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SPEED COORDINATION CONTROL OF THE PERMANENT MAGNET SYNCHRONOUS MOTOR BASED ON SIGNAL AND ENERGY

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Abstract. *Aiming at the lack of consideration on signal and energy coordination control of permanent magnet synchronous motor (PMSM) speed servo system, a hybrid coordination control method based on signal and energy is proposed in this paper. The backstepping controller is used as the signal controller, and the port-controlled Hamiltonian (PCH) controller is used as the energy controller. The design of coordination control strategy is used to adjust the strength of the two control methods. The PMSM speed control system with known load torque combines the advantages of the signal control and the energy control. The system not only shows the fast tracking control of speed signal, but also optimizes the input and output energy. The simulation results show that the coordination control system has good dynamic and steady-state performances, and the energy consumption of the system is minimum.*
Keywords: PMSM, Signal, Energy, Backstepping, PCH, Coordination control

1. **Introduction.** Permanent magnet synchronous motors (PMSMs) are widely used in industrial fields, because PMSMs have high efficiency, high power factor, and robustness [1]. The existing control methods of PMSM can be classified into two categories. One is signal control. The motor is considered as a signal conversion device, which can transform input signal into the output signal. Its control goal is to improve the dynamic and steady state response of the system. The other is energy control. The motor is considered as an energy conversion device, which can transform input energy into the output energy. Its control goal is to optimize input and output energy of the whole system, and the system can reach its minimum energy consumption. For nonlinear systems, fuzzy control system does not need to establish the accurate mathematical model of the PMSM, but it cannot eliminate the system's speed steady-state error [2]. Sliding mode control systems have good anti-disturbance performances, but at the same time it brings chattering to the system [3]. The PCH control method can simplify the controller design and the stability analysis [4,5]. In this paper, backstepping control and PCH control of PMSM energy optimizing method are combined to ensure that the system has the advantages of the two control methods. The coordination control strategy is proposed to change the control strength of signal controller and energy controller over time. Each control can play a role in corresponding period of time to maximize its control effect. The fast dynamic response and minimum energy loss make the system achieve the desired control effect.

The paper is organized as follows. Section 2 presents the mathematical model of the PMSM including iron loss. Signal and energy controllers are designed in Section 3. Section 4 presents the coordination control strategy design. Furthermore, the simulation results are given in Section 5. Section 6 states our conclusions.

2. **The Model of PMSM Including Iron Loss.** The model of the PMSM including iron loss can be described in the d-q frame as follows [6]

$$\begin{cases} L_{ld}di_d/dt = -\left(R_s + R_{Fe}\right)i_d + R_{Fe}i_{wd} + u_d \\ L_{lq}di_q/dt = -\left(R_s + R_{Fe}\right)i_q + R_{Fe}i_{wq} + u_q \\ L_{md}di_{wd}/dt = R_{Fe}\left(i_d - i_{wd}\right) + n_p\omega L_q i_{wq} \\ L_q di_{wq}/dt = R_{Fe}\left(i_q - i_{wq}\right) - n_p\omega\left(L_d i_{wd} + \Phi\right) \\ J_m d\omega/dt = \tau - \tau_L = n_p\left[\left(L_{md} - L_{mq}\right)i_{wd}i_{wq} + \Phi i_{wq}\right] - \tau_L \end{cases} \quad (1)$$

where i_{wd} and i_{wq} are active currents, R_s is the stator resistance, R_{Fe} is the iron loss resistance, u_d and u_q are the d-q axes voltages, i_d and i_q are the d-q axes currents, L_d and L_q are the stator inductors, L_{ld} and L_{lq} are the leakage inductors, L_{md} and L_{mq} are the active inductors, Φ is the rotor flux linking the stator, n_p is the number of pole pairs, ω is the angular velocity of rotor, J_m is the moment of inertia, τ_L is the load torque, and τ is the electromagnetic torque. For surface mounted permanent magnet synchronous motors, we have $L_d = L_q$, $L_{ld} = L_{lq}$ and $L_{md} = L_{mq}$.

