International Journal of Mechatronics, Electrical and Computer Technology

Vol. 3(6), Jan, 2013, pp 1 - 12, **ISSN**: 2305-0543
Available online at: http://www.aeuso.org

Advance Vector Control on Based Energy Shaping for control in Wide Speed Range and Quicker Dynamic Response

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Abstract

Based on the vector of the permanent magnet synchronous motor (PMSM) and in order to obtain the system operation of wide variable speed range, quicker dynamic response, the maximum torque per ampere (MTPA) control is often applied for the constant torque region, the flux-weakening control is used in the constant power region, moreover, the classical two closed-loop PI controller are often used. Recently, the energy-shaping nonlinear controller is increasingly used to control the nonlinear induction motor or PMSM, therefore, the comparison between both PMSM systems is devoted to research in this paper, one adopts the PI current controller, the other adopts the energy-shaping current controller. Both PMSM control systems are modeled based on the MATLAB/SIMULINK, and the system performances are tested and some conclusions are given.

Keywords: energy shaping, vector control, wide speed range

1. Introduction

PMSM with the salient rotor are used in many fields and particularly become the domination of the new energy automobile in automotive industry, how to carry out a control technique which possesses the advantages such as simple control, low price, low torque ripple, especially wide variable speed and high efficient operation attracts many investigators' attentions and inspires their devotion. Some methods have been proposed such

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as the adaptive control [1], the sliding mode control [2], the intelligent control, the passive-based control [3] and so on.

In recent years, the energy-shaping control [4] has been paid more and more attention, however, the comparison between the PI control [5] and the energy-shaping control [6] have not been implemented, which control is more better? Therefore, the perplexity is devoted to solved in this paper. Both PMSM control systems are set up, the PI controller is adopted for the speed outer-loop, and the current command converters are both used to generate the current commands. Considering that the current inter-loop, one adopts the PI current controller, the other adopts the energy-shaping current controller.

This paper is organized as follows. First, the mathematical model of PMSM is set up. Next, the speed PI controller including the current command converter is introduced. Then, the current PI controller and the energy-shaping controller are presented. And then, the performance tests are realized through MATLAB/SIMULINK system modeling, and the comparison between both PMSM control systems are implemented and some conclusions are shown.

2. The Mathematical Model of PMSM

Using the synchronous rotating d-q frame mathematical model of PMSM is written as:

$$\begin{aligned} L_d i_d &= V_d \quad R_s i_d + n_p \omega_r L_q i_q \\ L_q i_q &= V_q \quad R_s i_q \quad n_p \omega_r L_q i_q \quad n_p \omega_r \varphi \\ J\omega_r &= T_e \quad T_L = n_p[(L_d \quad L_q) i_d i_q + \varphi_q] \quad T_L \end{aligned} \tag{1}$$

Where u_d, u_q, i_d, i_q expressthe d-axis and q-axis stator voltages and currents, respectively. R_s, L_d and L_q indicate the stator resistance d-axis and q-axis inductances. φ express the permanent magnet flux. T_e, T_L denote the electromagnetic torque and load torque. ω_r, J, n_p represent the mechanical rotor speed, the inertia moment and number of pole pairs.

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3. CURRENT COMMAND CONVERTER

3.1. The Voltage and Current Limitation

Supposing that PMSM is driven by a PWM inverter, due to the limited inverter output capacity, therefore, the stator current and voltage of PMSM are limited. The limit value of stator current is used to achieve the current commands, and the limit value of stator voltage determines whether the working region of PMSM is located in the constant torque area or the constant power area.

$$\begin{aligned} i_{\max}^2 &= i_d^2 + i_q^2 \\ v_{\max}^2 &= (n_p \omega_r)^2 \left((L_q i_q)^2 + (L_d i_d + \quad)^2 \right) \end{aligned} \qquad (2)$$

where u_{max}, i_{max} express the maximum output voltage and current of inverter.

3.2. Current References

The current command converter is introduced and its func-tion block is shown in Fig. 1. The PI controller is working with saturation which is determined by the requiring peak electromagnetic torque of PMSM, and the current command norm is affected by the difference between the reference rotor speed and the actual rotor speed, electromagnetic torque, load torque and PI controller parameters.

