variables on left side represent the components of rotor fluxes, stator currents, and stator voltage vectors, respectively. They all are attached with the *d*-*q* rotating axis at speed $\omega_e$, and are identified by the angle $\varphi$. With the new state variables $(\omega, \psi_d, \psi_q, i_d, i_q)$ and new control inputs $(u_d, u_q)$, the motor dynamics become:

$$\frac{d\omega}{dt} = \frac{M}{JL_r}(\psi_d i_q - \psi_q i_d) - \frac{T_L}{J} \tag{9}$$

$$\frac{d\psi_d}{dt} = \frac{R_r M}{L_r} i_d - \frac{R_r}{L_r}\psi_d + (\omega_e - \omega)\psi_q \tag{10}$$

$$\frac{d\psi_q}{dt} = \frac{R_r M}{L_r} i_q - \frac{R_r}{L_r}\psi_q - (\omega_e - \omega)\psi_d \tag{11}$$

$$\frac{di_d}{dt} = -\left(\frac{L_r R_s}{L_r L_s - M^2} + \frac{M^2 R_r}{(L_r L_s - M^2)L_r}\right) i_d + \omega_e i_q + \frac{M R_r}{(L_r L_s - M^2)L_r}\psi_d + \frac{M}{L_r L_s - M^2}\omega\psi_q + \frac{L_r}{L_r L_s - M^2} u_d \tag{12}$$

$$\frac{di_q}{dt} = -\left(\frac{L_r R_s}{L_r L_s - M^2} + \frac{M^2 R_r}{(L_r L_s - M^2)L_r}\right) i_q - \omega_e i_d + \frac{M R_r}{(L_r L_s - M^2)L_r}\psi_q + \frac{M}{L_r L_s - M^2}\omega\psi_d + \frac{L_r}{L_r L_s - M^2} u_q \tag{13}$$

When the current-controlled PWM inverter is applied, the model can be reduced to a third-order system, which is widely used in the induction motor control design[5, 6, 7].

$$\frac{d\omega}{dt} = \frac{M}{JL_r}(\psi_d i_q - \psi_q i_d) - \frac{T_L}{J} \tag{14}$$

$$\frac{d\psi_d}{dt} = \frac{R_r M}{L_r} i_d - \frac{R_r}{L_r}\psi_d + (\omega_e - \omega)\psi_q \tag{15}$$

$$\frac{d\psi_q}{dt} = \frac{R_r M}{L_r} i_q - \frac{R_r}{L_r}\psi_q - (\omega_e - \omega)\psi_d \tag{16}$$

According to the concept of indirect field-oriented control[8, 9], the rotor flux is aligned with the *d* axis and kept at a constant so that we have the following relations in steady state:

$$\psi_q = \dot{\psi}_q = 0 \tag{17}$$

$$\psi_d = \psi_r = const. \tag{18}$$

Applying (17) and (18) into (15) and (16), we can get the slip frequency and the flux current in steady state

$$\omega_s = \omega_e - \omega = \frac{R_r M}{L_r \psi^*} i_q = \frac{M}{T_r \psi^*} i_q \tag{19}$$

$$i_d = \frac{\psi^*}{M} \tag{20}$$

The technique of field-oriented control guarantees that the transient terms vanish in a short time. Therefore, the steady state equations are sufficient for the derivation of speed control design. The control objective now is to design a speed controller so that $\omega$ tracks $\omega^*$. As a consequence, Figure 1, in which $K_T = \frac{M\psi^*}{L_r}$, shows the block diagram of speed control design.

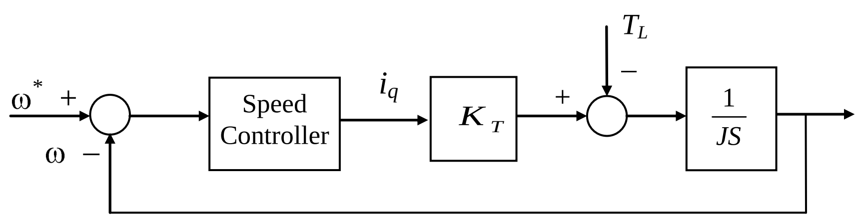


*Figure 1 Speed control design for field-oriented induction motor drive*

## III. Main Modules of the Simulation Program

Based on the principle shown in Section II, a simulation program has been developed by using Matlab/ Simulink. Figure 2 shows the block diagram of the entire motor drive system. The whole simulation program is shown in Figure 3. Figure 4 shows the model of induction motor.

