

Simulation of Field Oriented Control in Induction Motor Drive System

Xiang Zhao*, Huijuan Liu, Jingxiong Zhang, Haijiao Zhang

School of Electrical Engineering, Beijing Jiaotong University,
No.3 Shang Yuan Cun, Hai Dian District Beijing, China, 86 10 51684831

*Corresponding author, e-mail: 11121716@bjtu.edu.cn

Abstract

In this paper, a 3-phase induction motor model for simulation the field oriented control (FOC) system based on space vector pulse width modulation (SVPWM) is established in Ansoft/Simplorer software. The theory of field oriented control (FOC) and the principle of space vector pulse width modulation (SVPWM) were introduced. The simulation results are presented and analyzed. A Simulink simulation model of field oriented control system is presented as a comparison under the same conditions. The results indicated that the Simplorer model had quick response speed, small torque fluctuations and good performance both in steady and dynamic states. Furthermore, the Simplorer model can be coupled with the finite element model of the motor to achieve field-circuit coupling simulation of induction motor's field oriented control system.

Keywords: SVPWM, FOC, induction motor, vector control, simplorer

Copyright © 2013 Universitas Ahmad Dahlan. All rights reserved.

1. Introduction

Traditional control methods of AC motor based on Sinusoidal Pulse Width Modulation (SPWM) are the methods that apply three 120° spatially displaced sinusoidal voltages to the three-phase windings of stator. In most of traditional AC drives, the generation of the three sine waves is based on motor electromechanical characteristics and equivalent model of the motor's steady state. Furthermore, the control looks like three-phase independent control rather than a total system control of the three phase system [1, 2].

Advanced control methods of induction motor require independent control of magnetic flux and torque as DC-motor. In order to obtain the separation characteristics like DC-motor in induction motors, many high performance methods have been analyzed like Direct Torque Control (DTC) and Field Oriented Control (FOC) [3]. Due to its properties like simplicity, high efficiency, extremely rugged, good power factor, FOC of induction motor is widely used. In addition, with the developments in power electronic and semiconductor, pulse width modulation technology has been improved. As a result that Space Vector Pulse Width Modulation (SVPWM) variable speed drive is becoming popularity because of their superior performance [4]. The SVPWM is the control method that basing on the switching of space voltage vectors, an approximate circular rotary magnetic field can be obtained [5, 6]. SVPWM has the advantages of it 15% higher utilization ratio of voltage and less harmonic distortion than SPWM [7, 8].

Most of induction motor FOC system were established and simulated based on Simulink in published literature, but their algorithms are based on circuit not magnetic field. Simplorer is professional and powerful electro-mechanical system simulation software developed by Ansoft Company. A major advantage of Simplorer is that it can be integrated with FEA models to simulate the total control system in taking into account the the complicated lamination geometries and the nonlinear magnetic materials. Therefore, the Simplorer simulation model of Field Orientated Control (FOC) based on SVPWM in an induction motor is introduced, and it has three features: the three phase speed and time dependent system is converted into a two co-ordinate time invariant system, the FOC strategy and effective Pulse Width Modulation pattern generation is established. Thanks to these features, the control of AC machine has the total advantages of DC machine control. Furthermore, by complying a very

accurate steady state and transient control, this control method can achieve high dynamic performance in terms of response times and power conversion. Moreover, a Simulink simulation is presented as a comparison under the same conditions. Also the FOC system in this paper can be regarded as a reference for future field-circuit coupling simulation.

2. Field Oriented Control

In Field Orientated Control system, the stator currents are represented by a vector. This control method is based on projections which transform a three phase time and speed dependent system into a two co-ordinate (d and q co-ordinates) time invariant system. These projections lead to a structure similar to that of a DC machine control. Field orientated controlled machines need two constants as input references: the torque component (aligned with the q co-ordinate) and the flux component (aligned with d co-ordinate). As Field Orientated Control is simply based on projections the control structure handles instantaneous electrical quantities. This makes the control accurate in every working operation (steady state and transient) and independent of the limited bandwidth mathematical model.