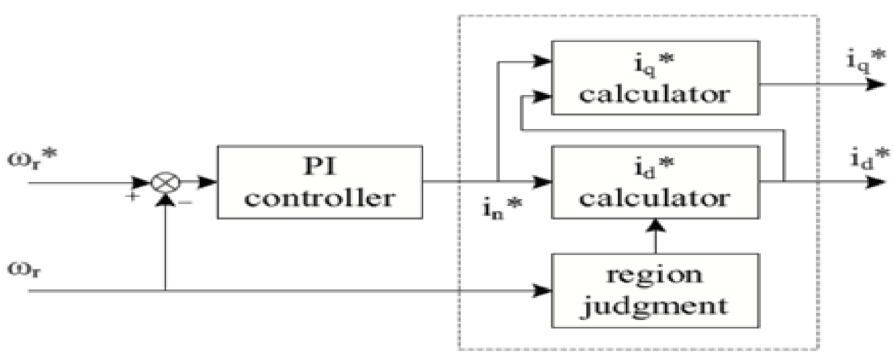

Figure 1: The current command generator

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3.2.1. Constant torque region:

In this area, the maximum torque per ampere method is suggested to obtain the maximal electromagnetic torque in this paper, then, based on (1) and (2), the optimized current command is given as

$$i_d^* = \frac{1}{2}\ \frac{}{(2L_d \quad 2L_q)} + \sqrt{\frac{}{4(L_d \quad L_q)^2} + 2i_n^{*2}}$$
$$i_q^* = sign(i_n^*)\sqrt{(i_n^{*2} \quad i_q^{*2})} \qquad (3)$$

3.2.2. Constant power region:

When the PMSM system operates above the base speed, the flux-weakening control is achieved to satisfy the restriction that the stator voltage is located inside the voltage limitation circle,moreover, it is necessary to control the current command vector inside the current limitation circle. Therefore, the current command value is determined by the intersection point of two limitation circles. According to (2), the current command is then obtained and given as

$$i_d^* = \frac{1}{(L_d^2 \quad L_q^2)} \quad L_d + \sqrt{{}^2L_q^2 \quad (L_d^2 \quad L_q^2)\ L_q^2 i_n^{*2} \quad \frac{v_{\max}}{n_p\omega_r}\ ^2}$$
$$i_q^* = sign(i_n^*\ )\sqrt{(i_n^{*2} \quad i_q^{*2})}$$

(4)

3.2.3. Definition of constant torque and constant power region:

Use (2) and (3) to solve the solution, then the base speed from the constant torque to constant power or the direct opposite is given as

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$$\omega_{rs} = \sqrt{\frac{v_{\max}^2}{n_p^2\left((L_q i_q^*)^2 + (L_d i_d^* + \quad)^2\right)}} \tag{5}$$

where d-axis and q-axis currents which use above are from (3). As we know, the d-axis and q-axis currents are influenced by many factors, therefore, the base speed varies with operation conditions of PMSM.

It is obvious that the aforementioned current command converter is nonlinear, the output of PI speed outer-loop is restricted by the current command norm [5]. The reason of the current command converter is suggested to adopt is that it possesses of the following advantages, that means, the current command norm only confines the current amplitude, the current phase can be controlled freely based on the different requirements such as the maximum torque per ampere control, the flux-weakening control, the maximum output power control [7] and so on. Then, the desired d-axis and q-axis currents are able to be analytically solved. No matter the proportion of d-axis and q-axis is a constant or not, the electromagnetic torque limitation is simply and precisely achieved by the restricted current command norm, moreover, once the current amplitude is defined, the maximum torque is decided with the definite control strategy.

4. CURRENT CONTROLLER

4.1. PI Current Controller

As we known, the classical PMSM system figures out the d-axis and q-axis voltage of PMSM on the basis of two closed-loop PI controllers named by the outer-loop PI speed controller and the inter-loop PI current controller.

4.2. Energy-Shaping Nonlinear Current Controller

The Energy-shaping controller [9] has been already pre-sented based on the port-controlled hamiltonian (PCH) theory. Here, the PCH model of PMSM is first given, then the feedback

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control is introduced aiming to make PCH system stable at equilibrium points obtained from the current command converter, and then, the d-axis and q-axis voltages are obtained through solving a partial differential equation.