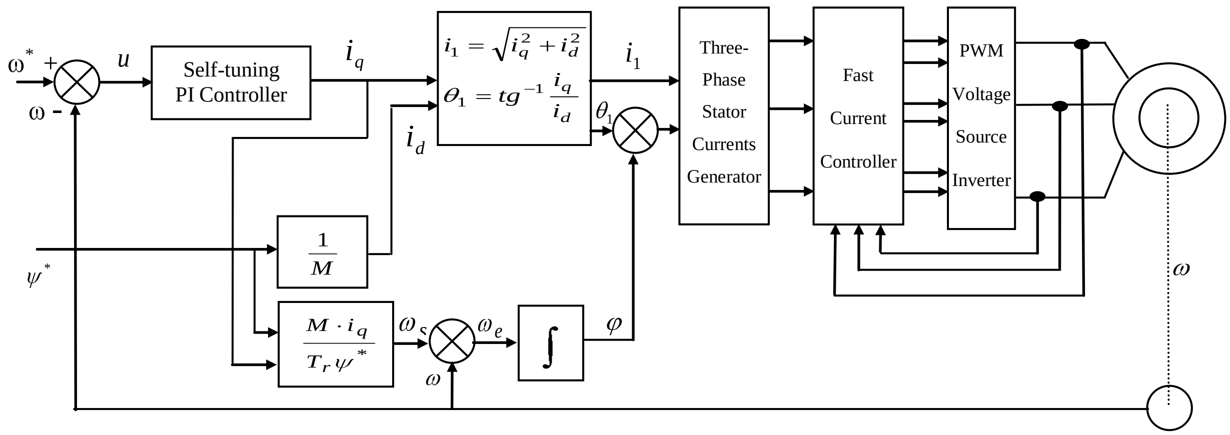


*Figure 2 Block diagram of an entire induction motor drive system*

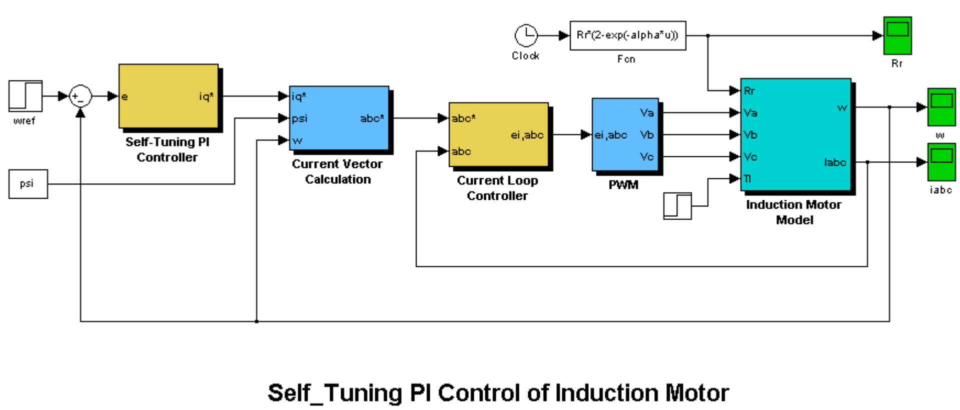


*Figure 3 Matlab/Simulink program of an induction motor drive system*

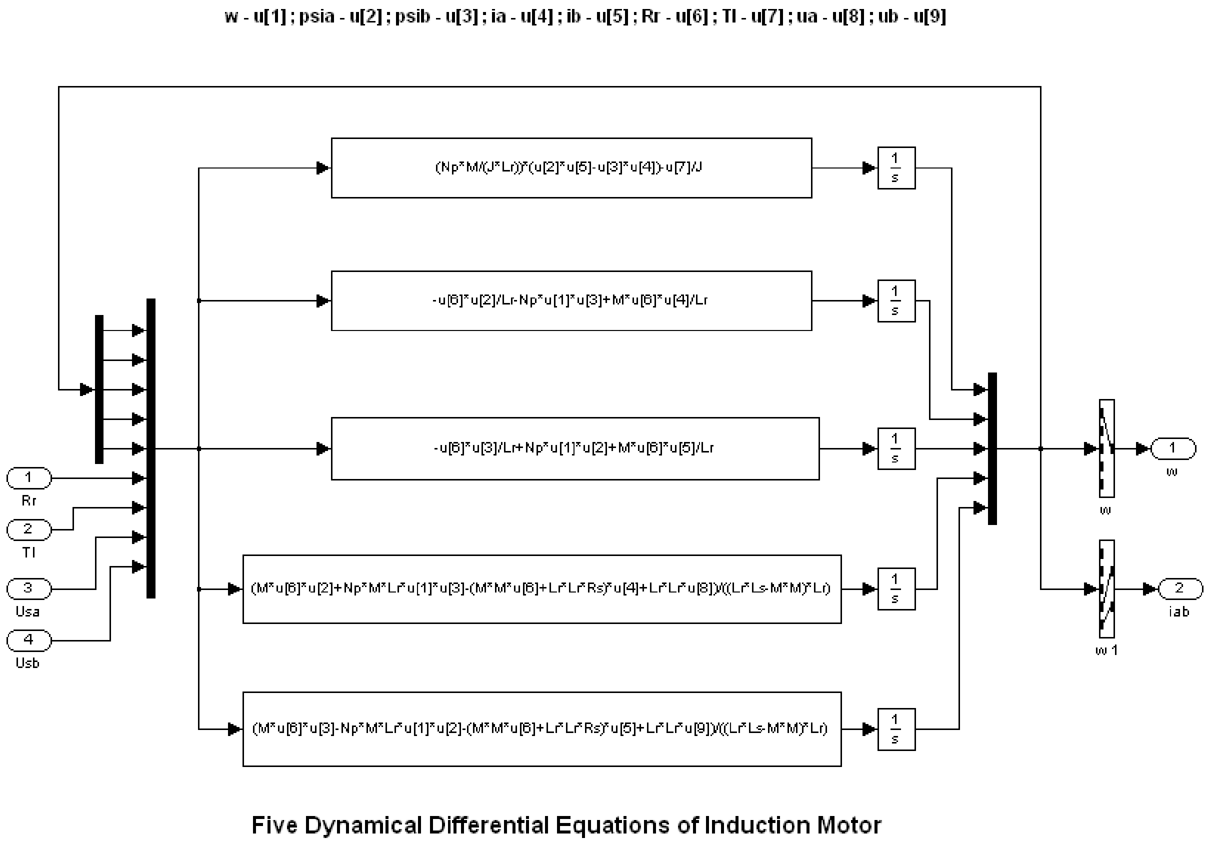