2.1. Space Vector Definition

The three-phase currents, voltages and fluxes of induction motor can be analyzed in terms of complex space vectors [9]. With regard to the currents, the space vector can be defined as follows. Assuming that i_a , i_b , i_c are the instantaneous currents in the stator phases, then the complex stator current vector \bar{i}_s is defined by:

$$\bar{i}_s = i_a + \alpha i_b + \alpha^2 i_c \quad (1)$$

Where $\alpha = e^{\frac{2}{3}\pi}$ and $\alpha^2 = e^{\frac{4}{3}\pi}$, represent the spatial operators. Figure 1 shows the stator current complex space vector:

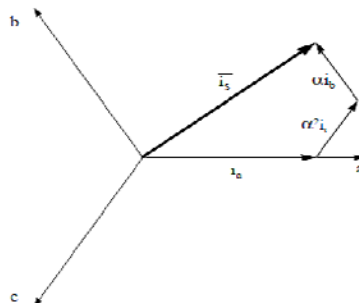


Figure 1. Stator Current Space Vector and its Component in (a,b,c)

2.2. Coordinate Transformation

There are three coordinate transformation in FOC system: clarke transformation, park transformation and inverse park transformation.

Clarke transformation is that transforms from a three-phase static coordinate system (a,b,c) to a two-phase static coordinate system ($\alpha - \beta$). Assuming that the axis a and axis α in the same direction. Equation (2) gives clarke transformation.

Park transformation is that transforms from a two-phase static coordinate system ($\alpha - \beta$) to a two-phase rotating coordinate system (d-q). If we consider the d axis aligned with the rotor flux, for the current vector, the relationship from the two coordinate systems is shown in Figure 3.

Inverse park transformation is that transforms from a two-phase rotating coordinate system (d-q) to a two-phase static coordinate system ($\alpha - \beta$).

Equation (3), (4) give park transformation and inverse park respectively. Where θ is the rotor flux position.

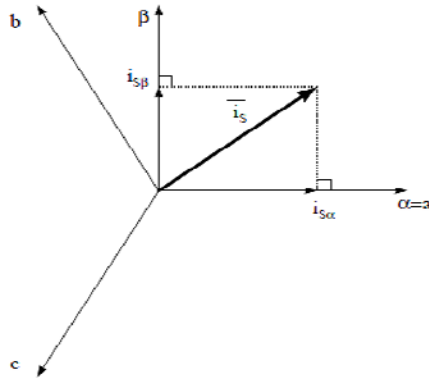


Figure 2. Stator Current Space Vector and its Components in $(\alpha - \beta)$

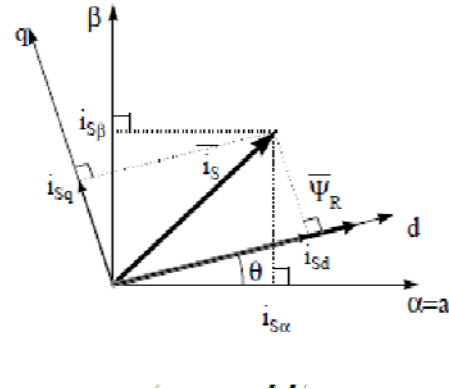


Figure 3. Stator Current Space Vector and its Component in Two Coordinate Systems

$$\begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \quad (2)$$

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} \quad (3)$$

$$\begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} i_d \\ i_q \end{pmatrix} \quad (4)$$

2.3 Basic Equation

D axis of the above transformation rotates in synchronous speed ω_1 of asynchronous motor, has no specific physical concept. Furthermore, we can define its direction and make it has physical meaning. Defining d axis direction is the direction of the rotor flux, called M axis. Then q axis is called T axis [10].

