



Research Article

Simulation of SPWM Fed Three-phase Induction Motor Drive Mathematical Model Using MATLAB Simulink

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ABSTRACT

Three-phase induction motors are used in a vast area of applications mainly due to their simplicity, ruggedness and high reliability. With recent advancement in semiconductor technologies, the use of fixed speed induction motor drive is becoming obsolete, majority of the applications now requires inverter-based drives for variable speed operation. In the study of induction motor drive operation, mathematical models are often used to simulate the steady state and transient behavior of induction motor. However, developing such models are not as simple. One must develop the understanding of the mathematical equations to be used and also having the knowledge to solve the equations with the use of computer simulation software. To address this issue, this work presents an approach to implement the mathematical model of a Sinusoidal Pulse Width Modulation (SPWM) fed three-phase induction motor drive in MATLAB Simulink. The sub models include induction motor direct quadrature-model and a voltage source inverter fed by SPWM signal generator. The presented model implementation is able to simulate the dynamic behavior of an induction motor operation, this mathematical model implementation would be useful for further studies on the development of induction motor drive system.

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1. INTRODUCTION

Recent advancement in semiconductor technologies have further extended the capability of induction motors from the traditional fixed speed to the modern variable speed operation with the use of Pulse Width Modulation (PWM) fed inverter-based drives. Some of the applications include industrial pumps, crane lifters, drilling machines, traction applications such as in electric vehicles, and many others. Developing elaborate models have now become crucial in the designing process of induction motor drive system as the application complexity increases. The model should be able to predict and simulate operational characteristics and performances which would be useful to validate the design process and minimize designing error¹. However, building such model is not a straight forward task, knowledge of the machine basic electric, magnetic, and mechanical behaviors and also some experience in using computer simulation software are required.

Several available literatures have published their respective induction motor mathematical model implementation approach. Some of the works suggest the use of Simulink's-function [1,2], others use Simulink's mathematic operation blocks [3,4], and there are also works that have proposed a solution to avoid MATLAB/Simulink [5] where the motor are modeled completely using C++ programming language. Their works however does

not focused on modeling of the Sinusoidal PWM (SPWM) signal and the inverter equations. This paper chooses SPWM control method because it is one simplest. With this, a better understanding on the fundamentals can be developed without the need to dive into the other complex control method. The overview of the equations needed to mathematically model an induction motor drive and the approach to implement them in computer simulation software specifically using MATLAB Simulink are presented here. Three main components of the induction motor drive system are included in this work which are the induction motor DQ-model, the three-phase voltage source inverter [6], and the SPWM signal generator for Voltage Source Inverter (VSI) switching [7,8].

The model be entirely built by writing MATLAB programming code from ground up, or one can use Simulink which provides a better system representation in block diagram form as an alternative. The main advantage of Simulink is that it uses functional blocks instead of programming code.

2. MODEL IMPLEMENTATION

The model describe in this work include the Induction motor Direct Quadrature (DQ)-model, the SPWM model, and the voltage source inverter model. Each of the sub model is presented as follows.

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2.1. Induction Motor Direct Quadrature-Model

This is the very first step of modeling an induction motor, it involves reference frame transformation of the three-phase supply (V_{as} , V_{bs} , V_{cs}) voltage into two-phase voltage [9,10]. To simplify later implementation in Simulink, it is convenient to first transform the three-phase voltage using Eq. (1) into a two-phase voltage in stationary reference frame (V_{ds} , V_{qs}), then from the stationary reference frame to the arbitrary reference frame using Eq. (2).

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_{qs} \\ v_{ds} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \end{bmatrix} \quad (2)$$

The DQ model can be then be calculated once v_{ds} and v_{qs} are obtained. Implementations of the DQ-model are divided into three parts as follows.