*Figure 4 Simulink model of an induction motor*

The PWM module is shown in the following Figure 5.

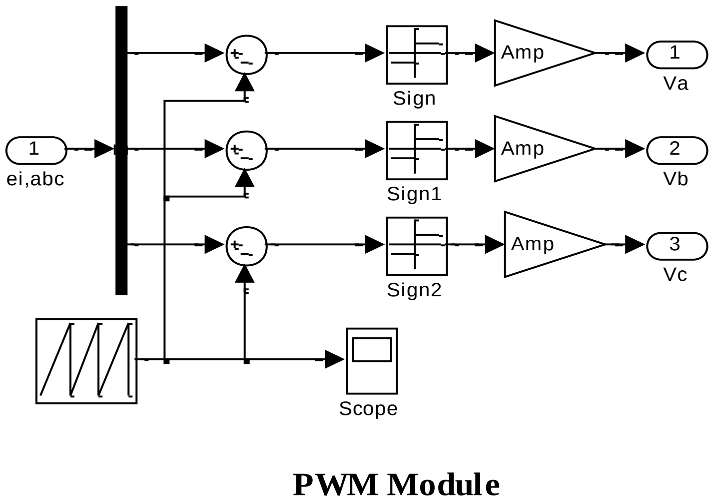


*Figure 5 Simulink Module of PWM drive*

Figure 6 shows the module of intelligent speed controller and Figure 7 shows the module of PI current controller

