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ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 13 (3): 578-582, 2014
ISSN 1812-5638 / DOI: 10.3923/itj.2014.578.582

Modeling and Simulation of Permanent Magnet Synchronous Motor Vector Control

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Abstract: Due to the difference between two types of definitions and transforms of the vector in Permanent Magnet Synchronous Motor (PMSM) vector control, the study introduces and analyzes the essential relationships between them and the transforming method in PMSM modeling procedure. A PMSM simulation model with variable PMSM parameters is proposed. The new model has many advantages in simulation. The detailed structure of the simulation model in MATLAB/Simulink is presented. Finally, a simulation example is proposed to verify the feasibility.

Key words: Motor, vector definition, vector control, simulation

INTRODUCTION

With lots of advantages, such as high torque density, small size and low maintenance cost, the Permanent Magnet Synchronous Motors (PMSMs) are widely used in industrial and domestic fields (Liu *et al*., 2009; Zaher, 2008; Yan *et al*., 2008). Performance improvement and cost reduction of the motor control system have been always hot topics because PMSM is a high order, nonlinear, strong coupling and time-dependent system. The main modern motor control theory and technology can be divided into two categories: vector control and direct torque control. Current, voltage and magnetic chain are regarded as vectors which provides a very convenient approach to motor analysis and control. Many fundamental and improved algorithms of vector control and direct torque control for the AC machine have been proposed and discussed by many scientists, such as Wang *et al.* (2006) and Tang (2004). But transform methods and formulae are different in form of expression in literature, although the essence is same. Based on the literature (Liu *et al*., 2009; Zaher, 2008; Yan *et al*., 2008; Wang *et al*., 2006, 2009; Xie, 2003; Tang, 2004), the study discusses comparisons between two common transforms in PMSM vector control. The computer simulation is a powerful tool to assess the control system and always be used. With the performance of computer and simulation software greatly improved, the computer simulation has become more and more powerful and easier and easier. The simulation makes engineers and scientists discover the essence behind the phenomena and evaluate their design quickly, so the research and development cost and cycle can be significantly reduced (Zaher, 2008). The literature (Liu *et al*., 2009; Zaher, 2008; Yan *et al*., 2008; Wang *et al*., 2006, 2009; Xie, 2003; Tang, 2004) discussed how to build and analyze PMSM model and the control system. The powerful simulation software package MATLAB/Simulink has been widely utilized in electrical engineering and power electronics simulation. In MATLAB/ Simulink/ SimPowerSystems toolbox, many basic blocks can be directly used, such as PMSM model block, Park transform block and Clarke transform block. Because of difference between different reference coordinate systems, some blocks cannot always used directly. Xie (2003) discussed the problem of PMSM model in the power system block set in MATLAB 5.3 and given a modification method. Karabacak and Eskikurt (2012), Choi and Lee (2012), Elsayed *et al.* (2012), Shou-Quan *et al.* (2011) and Chen *et al.* (2011) discussed computer simulation methods to PMSM control system.

VECTOR DEFINITION AND TRANSFORM

Coordinate system: Three coordinate systems are always used in vector control, as shown in Fig. 1 (Wang *et al*., 2006; Holmes and Lipo, 2003). The static frame ABC derives from axes of the three stator windings. The other two are the static frame $\alpha\beta$ and the rotor frame dq. The axis α is consistent with the axis A. The axis β has a 90° leading phase to α. The axis d is oriented by the rotator flux linkage and q has a 90° leading phase to d.

Vector definition: In the three-phase PMSM, the stator steady state current can be expressed as:

$$\begin{cases} i_A = I_1 \cos(\omega t + \varphi_0) \\ i_B = I_1 \cos(\omega t + \varphi_0 - 2p/3) \\ i_C = I_1 \cos(\omega t + \varphi_0 + 2p/3) \end{cases} \tag{1}$$

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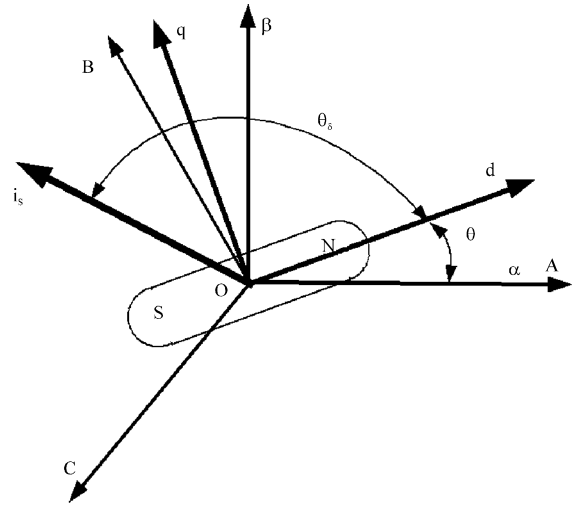

Fig. 1: Diagram of reference frames and vectors

where, I_1 is the phase current peak value, ω is the electrical angular velocity and φ_0 is the initial phase angle.