2.1.1. Flux linkages

The first set of equations to be solve part is on the flux linkage as defined in Eqs. (3)–(6):

$$\frac{dF_{qs}}{dt} = \omega_b \left[v_{qs} - \frac{\omega}{\omega_b} F_{ds} + \frac{R_s}{x_{ls}} \left(\frac{x_{ml}^*}{x_{lr}} F_{qr} + \left(\frac{x_{ml}^*}{x_{ls}} - 1 \right) F_{qs} \right) \right] \quad (3)$$

$$\frac{dF_{qs}}{dt} = \omega_b \left[v_{ds} - \frac{\omega}{\omega_b} F_{qs} + \frac{R_s}{x_{ls}} \left(\frac{x_{ml}^*}{x_{lr}} F_{dr} + \left(\frac{x_{ml}^*}{x_{ls}} - 1 \right) F_{ds} \right) \right] \quad (4)$$

$$\frac{dF_{qr}}{dt} = \omega_b \left[0 - \frac{(\omega_e - \omega_r)}{\omega_b} F_{dr} + \frac{R_r}{x_{lr}} \left(\frac{x_{ml}^*}{x_{ls}} F_{qs} + \left(\frac{x_{ml}^*}{x_{lr}} - 1 \right) F_{qr} \right) \right] \quad (5)$$

$$\frac{dF_{dr}}{dt} = \omega_b \left[0 - \frac{(\omega_e - \omega_r)}{\omega_b} F_{qr} + \frac{R_r}{x_{lr}} \left(\frac{x_{ml}^*}{x_{ls}} F_{ds} + \left(\frac{x_{ml}^*}{x_{lr}} - 1 \right) F_{dr} \right) \right] \quad (6)$$

where:

ω_b : Motor angular base frequency

ω_e : Electrical supply angular frequency

ω_r : Rotor angular frequency (rad/s)

v_{qs} , v_{ds} : Stator voltages (V) of q and d -axis

v_{qr} , v_{dr} : Rotor voltages (V) of q and d -axis

2.1.2. Magnetizing flux

The second part calculates the magnetizing flux with the equation shown by Eqs. (7) and (8):

$$F_{mq} = x_{ml} \left[\frac{F_{qs}}{x_{ls}} + \frac{F_{qr}}{x_{lr}} \right] \quad (7)$$

$$F_{md} = x_{ml} \left[\frac{F_{ds}}{x_{ls}} + \frac{F_{dr}}{x_{lr}} \right] \quad (8)$$

$$x_{ml} = \frac{1}{\left[\frac{1}{x_m} + \frac{1}{x_{ls}} + \frac{1}{x_{lr}} \right]} \quad (9)$$

From there, the stator and rotor current (A) in the arbitrary reference frame can be solved as follows.

$$i_{qs} = \frac{1}{x_{ls}} (F_{qs} - F_{mq}) \quad (10)$$

$$i_{ds} = \frac{1}{x_{ls}} (F_{ds} - F_{md}) \quad (11)$$

where:

i_{qs} , i_{ds} : stator current (A) of quadrature and direct axis

x_{ls} : leakage reactance (Ω) of stator

F_{qs} , F_{ds} : stator flux linkage (Wb-t) of quadrature and direct axis

2.1.3. Electromagnetic torque and rotor speed

The final set of equations calculate the electromagnetic torque T_e (Nm) and rotor speed ω_r (rad/s) outputs as shown in Eqs. (12) and (13).

$$T_e = \frac{3}{2} \left(\frac{p}{2} \right) \frac{1}{\omega_b} (F_{ds} i_{qs} - F_{qs} i_{ds}) \quad (12)$$

$$\frac{d\omega_r}{dt} = \frac{p}{2J} (T_e - T_l) \quad (13)$$

where p is the number of poles, J (Kg/m²) is the moment of inertia and T_l (Nm) is the input load torque.

2.2. Sinusoidal Pulse Width Modulation

Three-phase VSI is typically made up of six power switches that requires proper switching sequence to transform the DC voltage supply into a variable frequency three-phase PWM voltage output. As mentioned, the SPWM is used in this work. To model the three-phase SPWM switching signals, three sinusoidal reference signals which are set 120° phase apart from each other; $V_{ref,n}$ where n represents the three phase a , b , c , the signals are then compared with a high frequency triangular signal V_T . The changing of the reference signal frequency f_{ref} changes the inverter frequency which then changes the speed of the induction motor [11]. Hence, this relation provides a simple control over the speed of induction motor. However, to produce the varying frequency reference signal, the standard sine function as shown in Eq. (14) is not applicable.

