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Signal processing and energy transformation-based cooperative control for PMSM servo systems

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With the advancement of science and technology, for servo-drive devices, particularly permanent magnet synchronous motor (PMSM) servo systems, in practical applications, ensuring fast response speed, high tracking accuracy, strong robustness, and high safety in high-performance control has consistently been a critical research focus from the perspective of performance requirements [1, 2]. However, the PMSM servo systems is a strongly coupled multi-variable nonlinear system, inevitably affected by various uncertainties [3, 4]. Moreover, the input-voltage saturation constraint can be treated as an input saturation problem. If the control input exceeds the inverter's voltage limit, it will cause negative phenomena such as decreased system control performance or even instability. Therefore, ensuring both trajectory tracking and disturbance suppression under the input-voltage saturation constraint of PMSM servo systems is a challenging problem that deserves further research.

Currently, most methods for addressing the aforementioned problem primarily rely on signal processing-based control, which assumes that PMSM servo systems are signal processing devices that convert input signals into output signals. The control goal is to quickly reduce or eliminate the trajectory signal errors of the system. Moreover, from the perspective of energy transformation-based control, PMSM servo systems are considered energy transformation devices that convert input energy into output energy, thereby optimizing input energy, output energy, and energy dissipation control. Therefore, the essence of the aforementioned problem can be fully revealed only by jointly considering trajectory signal processing and energy transformation within a cooperative control strategy for PMSM servo systems.

In this work, a smooth convex combination mechanism-based cooperative control strategy is designed, which fully draws on the advantages of signal processing-based control and energy transformation-based control, simultaneously achieving fast dynamic trajectory signal regulation, accurate trajectory tracking, and energy optimization control.

Problem description. In the *d*-*q* synchronous rotating coordinate of the PMSM servo systems, the relevant dynamic model is expressed as follows [1, 2]:

$$\begin{cases} L_{dt}\frac{\mathrm{d}i_d}{\mathrm{d}t} = -R_{st}i_d + n_p\omega L_{qt}i_q + Sat(u_d) + d_{ex1}, \\ L_{qt}\frac{\mathrm{d}i_q}{\mathrm{d}t} = -R_{st}i_q - n_p\omega L_{dt}i_d - n_p\omega\Phi_t + Sat(u_q) + d_{ex2}, \\ \frac{2}{3}J_{mt}\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{2}{3}\tau_e + d_{ex3}, \end{cases} \tag{1}$$

where i_d and i_q denote the stator currents in the *d*-*q* axis. ω represents the mechanical angular velocity of the motor. n_p indicates the number of pole pairs. u_d and u_q denote the stator voltages in the *d*-*q* axis, and $Sat(u_d)$ and $Sat(u_q)$ represent the control input signals with the voltage saturation constraint. Furthermore, $L_{dt} = L_d + \Delta L_d$, $L_{qt} = L_q + \Delta L_q$, $J_{mt} = J_m + \Delta J_m$, $\Phi_t = \Phi + \Delta\Phi$, and $R_{st} = R_s + \Delta R_s$ denote the *d*-*q* stator inductance, moment of inertia, rotor flux, and the per-phase stator resistance of the motor at run time, respectively. ΔL_d, ΔL_q, ΔJ_m, $\Delta\Phi$, and ΔR_s indicate the perturbation variations of the system's nominal parameters L_d, L_q, J_m, Φ, and R_s, respectively. τ_f, τ_L, and τ_e ($\tau_e = \frac{3}{2}n_p\{(L_{dt} - L_{qt})i_d i_q + \Phi_t i_q\}$) represent the friction torque, load torque, and electromagnetic torque, respectively. d_{ex1}, d_{ex2}, and d_{ex3} ($d_{ex3} = -\frac{2}{3}(\tau_f + \tau_L)$) denote the external disturbances.

This study considers the PMSM servo systems with the input saturation constraint and the unknown external load disturbance to be a multi-port signal processing and energy transformation device, and establishes its dynamic model as follows:

$$\dot{x} = f(x, p) + g\rho(u) + f_d, \tag{2}$$

where $x = [x_1, x_2, x_3]^{\mathrm{T}} = [L_d i_d, L_q i_q, 2/3 J_m\omega]^{\mathrm{T}}$ denotes the state vector, $f(x, p)$ represents the n-dimensional smooth vector field with perturbation parameters p, $\rho(u) = [\rho_1(u_1), \rho_2(u_2)]^{\mathrm{T}}$ indicates the smooth saturation approximation function, $Sat(u) = \rho(u) + S(u)$, $Sat(u) = [Sat(u_d), Sat(u_q)]^{\mathrm{T}}$ refers to the control input with voltage saturation constraint, $S(u)$ stands for the approximation error, $u = [u_d, u_q]^{\mathrm{T}}$ denotes the practical control input signal, and $\Delta u = \rho(u) - u$ denotes control input deviation caused by saturation. $f_d = gS(u) + d_{ex}$, $d_{ex} = [d_{ex1}, d_{ex2}, d_{ex3}]^{\mathrm{T}}$ represents the unknown external disturbance.

The aforementioned problems of model parameter perturba-

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tions, unknown external disturbances, and input-voltage saturation constraints in the PMSM servo systems are discussed next.

Control system design. To address the noise impact of the measurement signals, we introduced a new filtering error variable as $\varepsilon = e+\gamma\int_0^t e\mathrm{d}\tau$, where $e = x-x_0-\chi$ denotes the trajectory tracking error, x_0 represents the desired trajectory tracking signal, and γ refers to the designed parameter. χ denotes the auxiliary vector, and the following standard auxiliary system-based anti-saturation constraint compensation mechanism is structured to handle the input-voltage saturation as follows:

$$\dot{\chi} = -\ell\chi + g\Delta u, \tag{3}$$

where $\ell = \mathrm{diag}\{\ell_1, \ell_2, \ell_3\}$, ℓ_i denotes a positive parameter.