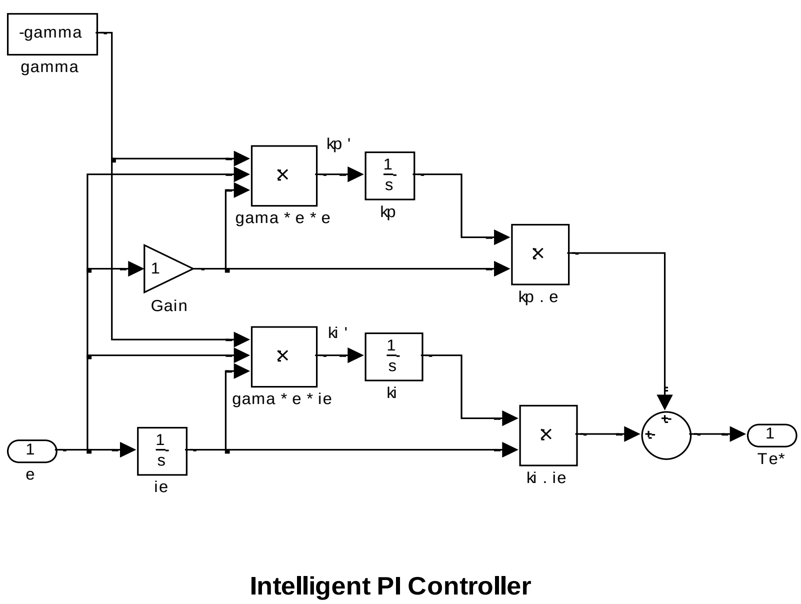


*Figure 6: Intelligent speed controller*

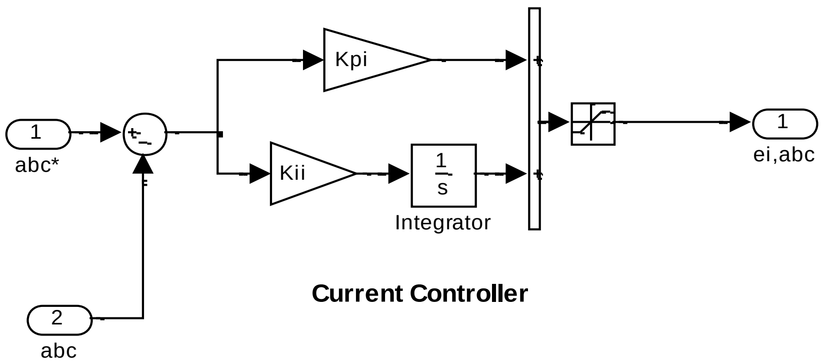


*Figure 7: Current controller*

Figure 8 shows the module of three-phase currents producer.

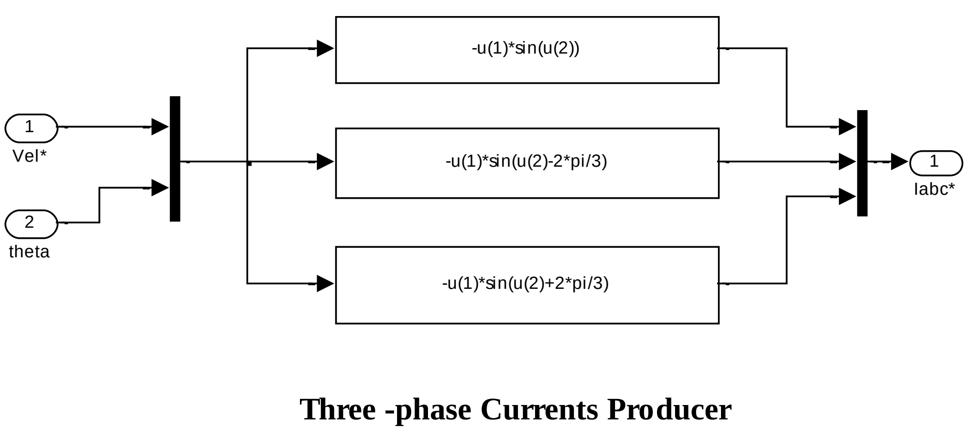


*Figure 8 Three-phase currents producer*

## IV. Simulation Results

In order to evaluate and validate the effectiveness of the developed project presented in the previous sections, the simulation program was run under different conditions. The specifications for the induction motor are[10] : motor power = 15*kW* (rated), load torque = 70*nM* (rated), rotor flux linkage = 1.3*Wb* (rated), angular speed = 220 *rad/s* (rated), $n = 1$, $J = 0.0586 kgm^2$, $Rs = 0.18\Omega$, $Ls = 0.0699H$, $M = 0.068H$, $Rr = 0.15\Omega$, $Lr = 0.0699H$. In the simulation, the change of rotor resistance is considered as $Rr(t) = Rr^*(2 - exp(-at))$ in which $a = 2$, and different load torques are given.

Let us see the dynamic behaviors of induction motor from the results of Figure 9 and Figure 10 when the motor runs in four quadrants. Figure 9 shows that the motor runs without load. Figure 10 presents that the motor runs with 100% load. From both figures, one can see that the control system of induction motor achieves good tracking performance.