3. **The Coordination Control Strategy of PMSM Speed Control System.** Define $c_{sd}(t)$ and $c_{ed}(t)$ as d-axis coordination functions of backstepping controller and PCH controller, $c_{sq}(t)$ and $c_{eq}(t)$ as q-axis coordination functions of the backstepping controller and PCH controller, and the signal ω_0 as the reference of rotor angular speed. The PMSM speed control system based on signal and energy coordination control strategy is shown in Figure 1.

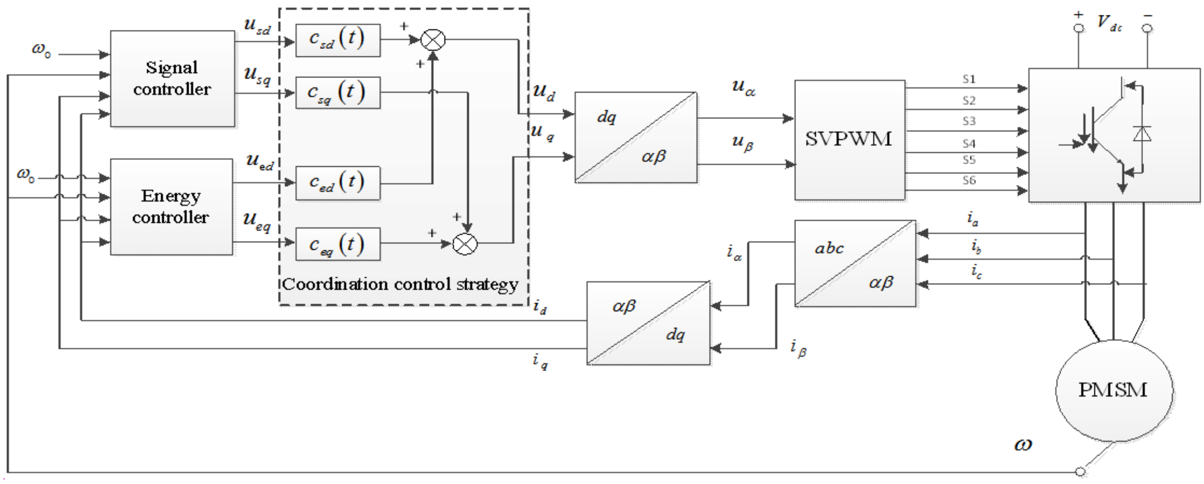

FIGURE 1. The PMSM speed coordination control system block diagram

3.1. **The design and stability analysis of the signal controller.** The backstepping control is used in signal controller. Lyapunov function is designed to figure out the input of the system, and to realize the system's stabilization [7].

Step 1: According to Equation (1), the time derivative of the speed error e_ω is

$$\dot{e}_\omega = \dot{\omega}_0 - \dot{\omega} = \dot{\omega}_0 - \left[n_p\Phi i_{wq} + n_p\left(L_{md} - L_{mq}\right)i_{wd}i_{wq}\right]/J_m + \tau_L/J_m \quad (2)$$

In order to obtain stable feedback, the Lyapunov function candidate $V_1 = e_\omega^2/2$ is considered for (e_ω)-subsystem. The i_{wq} is taken as virtual control, and its reference i_{wqr} is

$$i_{wqr} = (J_m k_1 e_\omega + J_m\dot{\omega}_r + \tau_L)/(n_p\Phi) \quad (3)$$

where $k_1 > 0$. Replacing i_{wq} with i_{wqr}, and substituting it into Equation (2), we have $\dot{e}_\omega = -k_1 e_\omega$. Therefore, we can get $\dot{V}_1 = e_\omega\dot{e}_\omega = -k_1 e_\omega^2 < 0$.