The current can be expressed using a vector as:

$$i_{s0} = i_A + i_B \exp\left(\frac{j2p}{3}\right) + i_C \exp\left(\frac{j4p}{3}\right) = 3I_1 \exp\frac{j(\omega t + \varphi_0)}{2} \quad (2)$$

The current vector is a rotary one with constant amplitude which is 3/2 times of the phase current peak value. This is same to the first-harmonic magnetic motive force vector and voltage vector.

Always two types of definitions of current, voltage or flux linkage are adopted (Wang *et al*., 2006; Tang, 2004):

$$T1: i_{s1} = 2i_{s0}/3 = I_1 \exp(j(\omega t + \varphi_0)) \quad (3)$$

$$T2: i_{s2} = \sqrt{2/3}i_{s0} = \sqrt{3/2}I_1 \exp(j(\omega t + \varphi_0)) \quad (4)$$

So:

$$i_{s2} = \sqrt{3/2}i_{s1} \quad (5)$$

Coordinate transformation: In frame αβ, currents can be expressed as:

$$\begin{cases} i_{\alpha 1} = |i_{s1}|\cos(\omega t + \varphi_0) = I_1 \cos(\omega t + \varphi_0) \\ i_{\beta 1} = |i_{s1}|\sin(\omega t + \varphi_0) = I_1 \sin(\omega t + \varphi_0) \end{cases} \quad (6)$$

$$\begin{cases} i_{\alpha 2} = |i_{s2}|\cos(\omega t + \varphi_0) = \sqrt{3/2}I_1 \cos(\omega t + \varphi_0) \\ i_{\beta 2} = |i_{s2}|\sin(\omega t + \varphi_0) = \sqrt{3/2}I_1 \sin(\omega t + \varphi_0) \end{cases} \quad (7)$$

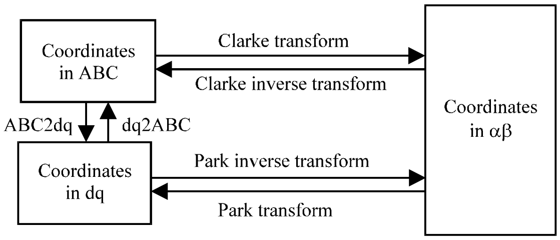

Fig. 2: Relation between static frame ABC, αβ and rotor frame dq

In frame dq, currents can be expressed as:

$$\begin{cases} i_d = |i_s|\cos\theta_\delta \\ i_q = |i_s|\sin\theta_\delta \end{cases} \quad (8)$$

where, θ_δ is the electrical angle between the current vector and d axis, as shown in Fig. 1.

It can be found Eq. 3 is the equal modulus transform but Eq. 4 is not. That is to say, T1 makes the peak amplitudes of A, B, C, α and β equal. The magnetic linkage vector and voltage vector are similar to the current vector.

The transform relations between three coordinates can be shown in Fig 2. Always the combination transform of Clarke and Park is called ABC2dq transform (the block is named abc_to_dq0 in MATLAB, 3ph->RRF in Plecs) and the inverse transform called dq2ABC (dq0_to_abc in MATLAB, RRF->3ph in Plecs). From Eq. 6-8, the transform formulae can be gotten. Equation 9 and 10 are from definition T1 and Eq. 11 and 12 from T2:

$$\begin{pmatrix} i_d \\ i_q \\ i_0 \end{pmatrix} = \frac{2}{3}\begin{pmatrix} \cos\theta & \cos(\theta - 2p/3) & \cos(\theta + 2p/3) \\ -\sin\theta & -\sin(\theta - 2p/3) & -\sin(\theta + 2p/3) \\ 1/2 & 1/2 & 1/2 \end{pmatrix}\begin{pmatrix} i_A \\ i_B \\ i_C \end{pmatrix} \quad (9)$$