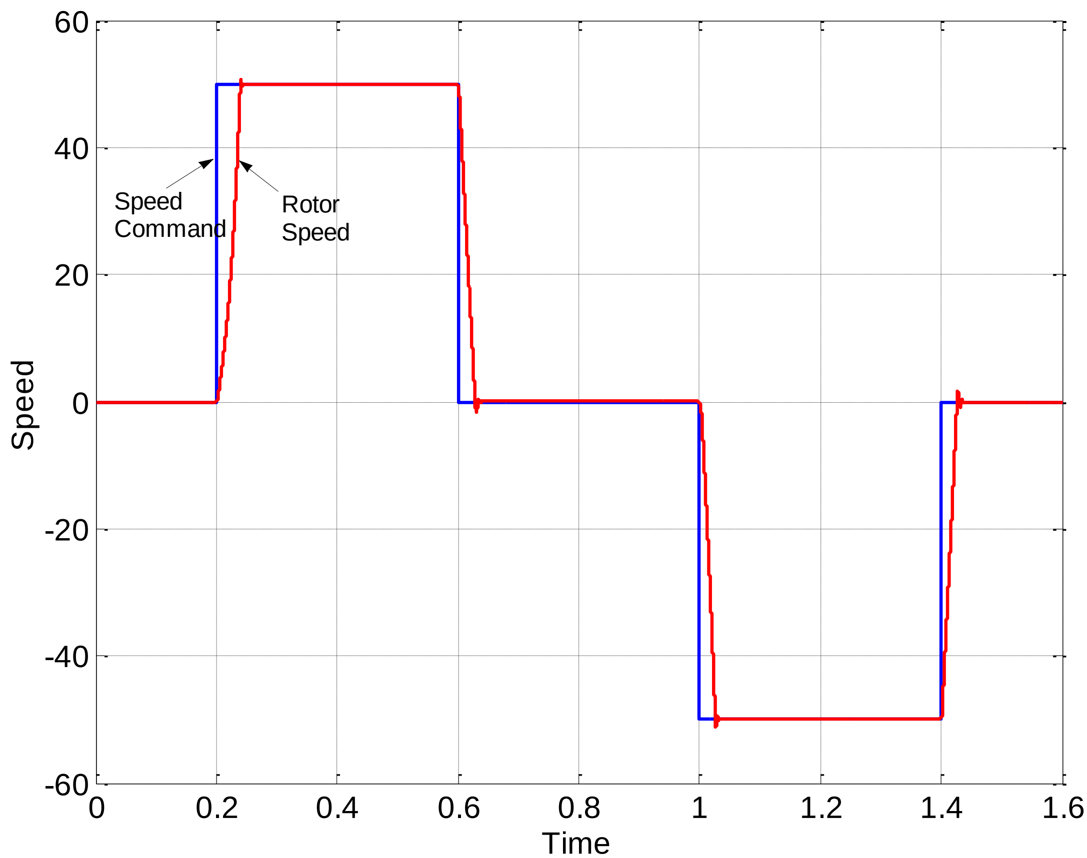


*Figure 9 Speed responses in four quadrants with zero load*

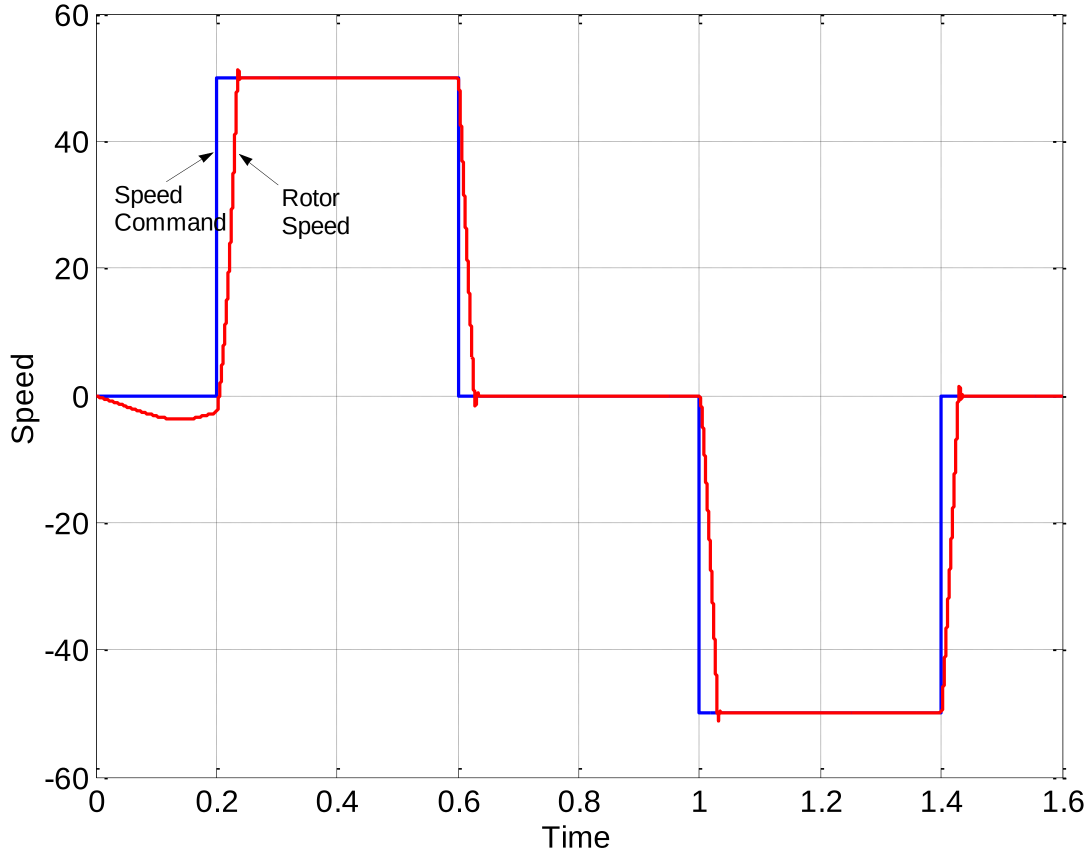


*Figure 10 Speed responses in four quadrants with 100% load*

## V. Conclusions

In this paper, a senior design project (Independent Study) was presented, which includes modeling and simulation of an entire induction motor drive system controlled by an intelligent controller. It first described the principle of induction motor modeling with indirect vector current control. Then it provided main modules of the simulation program. Finally this paper demonstrated the success of the computer program with simulation results. With the use of Matlab/Simulink, it is possible for an educator to offer the opportunity for young engineering students to get first-hand experiences in their design projects, as presented above. Through the hands-on design by using computer program, our students will be able to gain deep insights on the dynamic performance and interactions of electric machinery, which often are not easily mastered through studying theory.

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**Bibliography**


1. R. Marino and P. Tomei, *Nonlinear Control Design: Geometric, Adaptive and Robust*, Prentice Hall, London, 1995.
2. P. C. Krause, *Analysis of Electric Machinery*, New York, McGraw Hill, 1986.