Step 2: Similarly, $e_{wq} = i_{wqr} - i_{wq}$ is taken as virtual control error. Then computing its derivative and substituting the fourth equation of Equation (1) into its derivative, we have

$$\dot{e}_{wq} = \dot{i}_{wqr} - \dot{i}_{wq} = \dot{i}_{wqr} - R_{Fe}i_q/L_{mq} + R_{Fe}i_{\omega q}/L_{mq} + n_p\omega L_d i_{wd}/L_{mq} + n_p\omega\Phi/L_{mq} \quad (4)$$

Consider the Lyapunov function candidate $V_2 = e_{wq}^2/2 + V_1$ for (e_ω, e_{wq})-subsystem. In order to obtain stable feedback, the actual control i_{wdr} and i_{qr} are selected as

$$i_{qr} = L_{mq}\dot{i}_{wqr}/R_{Fe} + n_p\omega L_d i_{wd}/R_{Fe} + i_{wq} + n_p\omega\Phi/R_{Fe} + k_2 L_{mq}e_{wq}/R_{Fe} \quad (5)$$

where $k_2 > 0$. Substituting Equation (5) into Equation (4), we can get $\dot{e}_{wq} = -k_2 e_{wq}$. Then, $\dot{V}_2 = -k_1 e_\omega^2 - k_2 e_{wq}^2 < 0$.

Step 3: The derivative of $e_q = i_{qr} - i_q$ is computed as

$$\dot{e}_q = \dot{i}_{qr} - \dot{i}_q = \dot{i}_{qr} + i_q(R_s + R_{Fe})/L_{lq} - R_{Fe}i_{wq}/L_{lq} - u_{sq}/L_{lq} \quad (6)$$

Consider the Lyapunov function candidate $V_3 = e_q^2/2 + V_1 + V_2$ for (e_ω, e_{wq}, e_q)-subsystem. In order to obtain stable feedback, the actual control u_{sq} is selected as

$$u_{sq} = (R_s + R_{Fe})\, i_q - R_{Fe}i_{wq} + L_{lq}\dot{i}_{qr} + k_3 L_{lq}e_q \quad (7)$$

where $k_3 > 0$. Substituting Equation (7) into Equation (6), we have $\dot{e}_q = -k_3 e_q$. Then, $\dot{V}_3 = -k_1 e_\omega^2 - k_2 e_{wq}^2 - k_3 e_q^2 < 0$.

Step 4: The derivative of $e_{wd} = i_{wdr} - i_{wd}$ is computed as

$$\dot{e}_{wd} = \dot{i}_{wdr} - \dot{i}_{wd} = \dot{i}_{wdr} - R_{Fe}i_d/L_{md} + R_{Fe}i_{wd}/L_{md} - n_p\omega L_q i_{wq}/L_{md} \quad (8)$$

Consider the Lyapunov function candidate $V_4 = e_{wd}^2/2 + V_1 + V_2 + V_3$ for $(e_\omega, e_{wq}, e_q, e_{wd})$-subsystem. We choose $i_{wdr} = 0$ control, and then the actual control i_{dr} is selected as

$$i_{dr} = -n_p\omega L_q i_{wq}/R_{Fe} + i_{wd} + k_4 L_{md}e_{wd}/R_{Fe} \quad (9)$$

where $k_4 > 0$. Substituting Equation (9) into Equation (8), we have $\dot{e}_{wd} = -k_4 e_{wd}$. Then, $\dot{V}_4 = -k_1 e_\omega^2 - k_2 e_{wq}^2 - k_3 e_q^2 - k_4 e_{wd}^2 < 0$.

Step 5: The derivative of $e_d = i_{dr} - i_d$ is computed as

$$\dot{e}_d = \dot{i}_{dr} - \dot{i}_d = \dot{i}_{dr} + i_d\,(R_s + R_{Fe})/L_{ld} - R_{Fe}i_{wd}/L_{ld} - u_{sd}/L_{ld} \quad (10)$$

Consider the Lyapunov function candidate $V_5 = e_d^2/2 + V_1 + V_2 + V_3 + V_4$ for $(e_\omega, e_{wq}, e_q, e_{wd}, e_d)$-subsystem. In order to obtain stable feedback, the actual control u_{sd} is selected as

$$u_{sd} = (R_s + R_{Fe})\, i_d - R_{Fe}i_{wd} + L_{ld}\dot{i}_{dr} + k_5 L_{ld}e_d \quad (11)$$

where $k_5 > 0$. Substituting Equation (11) into Equation (10), we have $\dot{e}_d = -k_5 e_d$. Then, $\dot{V}_5 = -k_1 e_\omega^2 - k_2 e_{wq}^2 - k_3 e_q^2 - k_4 e_{wd}^2 - k_5 e_d^2 < 0$. Obviously, V_5 is positive definite and $\dot{V}_5$ is negative semi-definite. According to the Lyapunov stability theory, the backstepping control subsystem is asymptotically stable.