4.2.1. Port-Controlled Hamiltonian model of PMSM:

Allowing for the dissipation [8], the PCH model [9] of PMSM is written as

$$\begin{aligned} x' &= [j(x) \quad R(x)]\frac{\partial H}{\partial X}(x) + g(x)u \\ y &= g^T(x)\frac{\partial H}{\partial x}(x) \end{aligned} \quad (6)$$

Where $x \in R^n$ denote the state vector, $u, y \in R^m$ are the input and output vectors. $J(x) = \quad J^T(X), R(X) = R^T(X) \geq 0$, g(x) indicate the interconnection matrix, the damping matrix and the input matrix, respectively. H(x) represents the total energy of PCH system. Besides, we define

$$J(x) = \begin{matrix} 0 & 0 & n_p x_2 \\ 0 & 0 & n_p(x_1 + \varphi) \\ n_p x_2 & n_p(x_1 + \varphi) & 0 \end{matrix}$$

$$R(x) = \begin{matrix} R_x & 0 & 0 \\ 0 & R_x & 0 \\ 0 & 0 & R_x \end{matrix} \quad (7)$$

$$g(x) = \begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{matrix}$$

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where $D = diag[\, L_d \quad L_q \quad J]$

4.2.2. Design of energy-shaping current controller:

In order to make PCH system stable at the equilibrium points, based on the PCH theory, the voltage feedback control is introduced, the closed-loop Hamilton function is then selected as

$$H_d(x) = H(x^*) + \frac{1}{2}(x - x^*)^T D^{-1}(x - x^*) \tag{8}$$

Supposing that the feedback control u(x) is able to find and satisfy the following partial differential equation

$$[J_d(x) - R_d(x)]\frac{\partial H_a}{\partial x}(x) = -[J_a(x) - R_a(x)]\frac{\partial H}{\partial x}(x) + g(x)u(x) \tag{9}$$

Moreover

$$\frac{\partial H_d}{\partial x}(x) = 0\,, \quad \frac{\partial^2 H_d}{\partial x^2}(x) > 0 \tag{10}$$

Where

$$\begin{aligned} J_d(x) &= J(x) + J_a(x) = -J_d^T(x) \\ R_d(x) &= R(x) + R_a(x) = R_d^T(x) \geq 0 \\ H_d(x) &= H(x) + H_a(x) \end{aligned} \tag{11}$$

Then, the following is the closed-loop Hamilton system.

$$x' = [J_d(x) - R_d(x)]\frac{\partial H_d}{\partial x}(x) \tag{12}$$

$$\begin{aligned} u_d &= -r_1(i_d - i_d^*) + R_s i_d^* - k(i_q - i_q^*) - n_p L_d i_q^*(\omega_r - \omega_r^*) - n_p L_q i_q \omega_r^* \\ u_q &= -r_1(i_q - i_q^*) + R_s i_q^* + k(i_d - i_d^*) + n_p L_q i_d^*(\omega_r - \omega_r^*) + n_p(L_d i_d + \quad)\omega_r^* \end{aligned} \tag{13}$$

The energy-shaping current controller is then designed out and given as where r_1, r_2 express the positive damping parameters and k is a parameter which can be regulated freely. But the

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values of parameters r_1, r_2 may affect the maximum electromagnetic torque of PMSM heavily. It means the parameters adjustment need be careful so that the motor can work in the safety region. Considering the parameter adjustment, it will be discussed in the future paper.