The voltage equation of squirrel cage induction motor in M-T coordinate system is given by Equation (5). The control equations of induction motor vector control system are given by Equation (6), (7), (8). The equations of the rotor flux orientated are given by Equation (9).

$$\begin{pmatrix} u_{sM} \\ u_{sT} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} R_s + L_s p & -\omega_1 L_s & L_m p & -\omega_1 L_m \\ \omega_1 L_s & R_s + L_s p & \omega_1 L_m & L_m p \\ L_m p & 0 & R_r + L_r p & 0 \\ \omega_s L_m & 0 & \omega_s L_r & R_r \end{pmatrix} \begin{pmatrix} i_{sM} \\ i_{sT} \\ i_{rM} \\ i_{rT} \end{pmatrix} \quad (5)$$

$$\psi_r = \frac{L_m}{T_r p + 1} i_{sM} \quad (6)$$

$$T_e = n_p \frac{L_m}{L_r} i_{sT} \psi_r \quad (7)$$

component $i_{sM}^* = \psi_r^* / L_m$ and actual flux current component i_{sM} feed the other current regulator, the output of this current regulator is u_{sM}^* . The outputs of the current regulators are applied to the inverse park transformation module. The outputs of this projection are u_α and u_β which are the components of the stator vector in the $\alpha - \beta$ static coordinate system. These are inputs of the Space Vector PWM. The outputs of this block are the signals that drive the inverter. About how drive the inverter considerations are made in following paragraphs. The FOC system in this paper is a two-loop system, the speed loop is outer loop and the current loop is inner loop ensure that this system is stable.

3. SVPWM

Spave Vector PWM supplies the induction motor with the desired phase voltages. The phase voltage of induction motor is depended on the power switch state of its corresponding upper and lower arm of the inverter. There are eight voltage vectors determined by eight switch combinations in 3-phase inverter. Figure 5 shows the eight voltage vectors and the six sectors.

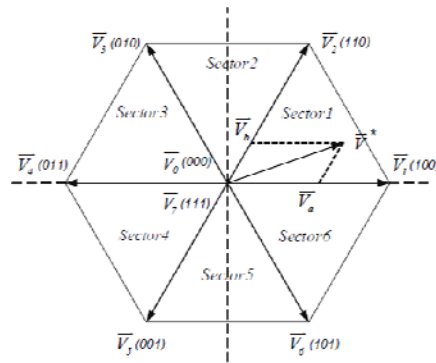


Figure 5. Vectors and Sectors

This paper no longer describe the working principle of SVPWM, because of there are many related literature on the working principle of SVPWM [11-13]. By its principle, there are three major steps to generate SVPWM: judging sector, calculating operating time, determining switching point. The three steps are discussed respectively in following paragraphs.

3.1. Judging Sector

Calculating variable P value using Equation (10), (11), and judging sector number N according to Table 1 [14, 15].

$$B_0 = u_\beta$$

$$B_1 = \frac{\sqrt{3}}{2} u_\alpha - \frac{1}{2} u_\beta \tag{10}$$

$$B_2 = -\frac{\sqrt{3}}{2} u_\alpha - \frac{1}{2} u_\beta$$

$$P = sign(B_0) + 2sign(B_1) + 4sign(B_2) \tag{11}$$

The sign(x) is sign function. If $x > 0$, sign(x)=1. If $x \leq 0$, sign(x)=0.

Table 1. Judging Sector

P	1	2	3	4	5	6
N	2	6	1	4	3	5

3.2. Calculating Operating Time

Calculating operating time T_1 , T_2 of two adjacent vectors according to Equation (12) and Table 2.

$$\begin{aligned} X &= u_\beta \frac{\sqrt{3}T}{U_{dc}} \\ Y &= \left(\frac{\sqrt{3}}{2}u_\alpha + \frac{1}{2}u_\beta \right) \frac{\sqrt{3}T}{U_{dc}} \\ Z &= \left(-\frac{\sqrt{3}}{2}u_\alpha + \frac{1}{2}u_\beta \right) \frac{\sqrt{3}T}{U_{dc}} \end{aligned} \quad (12)$$

Table 2. Value Assignment for T_1 , T_2

N	1	2	3	4	5	6
T_1	-Z	Z	X	-X	-Y	Y
T_2	X	Y	-Y	Z	-Z	-X

To different sectors, the evaluations of T_1 and T_2 can be derived from Table 2. When $T_1+T_2>T$, T is switching period, calculate the new value of T_1 and T_2 according to Equation (13).