3. R. Marino, S. Peresada, and P. Tomei, "Global Adaptive Output Feedback Control of Induction Motors with Uncertain Rotor Resistance", *IEEE Trans. Automat. Contr.* Vol. 44, pp. 967-983, May 1999.
4. K. Wang, J. Chiasson, M. Bodson, and L. M. Tolbert, "A Nonlinear Least-Squares Approach for Identification of the Induction Motor Parameters", *IEEE Trans. Automat. Contr.* Vol. 50, pp. 1622-1628, October 2005.
5. K. Shyu and H. J. Shieh, "A New Switching Surface Sliding-Mode Speed Control for Induction Motor Drive Systems," *IEEE Trans. Power Electron*., Vol. 11, pp. 660-667, July 1996.
6. R. Marino, S. Peresada, and P. Tomei, "Output Feedback Control of Current-Fed Induction Motors with Unknown Rotor Resistance," *IEEE Trans. Contr. Syst. Technol.*, Vol. 4, pp. 336-347, July 1996.
7. M. Bodson, J. Chiasson, and R. Novotank, "High-Performance Induction Motor Control via Input-Output Linearization," *IEEE Contr. Syst. Mag*., Vol. 14, pp. 25-33, Jan 1994.
8. B. K. Bose, *Power Electronics and AC Drives*, Englewood Cliffs, NJ, Prentice-Hall, 1986.
9. Y. Xia, X. Yu, and W. Oghanna, "Adaptive Robust Fast Control for Induction Motors", *IEEE Trans. Ind. Electron*., Vol. 47, pp. 854-862, August 2000.
10. R. Marino, S. Peresada, and P. Valigi, "Adaptive Input-Output Linearizing Control of Induction Motors", *IEEE Trans. Automat. Contr.* Vol. 38, pp. 208-221, Feb. 1993.