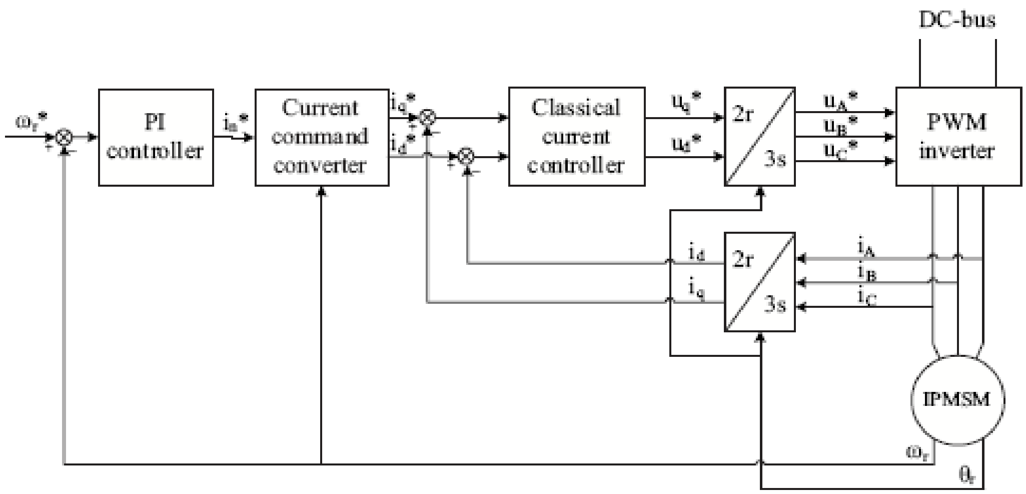

Figure 2: PMSM system based on classical control method

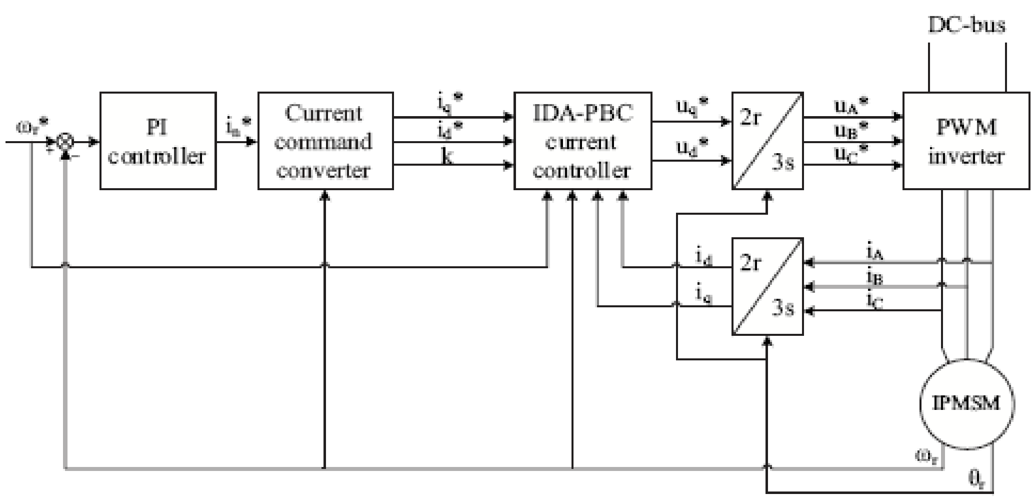

Figure 3: PMSM system based on energy-shaping control method

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5. COMPARISON OF PMSM CONTROL SYSTEMS

For the purpose of analytical studies on different PMSM control systems, their MATLAB/SIMULINK models are first set up and their configuration diagrams are shown in Fig. 2 and Fig. 3. The parameters of permanent-magnet synchronous motor are given in Table I, moreover, the following tests has been implemented under the condition that the maximium torque of PMSM is limited at rated torque 40 N·m.

The dynamic performance of PMSM system is shown in Fig. 4 when the reference speed is 200 rad/s with 20 N·m load torque. The effect of load torque disturbance on the system performance is shown in Fig. 5 in the condition of 600 rad/s reference speed, moreover, a 20 N·m load torque disturbance is added at 0.4 s and sustains until 0.6 s. In the conditions of 10 N·m load torque, the reference speed sustains 600 rad/s until 0.3 s, then it increases up to 1200 rad/s, and at last it gets back to 600 rad/s. The speed dynamics of two PMSM control systems are shown in Fig. 6.

Table 1: PARAMETERS OF PMSM

Stator resistance	$R_s = 0.0178\ (\Omega)$
Stator inductance	$L_d = 0.09$ (mH), $L_q = 0.228$ (mH)
Magnet flux	$\phi = 0.0335$ (Wb)
Rotate inertia	$J = 0.01275\ (kg\cdot m^2)$
Pole pairs	$n_p = 4$
Rated speed	400 (rad/s)

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Rated torque	40 (N·m)