$$\begin{pmatrix} i_A \\ i_B \\ i_C \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta - 2p/3) & -\sin(\theta - 2p/3) & 1 \\ \cos(\theta + 2p/3) & -\sin(\theta + 2p/3) & 1 \end{pmatrix}\begin{pmatrix} i_d \\ i_q \\ i_0 \end{pmatrix} \quad (10)$$

$$\begin{pmatrix} i_d \\ i_q \\ i_0 \end{pmatrix} = \sqrt{\frac{2}{3}}\begin{pmatrix} \cos\theta & \cos(\theta - 2p/3) & \cos(\theta + 2p/3) \\ -\sin\theta & -\sin(\theta - 2p/3) & -\sin(\theta + 2p/3) \\ \sqrt{1/2} & \sqrt{1/2} & \sqrt{1/2} \end{pmatrix}\begin{pmatrix} i_A \\ i_B \\ i_C \end{pmatrix} \quad (11)$$

$$\begin{pmatrix} i_A \\ i_B \\ i_C \end{pmatrix} = \sqrt{\frac{2}{3}}\begin{pmatrix} \cos\theta & -\sin\theta & \sqrt{1/2} \\ \cos(\theta - 2p/3) & -\sin(\theta - 2p/3) & \sqrt{1/2} \\ \cos(\theta + 2p/3) & -\sin(\theta + 2p/3) & \sqrt{1/2} \end{pmatrix}\begin{pmatrix} i_d \\ i_q \\ i_0 \end{pmatrix} \quad (12)$$

PMSM SIMULATION MODELLING METHOD

PMSM mathematical model: Based on some assumptions (Wang *et al*., 2006), the stator voltage vector equation can be expressed as:

$$u_s = R_s i_s + L_s\, di_s/dt + d\left(\psi_f e^{j\omega}\right)/dt \tag{13}$$

where, u_s is the voltage vector, R_s is the stator resistance, L_s is the stator inductance and ψ_f is the flux induced by rotator magnet.

ψ_{f0} is the amplitude of the flux in the stator sing phase winding induced by rotator magnets. In definition T1:

$$\psi_f = \psi_{f0} \tag{14}$$

In definition T2:

$$\psi_f = \sqrt{3/2}\,\psi_{f0} \tag{15}$$

In reference frame dq, Eq. 13 can be expressed as:

$$\begin{cases} di_d/dt = u_d/L_d - Ri_d/L_d + L_q\omega_e i_q/L_d \\ di_q/dt = u_q/L_q - Ri_q/L_q - L_d\omega_e i_d/L_q - \omega_e\psi_f/L_q \end{cases} \tag{16}$$

where, u_d, u_q are the voltage in d, q, respectively; L_d, L_q are the inductance in d, q; ω_e is the electrical angle speed.

In T2, the electromagnetic torque can be expressed as:

$$T_e = p_n(\psi_f i_q + (L_d - L_q) i_d i_q) \tag{17}$$

where, p_n is the pairs of poles.

In T1, the electromagnetic torque can be expressed as:

$$T_e = 3/2\ p_n(\psi_f i_q + (L_d - L_q) i_d i_q) \tag{18}$$

From Eq. 5 and 15, it can be found that Eq. 17 and 18 are same in essence.

The mechanical equations are:

$$\frac{d\omega_m}{dt} = \frac{1}{J}(T_e - F\omega_m - T_m) \tag{19}$$

$$\frac{d\theta}{dt} = \omega_m \tag{20}$$

where, ω_m is mechanical angle speed, J is rotary inertia, F is frication factor, θ is mechanical angle and T_m is load torque:

$$\omega_e = p_n \omega_m \tag{21}$$

PMSM simulation model: Almost all simulation models have the load torque input port T_m and the measurement port m (Fig. 3) that outputs PMSM states such as the stator current, rotator position, speed and electromagnetic torque. The difference between the four models in Fig 3 is the input voltage. MATLAB/Simulink and Plecs adopt the model as Fig. 3a. In Fig. 3c, the PMSM parameters such as R_s, L_d, L_q, ψ_f, are constant but this is too ideal to simulate the parameter time-varying case. So the study discusses how to build a PMSM model as shown in Fig. 3d. The model has some advantages as follows:

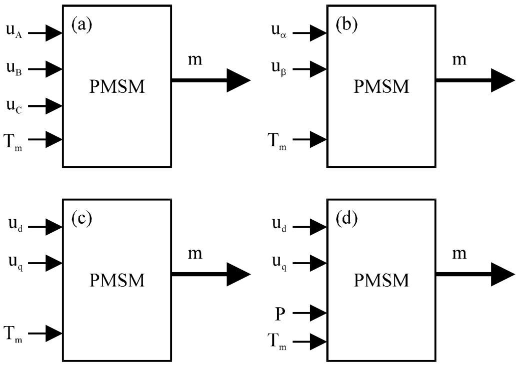

Fig. 3(a-d): Different inputs and outputs of permanent magnet synchronous motor (PMSM) simulation model (a) Three-phase voltage input in frame ABC with constant PMSM parameters, (b) Two-phase voltage input in frame $\alpha\beta$ with constant PMSM parameters, (c) Two-phase voltage input in frame dq with constant PMSM parameters and (d) Two-phase voltage input in frame dq with time-varying PMSM parameters

- PMSM parameter P (a vector) can be changed in simulation. It is very useful to analyze the effect of parameter variety on PMSM performance. The model also can be used to verify PMSM parameter identification algorithms
- PWM technology is widely in motor control. In the classical three closed-loop control system, the inner current loop gives u_d and u_q. Based on u_d and u_q, control signals to switch tubes such as IGBT are generated. But this is time-consuming or even simulation fails in MATLAB/Simulink. Figure 3b-d consider the inverter ideal

The simulation model is based on Eq. 16-21. The model is divided into three components: electrical model, mechanical model and measurement model, as shown in Fig. 4a. The mechanical model is shown in Fig. 4c. In

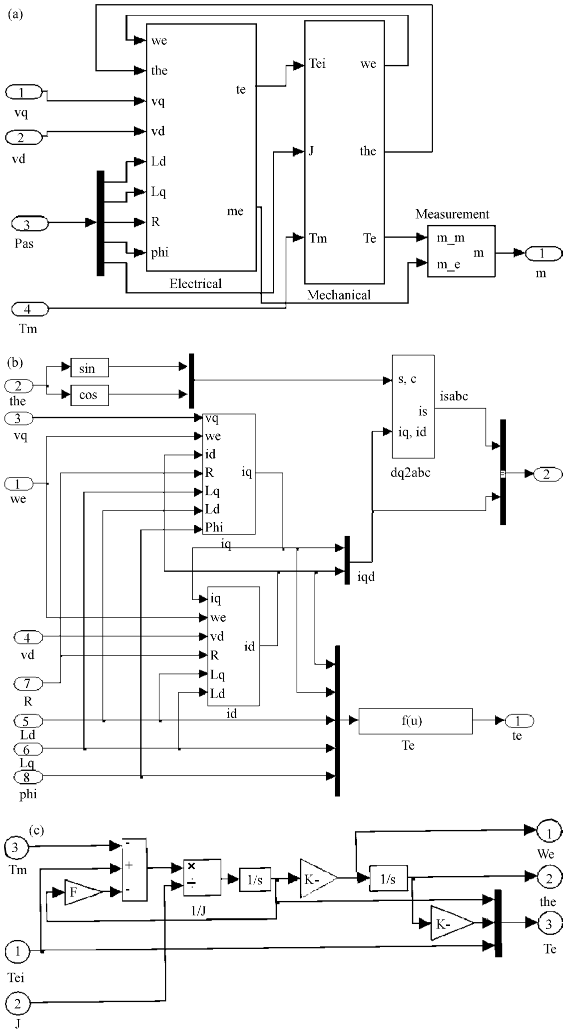

Fig. 4(a-c): Permanent magnet synchronous motor (PMSM) simulation model with parameters that can be changed in simulation (a) Structure of the model (b) Electrical model and (c) Mechanical model

Fig. 4b, iq and id models are derived from Eq. 16, electromagnetic torque function from Eq. 18 and mechanical model from Eq. 19-21.

SIMULATION RESULTS AND DISCUSSION

The simulation model using hysteresis current control is shown in Fig. 5. This model structure is derived from power_pmmotor.mdl in MATLAB Demos. The parameters are stator resistance Rs = 2.875 Ω, inductance Ld = Lq = 0.0085 H, flux induced by magnets ψ_f = 0.175 Wb, inertia J = 0.0008 kg m^{-2}, frication factor F = 0 and pairs of poles p_n = 4. The Step block with Step time 0.04 sec, Initial value 1 and Final value 3, is used to apply the load. The speed, stator current and torque are shown in Fig 6. From the figures, the built PMSM simulation model can be easily used and produce excellent application effectiveness. The SVPWM (space vector pulse width modulation) model and inverter model are negligible in simulation which can significantly improve the simulation speed with high precision. From this respect, the PMSM simulation in the study is better than that in the literature (Xie, 2003; Chen *et al*., 2011). But it should be noticed that the SVPWM model and inverter model must be used if the simulation focuses effect assessment of harmonic and dead time to PMSM. If the hysteresis current control is substituted by vector control or direct torque control, this simulation model still holds good.