Above all, the signal controller of the system is

$$\left\{\begin{array}{l} u_{sd} = (R_s + R_{Fe})\, i_d - R_{Fe}i_{wd} + L_{ld}\dot{i}_{dr} + k_5 L_{ld}e_d \\ u_{sq} = (R_s + R_{Fe})\, i_q - R_{Fe}i_{wq} + L_{lq}\dot{i}_{qr} + k_3 L_{lq}e_q \end{array}\right. \quad (12)$$

3.2. **Energy controller design.** The port-controlled Hamiltonian control of PMSM energy optimizing is used in energy controller design.

3.2.1. *The PCH model of PMSM including iron loss.* Define the state vector and the input vector of the system as [8]

$$x = \begin{bmatrix} L_{ld}i_d & L_{lq}i_q & L_{md}i_{wd} & L_{mq}i_{wq} & J_m\omega \end{bmatrix}^{\mathrm{T}}, \; u = \begin{bmatrix} u_{ed} & u_{eq} & -\tau_L \end{bmatrix}^{\mathrm{T}} \quad (13)$$

where u_{ed} and u_{eq} are the d-q axes voltages which correspond to u_d and u_q in Equation (1). Let the Hamilton function of PMSM system be

$$H(x) = \frac{1}{2}\left[L_{ld}i_d^2 + L_{lq}i_q^2 + L_{md}i_{wd}^2 + L_{mq}i_{wq}^2 + J_m\omega^2\right] \quad (14)$$

Therefore, the PCH model of system (1) is

$$\dot{x} = [J(x) - R(x)]\frac{\partial H(x)}{\partial x} + g(x)u \quad (15)$$

where, $R(x)$ is positive semi-definite symmetric matrix, and $R(x) = R^T(x) \geq 0$. The interconnection structure is captured in $g(x)$ and the skew-symmetric matrix $J(x) = -J^T(x)$. Then, Equation (1) can be expressed as Equation (15) with

$$J(x) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & n_pL_d\omega & 0 \\ 0 & 0 & -n_pL_d\omega & 0 & -n_p\Phi \\ 0 & 0 & 0 & n_p\Phi & 0 \end{bmatrix},$$
$$R(x) = \begin{bmatrix} R_s + R_{Fe} & 0 & -R_{Fe} & 0 & 0 \\ 0 & R_s + R_{Fe} & 0 & -R_{Fe} & 0 \\ -R_{Fe} & 0 & R_{Fe} & 0 & 0 \\ 0 & -R_{Fe} & 0 & R_{Fe} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \; g(x) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (16)$$

3.2.2. *The calculation and stability analysis of the energy controller.* When the load torque is constant and known, we have $\tau_L = \tau = \tau_{L0}$ and $\omega = \omega_0$ at the steady state. At the moment, from Equation (1), we can get $\tau_{L0} = n_p\Phi i_{wq}$, and it can be computed as $i_{wq} = \dfrac{\tau_{L0}}{n_p\Phi}$. If the mechanical loss is neglected, the total loss is [9]

$$\begin{aligned} P_{loss} = & \frac{3R_sR_{Fe}^2 + 3n_p^2\omega_0^2L_d^2(R_s + R_{Fe})}{2R_{Fe}^2}\left[i_{wd} + \frac{n_p^2\omega_0^2L_d\Phi(R_s + R_{Fe})}{R_sR_{Fe}^2 + n_p^2\omega_0^2L_d^2(R_s + R_{Fe})}\right]^2 \\ & + \frac{3\left(n_p^4\omega_0^2\Phi^4 + n_p^2\omega_0^2L_d^2\tau_L^2\right)(R_s + R_{Fe}) + 3\tau_L^2R_sR_{Fe}^2}{R_sR_{Fe}^2 + n_p^2\omega_0^2L_d^2(R_s + R_{Fe})} \\ & - \frac{3n_p^4\omega_0^4L_d^2\Phi^2(R_s + R_{Fe})^2}{2R_sR_{Fe}^4 + 2n_p^2\omega_0^2L_d^2R_{Fe}^2(R_s + R_{Fe})} \end{aligned} \quad (17)$$