$$\begin{aligned} T_1 &= \frac{T}{T_1 + T_2} T_1 \\ T_2 &= \frac{T}{T_1 + T_2} T_2 \end{aligned} \quad (13)$$

3.3. Determining Switching Point

The switching points are determined by Equation (14). To different sectors, the evaluations of T_{com1} , T_{com2} and T_{com3} can be derived from Table 3.

$$\begin{aligned} T_a &= (T - T_1 - T_2) / 4 \\ T_b &= T_a + T_1 / 2 \\ T_c &= T_b + T_2 / 2 \end{aligned} \quad (14)$$

Table 3. Determining Switching Point

N	1	2	3	4	5	6
T_{com1}	T_a	T_b	T_c	T_c	T_b	T_a
T_{com2}	T_b	T_a	T_a	T_b	T_c	T_c
T_{com3}	T_c	T_c	T_b	T_a	T_a	T_b

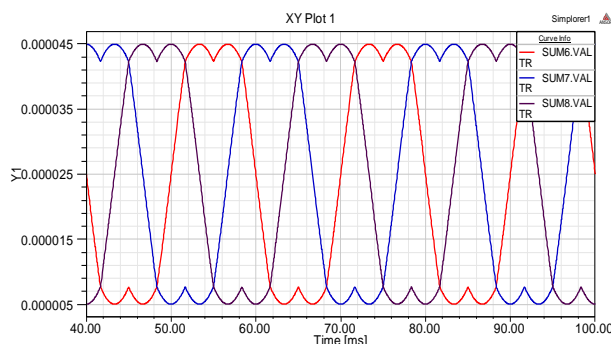


Figure 6. SVPWM Waveform

The carrier is a positive isosceles triangular wave which the period is T and the amplitude is $T/2$. Compare the carrier with T_{com1} , T_{com2} and T_{com3} , we can get the symmetric space vector PWM waveform as shown in Figure 6. The space vector PWM waveform is saddle shape.

4. Simulation and Analysis

The whole FOC system simulation model is built, and the parameters of induction motor are as follows: $U_N=380V$, $f=50Hz$, $P_N=7.5kW$, $n_N=1430r/min$, $R_s=0.7753\Omega$, $R_r=0.7773\Omega$, $L_{1s}=0.003197H$, $L_{1r}=0.003197H$, $L_m=0.1303H$, $p=2$, $J=0.036kg \cdot m^2$. The switching frequency is 10kHz. The given angular speed is 100rad/s, the given rotor flux is 1Wb, and the motor is starting in no-load condition. In 1 second moment, angular speed changes from 100 to 150rad/s (rated angular speed); In 1.4 second moment, load torque is changed from 0 to 50N·m (rated torque). The whole time of the simulation is 2s. The all simulation results are shown in Figure 7(a)-(d).