(1) Principle of cooperative control. Herein, we design a cooperative control strategy to achieve the following: (i) fast trajectory signal regulation during dynamics, (ii) optimized energy dissipation control and accurate trajectory tracking during steady-state processes, and (iii) continuous smooth changes in control variables during full operation.

The cooperative control controller u is composed of a convex combination mechanism with the signal processing-based controller u_S and the energy transformation-based controller u_E, whose form is designed as follows:

$$gu = C_S g u_S + C_E g u_E, \tag{4}$$

where $C_S + C_E = I$, I is a unit matrix. $C_S = \mathrm{diag}\{c_{S1}, c_{S2}, c_{S3}\}$ and $C_E = \mathrm{diag}\{c_{E1}, c_{E2}, c_{E3}\}$, c_{Si} and c_{Ei} are smooth switching functions to be designed, $0 \leqslant c_{Si} \leqslant 1$, $0 \leqslant c_{Ei} \leqslant 1$, $i = 1, 2, 3$.

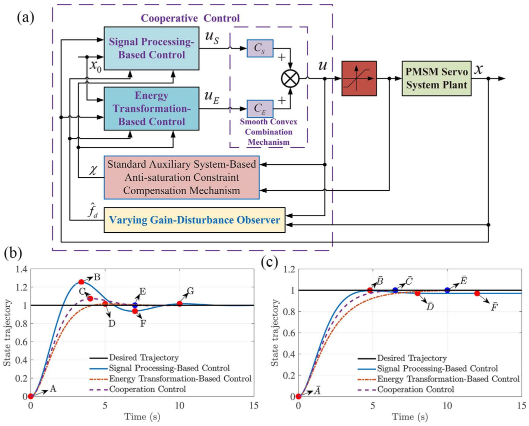

Figure 1 (Color online) The principle of cooperative control. (a) Cooperative control scheme; (b) response of underdamped processes; (c) response of overdamped processes.

Remark 1. Consider the response of the step function signal in both underdamped and overdamped processes as a case study to analyze the working principle of the cooperative control scheme based on the trajectory error and its rate of change. Figure 1 shows that this scheme is more adept at responding to variations in system states, enabling rapid adjustment of the trajectory signal during dynamic processes and precise trajectory tracking during steady-state processes. The detailed analysis is presented in Appendix C.1.

(2) Varying gain-disturbance observer. To further improve the system's anti-disturbance performance, a novel varying gain-disturbance observer (VGDO) is designed to estimate the unknown external disturbance f_d and compensate for it in the system. Furthermore, the VGDO serves as a solution to the well-known trade-off between estimation accuracy and transient spikes/noise amplification by high-gain observers.

On the basis of (2), the form of VGDO is constructed as

$$\begin{aligned} &\hat{f}_d = \Xi + \Psi(\varepsilon),\\ &\dot{\Xi} = -\hbar\Xi - \hbar(\Psi(\varepsilon) + f(x) + \gamma e - \dot{x}_0 + \ell\chi + gu), \end{aligned} \tag{5}$$

where $\hat{f}_d$ denotes the estimated vector of disturbances f_d, and Ξ represents the auxiliary variable of the designed VGDO.

The nonlinear function $\Psi(\varepsilon)$ and error-based time-varying gain matrix $\hbar$ are designed as follows:

$$\Psi(\varepsilon) = \hbar\varepsilon, \tag{6}$$

where $\hbar = \mathrm{diag}\{\hbar_1, \hbar_2, \hbar_3\}$, $\hbar = \hbar_c(\hbar_m + C_S)$, $\hbar_c = \mathrm{diag}\{\hbar_{c1}, \hbar_{c2}, \hbar_{c3}\}$ determines the adjustment rate of gain matrix $\hbar$, $\hbar_m = \mathrm{diag}\{\hbar_{m1}, \hbar_{m2}, \hbar_{m3}\}$ represents the minimum gain value of gain matrix $\hbar$, $\hbar_{ci} > 0$, $0 < \hbar_{mi} \leqslant 1$, $0 < \hbar_i \leqslant 2\hbar_{ci}$. The detailed analysis is presented in Appendix C.2.

The detailed design of the signal processing-based controller u_S and the energy transformation-based controller u_E is presented in Appendixes C.3 and C.4, respectively.

Stability analysis.

Theorem 1. For the system (2), we chose a standard auxiliary system-based anti-saturation constraint compensation mechanism (3), a smooth convex combination mechanism (4), VGDO (5), signal processing-based control, and energy transformation-based control, such that the error variable ε ultimately converges to a sufficiently small neighborhood of the origin, and all signals in the closed-loop system are uniformly bounded ultimately. The detailed proof of Theorem 1 is presented in Appendix D.

Experimental results. The detailed experimental results under different conditions are presented in Appendix E.

Conclusion. In this study, we consider an uncertain PMSM servo systems with input-voltage saturation constraints, parameter perturbations, and unknown external load disturbances to be a multi-port signal processing and energy transformation device. A smooth convex combination mechanism-based cooperative control strategy has been designed, which fully draws on the advantages of signal processing-based control and energy transformation-based control, simultaneously achieving fast dynamic trajectory signal regulation, accurate trajectory tracking, and energy dissipation optimization. The standard auxiliary system-based anti-saturation constraint compensation mechanism and error-based VGDO effectively handle the impact of the input-voltage saturation constraints and external load changes. Finally, the experimental results of the PMSM servo systems under different external load disturbances illustrate the efficacy of the proposed strategy.

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Supporting information Appendixes A–E. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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