Let $dP_{loss}/di_{wd} = 0$, the equilibrium point can be calculated when the system reaches its minimum loss at the steady-state

$$x_0 = \begin{bmatrix} L_{ld}i_{d0} & L_{lq}i_{q0} & L_{md}i_{wd0} & L_{md}i_{wq0} & J_m\omega_0 \end{bmatrix}^T \quad (18)$$

where,

$$i_{d0} = -\frac{n_p^2\omega_0^2L_d\Phi(R_s + R_{Fe})}{R_sR_{Fe}^2 + n_p^2\omega_0^2L_d^2(R_s + R_{Fe})} - \frac{L_d\omega_0\tau_{L0}}{R_{Fe}\Phi},$$

$$i_{q0} = \frac{\tau_{L0}}{n_p\Phi} + \frac{n_p\Phi\omega_0}{R_{Fe}} - \frac{n_p^3\omega_0^3L_d^2\Phi(R_s + R_{Fe})}{R_sR_{Fe}^3 + R_{Fe}n_p^2\omega_0^2L_d^2(R_s + R_{Fe})},$$

$$i_{wd0} = -n_p^2\omega_0^2 L_d \Phi \left(R_s + R_{Fe}\right) / \left[R_s R_{Fe}^2 + n_p^2 \omega_0^2 L_d^2 \left(R_s + R_{Fe}\right)\right],\ i_{wq0} = \tau_{L0}/(n_p\Phi).$$

Given desired closed-loop system

$$\dot{x} = [J_d(x) - R_d(x)] \frac{\partial H_d(x)}{\partial x} \tag{19}$$

Choose the desired Hamilton function as

$$\begin{aligned} H_d(x) = \frac{1}{2} \Big[& L_{ld} \left(i_d - i_{d0}\right)^2 + L_{lq} \left(i_q - i_{q0}\right)^2 + L_{md} \left(i_{wd} - i_{wd0}\right)^2 \\ & + L_{mq} \left(i_{wq} - i_{wq0}\right)^2 + J_m \left(\omega - \omega_0\right)^2 \Big] \end{aligned} \tag{20}$$

where $H_d(x) > 0$ and $H_d(0) = 0$. The Lyapunov function of PCH subsystem is defined as $V_e = H_d(x)$, and then the PCH subsystem is asymptotically stable at equilibrium point x_0 [10]. Furthermore, let $J_d(x) = J(x) + J_a(x) = -J_d^T(x)$, $R_d(x) = R(x) + R_a(x) = R_d^T(x) \geq 0$, and choose

$$\begin{aligned} J_d(x) &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & J_{34} & J_{35} \\ 0 & 0 & -J_{34} & 0 & J_{45} \\ 0 & 0 & -J_{35} & -J_{45} & 0 \end{bmatrix}, \\ R_d(x) &= \begin{bmatrix} R_s + R_{Fe} + r_1 & 0 & -R_{Fe} & 0 & 0 \\ 0 & R_s + R_{Fe} + r_1 & 0 & -R_{Fe} & 0 \\ -R_{Fe} & 0 & R_{Fe} + r_2 & 0 & 0 \\ 0 & -R_{Fe} & 0 & R_{Fe} + r_2 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \end{aligned} \tag{21}$$

where J_{34}, J_{35}, J_{45}, r_1 and r_2 are the designed parameters. Let Equation (15) be equal to Equation (19), and we can get $J_{34} = n_p L_d \omega$, $J_{35} = n_p L_d i_{wq}$ and $J_{45} = -n_p L_d i_{wd} - n_p \Phi$.