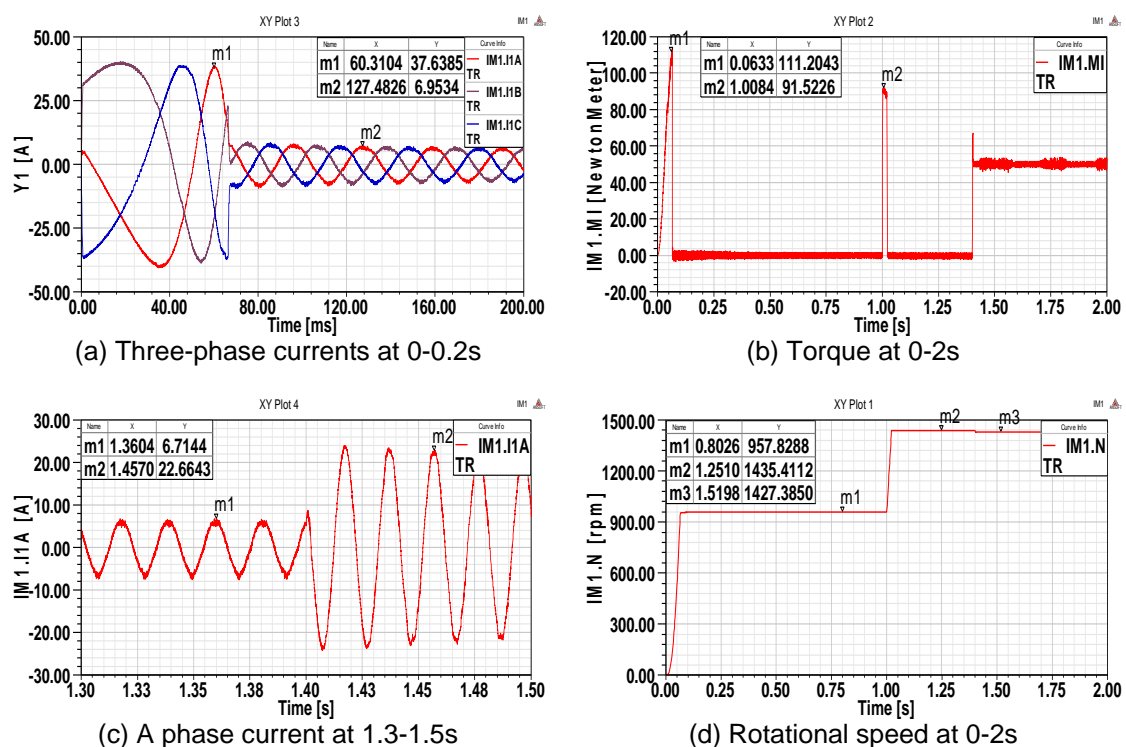


Figure 7. The Results of Simplerer Simulation

Figure 7(a) is the three-phase currents waveform of the stator windings. In Figure 7(a), the starting current maximum amplitude of the motor is about 37.64A, 5.4 times of no-load current amplitude. It is a reasonable result. In Figure 7(b), the acceleration torque is about 111 N·m, 2.22 times of rated torque. It is an acceptable result because that maximum torque is usually no more than 2 times of rated torque for normal motor. In Figure 7(c), the no-load current amplitude is about 6.71A, 0.3 times of rated current. It is a correct result because that no-load current is about 0.3-0.6 times of rated current for normal motor. In addition, the no-load torque is very small as shown in Figure 7(b). In 1.4 second, load torque changes from 0 to 50N·m (rated torque), the speed of the motor drop a little as shown in Figure 7(d).

The results of Simulink simulation are shown in Figure 8. Figure 8(a) shows the waveform rotational speed at 0-2s, Figure 8(b) shows the waveform of torque at 0-2s.

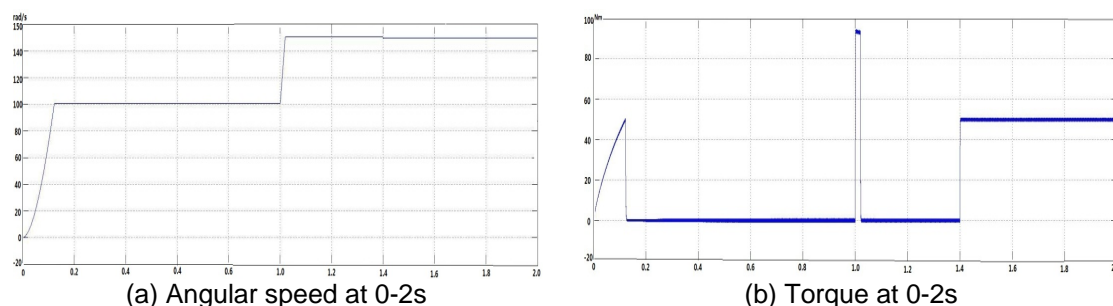


Figure 8. The Results of Simulink Simulation

4. Conclusion

Based on the rotor field oriented control (FOC) of 3-phase induction motor, the simulation models of FOC system using Ansoft/Simplorer and Matlab/Simulink software are established. The simulation results show that the FOC system can smoothly work and still has perfect static and dynamic characteristics under normal working condition. It provides a train of thought for the actual design and debugging of induction motor control system.