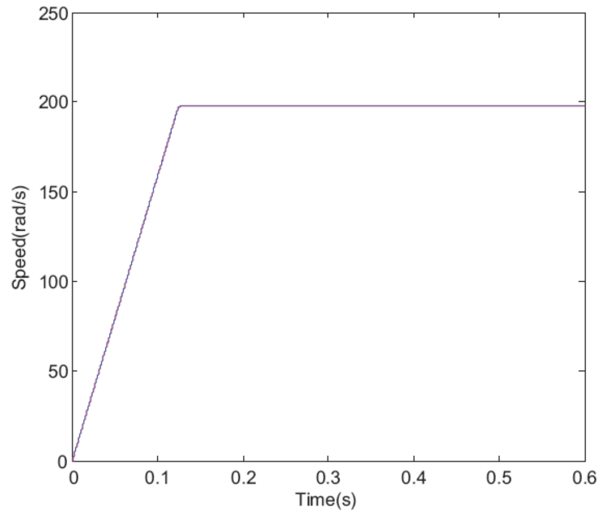

Figure 4: The rotor speed dynamic of both PMSM systems

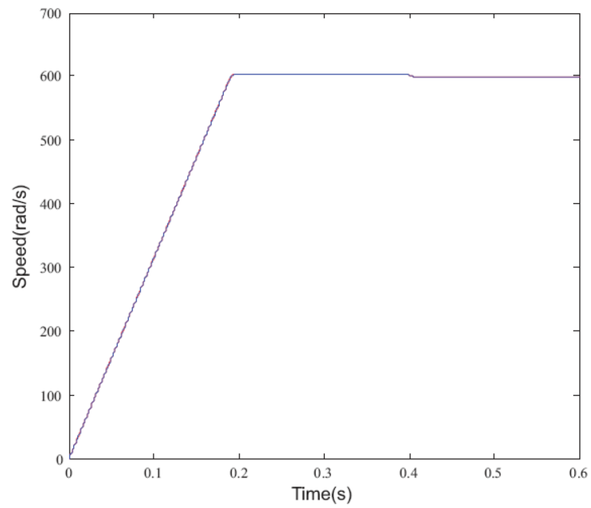

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Figure 5: The rotor speed dynamicwith the load torque disturbance

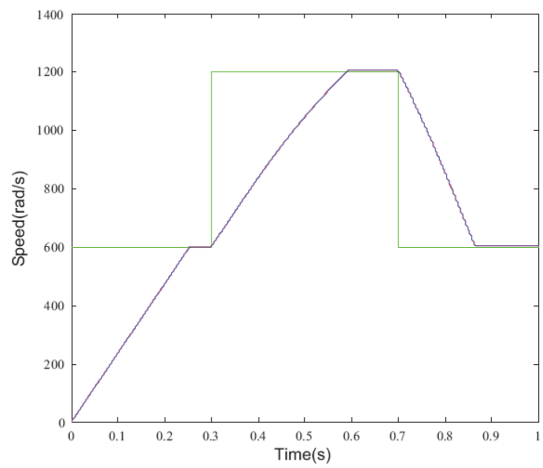

Figure 6: The rotor speed dynamic at wide speed range

The system simulation results clearly indicate that the energy-shaping current controller can obtain the same performances with the PI current controller, however, compared with the current inner-loop PI controller, the energy-shaping current controller is provided with the advantage of calculation simplification.

Conclusion

Through energy-shaping and port-controlled Hamiltonian system theory, using the current command converter, the system equilibrium points are easily obtained, and then, a nonlinear energy-shaping current controller is designed for PMSM with excellent performance. Considering that the both PMSM control systems, although their dynamic and static performances are same, the energy-shaping current controller is simpler and easier to implementation in the practical use. Therefore, it can be predicted that the energy-shaping controller and its developments shows a bright future for highperformance PMSM control.

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References

[1] V. Petrovic, R. Ortega, A. M. Stankovic, and G. Tadmor, "Design and implementation of an adaptive controller for torque ripple minimization in pm synchronous motors," Ieee Transactions on Power Electronics, vol. 15, no. 5, pp. 871–880, 2000. Cited Reference Count: 18 6713100 Usa Ieee.

[2] D. Q. Zhang and S. K. Panda, "Chattering-free and fast-response sliding mode controller," Control Theory and Applications, IEE Proceedings -,vol. 146, no. 2, pp. 171–177, 1999.

[3] R. Ortega, A. van der Schaft, B. Maschke, and G. Escobar, "Interconnection and damping assignment passivity-based control of port-controlled hamiltonian systems," Automatica, vol. 38, no. 4, pp. 585–596, 2002.

[4] Y. Haisheng, Z. Zongwei, and Y. Shanshan, "Speed regulation of pmsm based on port-controlled hamiltonian systems and pi control principle," in
2009 IEEE International Conference on Automation and Logistics (ICAL), (Shenyang, China), pp. 647–651, Ieee, 2009. Cited Reference Count: 1510892476.

[5] S. Shinnaka, "A new current control method for energy-efficient/wide speed-range drive of permanent magnet synchronous motor," Electrical Engineering in Japan, vol. 161, no. 3, pp. 66–77, 2007.

[6] W. X. Li Hongmei, "A novel controller for energy-efficient and widespeed- range drive for permanent magnet synchronous motor based on the interconnection and damping assignment passivity based control,"International Symposium on Traffic Information and Logistic Engineering, 2010.

[7] Z. W. Zou, H. S. Yu, Y. L. Tang, and Ieee, "Maximum output power control of pmsm based on energy-shaping and pwm control principle," 2008 Ieee International Conference on Automation and Logistics, vol. 1-6, 2008.

[8] R. Ortega, A. J. Van Der Schaft, I. Mareels, and B. Maschke, "Putting energy back in control," Control Systems Magazine, IEEE, vol. 21, no. 2, pp. 18–33, 2001.

[9] A. J. van Der Schaft, L2-Gain and Passivity Techniques in Nonlinear, London: Springer-Verlag, 2000. Control.