According to Equations (15), (18), (19) and (21), the energy controller of the system is

$$\begin{cases} u_{ed} = -r_1 i_d + \left(R_s + R_{Fe} + r_1\right) i_{d0} - R_{Fe} i_{wd0} \\ u_{eq} = -r_1 i_q + \left(R_s + R_{Fe} + r_1\right) i_{q0} - R_{Fe} i_{wq0} \end{cases} \tag{22}$$

4. **The Coordination Control Strategy Design.** In order to realize the coordination control strategy, the coordination functions are designed to change the control strength of signal controller and energy controller over time. When the motor starts, the control strength of signal controller is much bigger than the control strength of energy control. Therefore, the system can reach its steady state quickly. As time goes on, the percentage of energy control strength will increase. The total loss of the system is optimized at the steady state.

The coordination function can be designed as

$$c_{sd}(t) = e^{-t/T_c}, \quad c_{ed}(t) = 1 - e^{-t/T_c}, \quad c_{sq}(t) = e^{-t/T_c}, \quad c_{eq}(t) = 1 - e^{-t/T_c} \tag{23}$$

where T_c is the coordination time constant. Obviously, $c_{ed}(t) \in [0, 1]$, $c_{sd}(t) \in [0, 1]$, $c_{eq}(t) \in [0, 1]$, $c_{sq}(t) \in [0, 1]$. Therefore, the coordination strategy is

$$\begin{cases} u_d = c_{sd}(t) u_{sd} + c_{ed}(t) u_{ed} \\ u_q = c_{sq}(t) u_{sq} + c_{eq}(t) u_{eq} \end{cases} \tag{24}$$

5. **System Simulation.** The simulation results are performed by Matlab/Simulink. The parameters of the system are: Φ is 0.0844Wb, n_p is 3, R_s is 2.21Ω, $L_d = L_q$ is 9.77mH, $L_{md} = L_{mq}$ is 8mH, $L_{ld} = L_{lq}$ is 1.77mH, and J_m is 0.002kg $\cdot$ m^2. The desired rotor angular speed reference is ω_0 = 150rad/s, and the load torque is τ_L = 5N $\cdot$ m. Let k_1 = 10000, k_2 = 10000, k_3 = 500, k_4 = 500, k_5 = 5000 and T_c = 1. The switching frequency of SVPWM is 10kHz, and V_{dc} = 400V.

Figure 2 and Figure 5 show that the backstepping control system with high loss power has fast dynamic response without steady-state error. Figure 3 and Figure 5 show that the PCH control system with lower loss power responds more slowly. From Figure 2 and Figure 4, we can see that the dynamic response of the coordination control system is nearly as fast as the dynamic response of backstepping control system. According to Figure 4 and Figure 5, the coordination control system has the lower loss power at the steady state, just like the PCH control system. Therefore, the coordination control system has fast dynamic response and lower energy consumption at the steady state, which combines the advantages of both methods.