In the simulation, Eq. 3 is adopted. If Eq. 4 is adopted, flux induced by magnets $\psi_f = \sqrt{3/2} \times 0.175$ Wb and the coordinate transforms should adopt Eq. 11 and 12 in PMSM block and simulation model. The simulation results on speed, stator current and torque are consistent with Fig 6, because speed, stator current and torque are actual physical quantities in motor control system. The big difference between different transforms lies in the artificial definition. The vectors, such as current, voltage and magnetic chain, are artificial physical quantities,

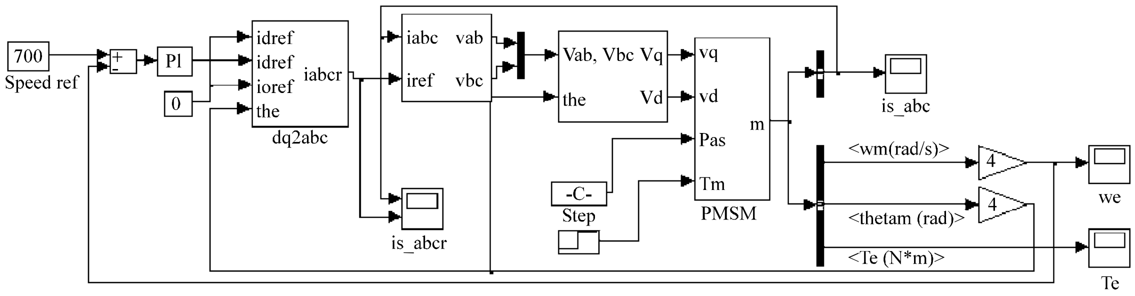

Fig. 5: Simulation experiment model using motor model in Fig. 4 and hysteresis current control method

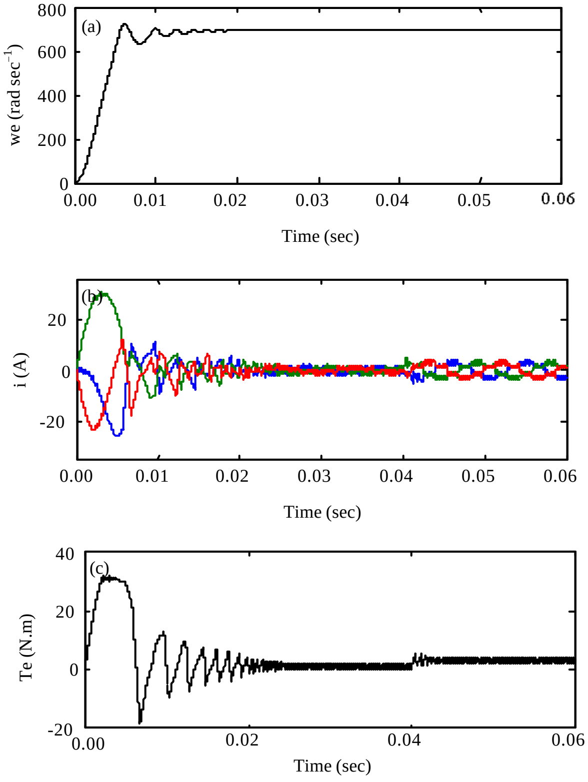

Fig. 6(a-c): Simulation results of Fig. 5 with parameters of stator resistance 2.875 Ω, d and q inductance 0.0085 H, flux induced by magnets 0.175 Wb, inertia 0.0008 kg m^{-2}, frication factor 0 and 4 pairs of poles (a) Speed response, (b) Stator current and (c) Torque response

although they come from the actual ones. Different definitions must lead to different transform methods and formulas. So in the literature (Chen *et al*., 2011; Choi and Lee, 2012; Shou-Quan *et al*., 2011; Elsayed *et al*., 2012; Holmes and Lipo, 2003; Liu *et al*., 2009; Tang, 2004; Wang *et al*., 2006; Yan *et al*., 2008) the transform and equation have to be coordinated with the definition.

CONCLUSION

The study introduces coordinate systems and vectors in PMSM control and compares the difference of two transforms and definitions. Although, there is phenomenal difference, the essence is same. A new PMSM model is built in which parameters can change with time. This model is more practical and has other advantages which is verified using simulation.

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