$$v_{refn}(t) = \sin(2\pi * f_{ref} * t) \quad (14)$$

Since the sin function takes argument of angles, simply changing f_{ref} by time will not produce a smooth frequency transition, jitter will be seen in the output as the results of jumping phase from one point of the waveform. To solve this issue, the use of phase accumulator is proposed with the Eq. (15) described below:

$$v_{\text{refn}}(t) = \sin(2\pi * \int f_{\text{ref}}(t) dt) \quad (15)$$

The phase accumulator can be built using the Backward Euler Method with Eq. (16) and modeled using Simulink's User-Defined Function block.

$$v_{\text{refn}}[n] = \sin(2\pi * ((V_{\text{refn}}[k-1]) + ((t[k]) - t[k-1]) * f_{\text{ref}}[n])) \quad (16)$$

The f_{ref} can now be varied as intended, even in discontinuous ways, the phase will still change smoothly by time, producing a continuous variable frequency sinusoid.

2.3. Voltage Source Inverter

One way of modeling a three-phase inverter is described by Bose in his book [6] based on the relation of phase voltages and pole voltages as in Eqs. (17)–(19).

$$v_{an} = \frac{2}{3}v_{ao} - \frac{1}{3}v_{bo} - \frac{1}{3}v_{co} \quad (17)$$

$$v_{bn} = \frac{2}{3}v_{bo} - \frac{1}{3}v_{ao} - \frac{1}{3}v_{co} \quad (18)$$

$$v_{cn} = \frac{2}{3}v_{co} - \frac{1}{3}v_{ao} - \frac{1}{3}v_{bo} \quad (19)$$

where:

v_{an} , v_{bn} , v_{cn} : Phase voltages

v_{ao} , v_{bo} , v_{co} : Pole voltages

With the voltage source inverter mathematical model is implemented, all the components required are completed and simulation can be run.

To validate the mathematical model implementation, the results of the model described in Section 2 is compared with the Simulink's preset asynchronous machine drive which is already built and made available by MATLAB in its Simulink library. During simulation, both the mathematical and the Simulink's preset model use the same 5 Hp motor with parameters as shown in Table 1.

The results of both models output are presented in the next section.

Table 1 | Induction motor parameter for mathematical modeling

Parameter	Abbreviation	Value	Unit
Rotor resistance	Rr	1.083	Ohm
Stator resistance	Rs	1.115	Ohm
Rotor inductance	Lr	5.974E-03	Henry (H)
Stator inductance	Ls	5.974E-03	Henry (H)
Magnetizing inductance	Lm	0.2037	Henry (H)
No. of poles	P	4	
Moment of inertia	J	0.02	kg/m ²

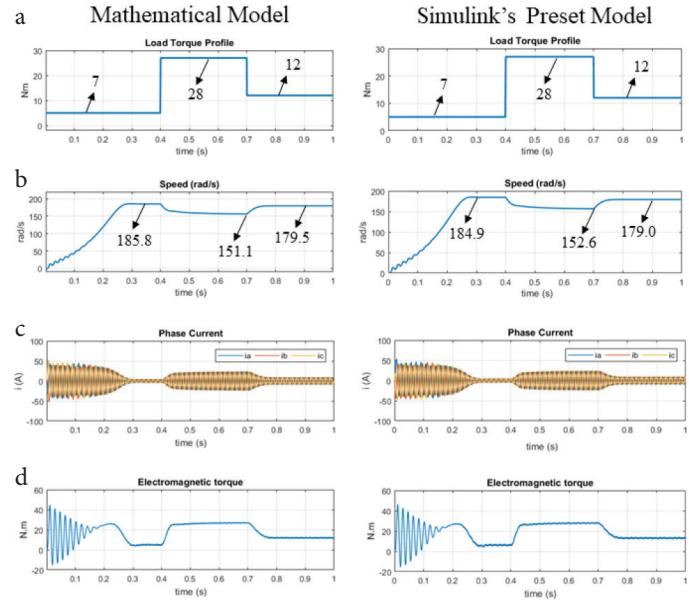


Figure 1 | Side by side Mathematical and Simulink's preset model comparison of (a) load torque applied, (b) rotor speed, (c) phase currents, (d) electromagnetic torque.