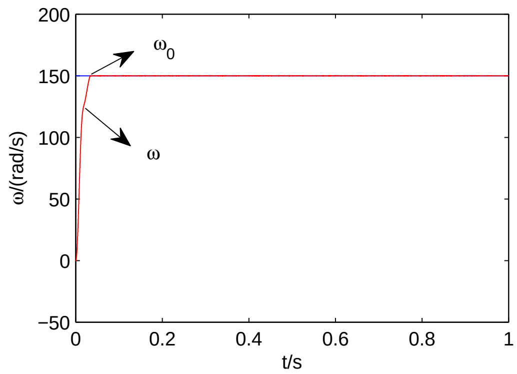

FIGURE 2. Speed curve of backstepping

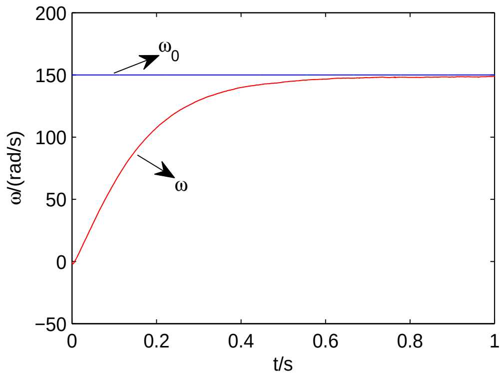

FIGURE 3. Speed curve of PCH

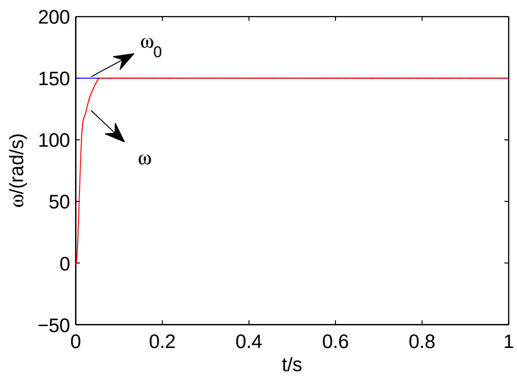

FIGURE 4. Speed curve of coordination

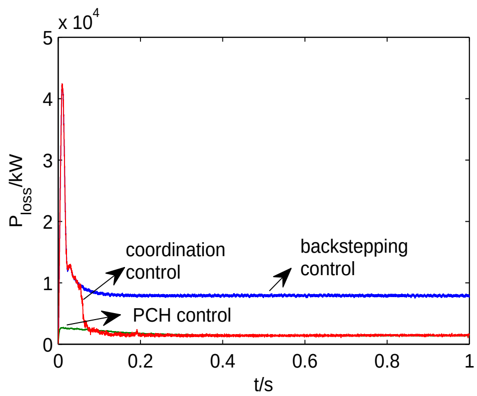

FIGURE 5. Loss power comparison

6. **Conclusions.** The signal and energy coordination control of PMSM including iron loss is designed in this paper. The backstepping control system has good dynamic performances, and the PCH control system of PMSM energy optimizing reaches its minimum loss. In addition, the backstepping control plays an important role when the motor starts. The PCH control plays an important role at the steady-state of the system. The advantage of each control does make sense when it is operating. The proposed control method has good application value and practical significance. In the follow-up study, a parameter identification module will be designed to identify the parameter variation of motors. The

coordination control strategy can be changed to inject signal control as soon as the parameter change is detected. The dynamic and steady state performances can get further optimization.

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REFERENCES

[1] J. Bai, C. Teng and Y. Du, Comparison of control strategies for permanent magnet synchronous motor, *Control Engineering of China*, vol.22, no.3, pp.490-494, 2015.

[2] O. Ouledali, A. Meroufel, P. Wira et al., Direct torque fuzzy control of PMSM based on SVM, *Energy Procedia*, vol.74, pp.1314-1322, 2015.

[3] T. Lu, H. Yu, B. Shan et al., Adaptive sliding mode maximum torque per ampere control of permanent magnet synchronous motor servo system, *Control Theory & Applications*, vol.32, no.2, pp.251-255, 2015.

[4] 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.

[5] W. Pei, X. Fu and C. Zhang, Feedback passive Hamilton control for dynamic equilibrium points of induction motors for electric vehicles, *Control Theory & Applications*, vol.30, no.9, pp.1138-1143, 2013.

[6] J. Sun, C. Zhang, W. Pei, N. Cui and K. Li, Hamiltonain stabilizing control of permanent magnet synchronous motor considering iron loss for electric vehicle, *Control and Decision*, vol.27, no.12, pp.1899-1906, 2012.

[7] B. Shan, H. Yu and J. Yu, Position control of the permanent magnet synchronous motor based on backstepping method and load torque observer, *ICIC Express Letters*, vol.7, no.3, pp.735-740, 2013.

[8] W. Pei, C. Zhang, N. Cui, Q. Han and K. Li, Loss-minimization Hamilton control of induction motor for electric vehicles, *Electric Machines and Control*, vol.16, no.4, pp.1-7, 2012.

[9] P. Cui and K. Zhao, Minimum-loss speed control of surface-mounted permanent magnet synchronous motor, *Electric Machines & Control Application*, vol.33, no.11, pp.35-38, 2006.

[10] H. Yu, J. Yu and X. Liu, Passivity-based control of PMSM based on state error PCH method and PI regulation, *ICIC Express Letters*, vol.5, no.8, pp.2811-2816, 2011.

[11] L. Yang, X. Chen and R. Wang, New loss minimization control of PMSM and an iron loss resistance identification method, *Electric Drive*, vol.43, no.12, pp.3-6, 2013.