Comparing the results of the two simulation models, we can find that there are three advantages of Simplorer simulation model. Firstly, the simulation time of Simplorer model is much shorter than that of Simulink model under the same conditions, and the simulation time of Simplorer model is about 15 minutes, but in Simulink model, that is about 10 hours. Secondly, Simplorer software has convenient image processing functions than Matlab/Simulink software. The main advantage of Simplorer is that Ansoft/Simplorer can provide a direct coupling with the finite element analysis software to simulate the total control system in taking into account the the complicated lamination geometries, and the nonlinear magnetic materials.

References

- [1] Tunyasirirut S, Srilad S, Suksri T. *Comparison Power Quality of the Voltage Source Inverter type SVPWM and SPWM Technique for Induction Motor Drive*. SICE Annual Conference. Tokyo. 2008; 241-246.
- [2] T Sutikno, WJ Hwa, A Jidin, NRN Idris. A Simple Approach of Space-Vector Pulse Width Modulation Realization Based on Field Programmable Gate Array. *Electric Power Components and Systems*. 2010; 38(14): 1546-1557.
- [3] Mena M, Touhami O, Ibtouen R, Fadel M. Sensorless Direct Vector Control of an Induction Motor. *Control Engineering Practice*. 2008; 16(1): 67-77.
- [4] Baskys A, Bleizgys V, Gobis V. *SVPWM Method with the Averaged Pulse Length Versus Conventional Modulation Method*. Proceedings of the 12th Biennial Baltic Electronics Conference. Tallinn. 2010; 321-322.
- [5] Vinoth Kumar, S Suresh Kumar, Kishore Reddy. Implementation of Scalar Control Technique in SVPWM Switched Three Level Inverter Fed Induction Motor Using DSP Controller. *International Journal of Power Electronics and Drive Systems*. 2011; 1(2): 83-93.
- [6] Saravanan M, Nandakumar R, Veerabalaji G. Effectual SVPWM Techniques and Implementation of FPGA Based Induction Motor Drive. *International Journal of Reconfigurable and Embedded Systems*. 2012; 1(1): 11-18.
- [7] Zhengguan Wang, Jianxun Jin, Youguang Guo, Jianguo Zhu. SVPWM Techniques and Applications in HTS PMSM Machines Control. *Journal of Electronic Science and Technology of China*. 2008; 6(2): 191-197.
- [8] Van der Broeck HW, Skudelny HC, Stanke GV. Analysis and Realization of a Pulsewidth Modulator Based on Voltage Space Vectors. *IEEE Transactions on Industry Applications*. 1988; 24(1): 142-150.
- [9] L Zhang, C Wathanasarn, F Hardan. *An Efficient Microprocessor-Based Pulse Width Modulator using Space Vector Modulation Strategy*. IEEE Industrial Electronics, Control and Instrumentation (IECON). Bologna. 1994; 1: 91-96.
- [10] Chunlei Gu, Zhong Chen, *Automatic Control System of Electric Drive and Matlab Simulation*. First Edition. Beijing. Tsinghua University Press. 2011: 199-201.
- [11] Guijie Yang. *Study of Space Vector Pulse Width Modulation*. Proceeding of the CSEE. 2001; 21(5): 79-83.

- [12] Shanmei Chen. Simulating Space Vector Pulse Width Modulation Based on Simulink. *Journal of Electric Automation*. 2002; 24(3): 38-41.
- [13] Khambadkone AM, Holz J. Compensated Synchronous PI Current Controller in Overmodulation Range and Six-step Operation of Space-Vector-Modulation-Based Vector-Controlled Drives. *IEEE Transactions on Industrial Electronic*. 2002; 49(3): 574-580.
- [14] Yafei Tian, Jiai He, Zhiwu Huang. *Simulation and Analysis Based on Space Vector Pulse Width Modulation Algorithm*. Proceedings of the CSU-EPASA. 2004; 16(4): 68-71.
- [15] Bo Li, Quntao An, Bingcheng Sun. Space Vector Pulse Width Modulation Simulation and Implementation. *Electric Machines and Control*. 2006; 33(6): 40-44.