3. RESULTS

The induction rotor speed, phase current, and electromagnetic torque response are as presented in Figure 1 showing side-by-side comparison of the mathematical model and the Simulink's preset model outputs with the applied load torque profile.

From the results shown, the mathematical model and the Simulink's preset model yield similar response behavior. During starting, transient conditions are observed before the motors got into a steady state condition at time 0.3 s. When the load torque is increased from 7 to 28 Nm, both the model responds with decrease in rotor speed, increase in phase currents amplitude, and increase electromagnetic torque, transient region can also be observed whenever load torque change occurred before getting back into steady state condition.

4. CONCLUSION

This work has presented an approach to implement an SPWM fed three-phase induction motor drive. The model was built in Simulink entirely based on the equations described in Section 2. The implementation process is also presented in a step-by-step approach so that the work can be easily followed. The results produced by this model have shown similar behavior to that of Simulink's preset induction motor drive model, which validates that the mathematical model implementation is working as expected. This model implementation would be useful for future development of induction motor drive systems.

NOTE

The complete Simulink model implementation described in this paper can be referred at MATLAB Central File Exchange: <https://www.mathworks.com/matlabcentral/fileexchange/73260-dq-model-of-3-phase-induction-motor-drive>.

CONFLICTS OF INTEREST

The authors declare they have no conflicts of interest.

REFERENCES

- [1] M.J. Asif, T. Shahbaz, S.U. Hassan, S.T.H. Rizvi, Mathematical modelling of 3-phase induction motor to study the Torque vs. Speed characteristics using MATLAB Simulink, 2016 19th International Multi-Topic Conference (INMIC), IEEE, Islamabad, Pakistan, 2016, pp. 1–7.
- [2] U. Zangina, U. Zainab, M.I. Ilyasu, M.A. Yusuf, I.B. Shah, I.H. Jibrin, et al., Implementation of the three-phase induction machine model using simulink / S-Function, IOSR J. Environ. Sci. Toxicol. Food Technol. 5 (2013), 67–71.
- [3] B. Ozpineci, L.M. Tolbert, Simulink implementation of induction machine model - a modular approach, IEEE International Electric Machines and Drives Conference (IEMDC), IEEE, Madison, WI, USA, 2003, pp. 728–734.
- [4] A.W. Leedy, Simulink/MATLAB dynamic induction motor model for use as a teaching and research tool, Int. J. Soft Comput. Eng. 3 (2013), 102–107.
- [5] J.K. Kim, E.S. Cho, Y.K. Lee, J.W. Lee, J.H. Lee, C++ based dynamic model of AC induction motor in discrete time domain, 2016 IEEE Transportation Electrification Conference and Expo (ITEC), Asia-Pacific (ITEC), IEEE, Busan, South Korea, 2016, pp. 272–276.
- [6] B.K. Bose, Modern power electronics and AC drives, Prentice Hall PTR, Upper Saddle River, NJ, 2002.
- [7] E.R.C. da Silva, E.C. dos Santos, B. Jacobina, Pulsewidth modulation strategies, IEEE Ind. Electron. Mag. 5 (2011), 37–45.
- [8] A. Rasyadan, Z. Ibrahim, T.M.A. Bin Tuan Dir, S. Yaacob, Modeling of time domain analysis for single and double open-circuit inverter switch faults in three-phase induction motor drives, 2018 International Conference on Computational Approach in Smart Systems Design and Applications (ICASSDA), IEEE, Kuching, Malaysia, 2018, pp. 1–7.
- [9] P.C. Krause, S.D. Sudhoff, O. Wasynczuk, S.D. Pekarek, Analysis of electric machinery and drive systems, Second ed., in: M.E. El-Hawary (Ed.), John Wiley & Sons, 2002.
- [10] O. Chee-Mun, Dynamic simulation of electric machinery: using MATLAB/simulink, Prentice Hall, Upper Saddle River, NJ, 1998.
- [11] I. Husain, Electric and hybrid vehicles: design fundamentals, CRC Press, Boca Raton, London, New York, Washington, D.C, 2003.

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