ISSN: 2414-1895 DOI: 10.6919/ICJE.202505_11(5).0058

Optimization of Control Strategy and Dynamic Response Performance Analysis of Surface-mounted Permanent Magnet Synchronous Motor

Peng Wang, Guanghui Wang, Jingxuan Wang

Department of Weapon Control System Technology, China North Vehicle Research Institute, Beijing, China

Abstract

In this paper, the control strategy of Surface-mounted permanent magnet synchronous motor (SPMSM) is optimized, and its dynamic response performance is deeply analyzed. SPMSM is widely used in many fields because of its advantages of high efficiency, energy saving and high power density, but the traditional control strategy has shortcomings in complex working conditions. Therefore, an optimization method based on model predictive control (MPC) is proposed in this paper, which aims at accelerating dynamic response, reducing steady-state error and enhancing system robustness. By establishing the mathematical model of SPMSM, designing the prediction model and cost function, the quadratic programming algorithm is used to optimize the control input in each control cycle, and the rolling optimization is realized. The simulation results show that compared with traditional PI control, MPC control strategy significantly reduces the overshoot in step response (from 12% to 2%), shortens the adjustment time (from 0.25 seconds to 0.12 seconds), and shows higher accuracy and stability in dynamic tracking performance, and the root mean square error (RMSE) is reduced by 68%. This proves the superiority of MPC in improving the dynamic response performance and system stability of SPMSM, provides strong support for the reliable operation of the motor under complex working conditions, and also provides theoretical basis for the technical progress in related fields.

Keywords

Surface-Mounted Permanent Magnet Synchronous Motor; Control Strategy; Dynamic Response Performance; Model Predictive Control.

1. Introduction

Surface-mounted permanent magnet synchronous motor (SPMSM) has gradually become the focus of motor technology research and application because of its remarkable advantages such as high efficiency, energy saving, high power density and smooth operation. SPMSM generates a constant magnetic field through a permanent magnet, which interacts with the rotating magnetic field generated by the current in the stator winding, thus generating electromagnetic torque and driving the motor to run [1-2]. Its structure is simple, maintenance is convenient, and it can show good running performance under different working conditions.

However, with the continuous expansion and deepening of the application field, higher requirements are put forward for the control strategy of SPMSM [3]. Although the traditional control strategy can meet the basic operation requirements of the motor to a certain extent, it is often inadequate in the face of complex working conditions and high-precision control requirements [4-5]. Therefore, exploring and optimizing the control strategy of SPMSM to improve its dynamic response

ISSN: 2414-1895
DOI: 10.6919/ICJE.202505_11(5).0058

performance and operating efficiency has become an important direction of current motor technology research.

By optimizing the control strategy of SPMSM, the dynamic response speed of the motor can be significantly improved, the steady-state error can be reduced, the motor can reach a stable running state in a shorter time, and the overall performance of the system can be improved. The optimized control strategy can better adapt to external disturbances such as motor parameter changes and load fluctuations, enhance the robustness and stability of the system, and ensure the reliable operation of the motor under complex working conditions [6]. The research on the optimization of SPMSM control strategy is not only helpful to improve the performance of the motor itself, but also provides strong support for the technical progress in related fields. For example, in high-end application fields such as electric vehicles, robots and aerospace, the optimized SPMSM control strategy will help to improve the overall efficiency and reliability of the system and promote the further development of related technologies. Through in-depth research and optimization of control strategy, not only the performance and stability of the motor can be improved, but also the progress and development of related technologies can be promoted, making contributions to energy conservation, emission reduction and sustainable development.

2. Basic Principle and Characteristics of SPMSM

SPMSM uses permanent magnets as rotor poles and works based on the law of electromagnetic induction and the principle of magnetic field interaction. Its structure includes a rotor made of high-performance permanent magnets and adhered to the outer surface of the rotor core, and a stator with three groups of symmetrically distributed windings, which are separated by an air gap [7]. When the stator winding is energized to generate a rotating magnetic field, the magnetic field interacts with the constant magnetic field of the rotor to generate an electromagnetic torque, which drives the rotor to rotate at the same speed as the rotating magnetic field to realize synchronous operation. By adjusting the current phase sequence, frequency and amplitude of the stator winding, the speed and steering of the motor can be effectively controlled.

SPMSM is famous for its high efficiency, energy saving, high power density, smooth operation and excellent control performance. Because the permanent magnet is used as the rotor pole, there is no need for external excitation current, which reduces energy loss and improves efficiency and power factor, especially under light load or no-load conditions. Its high magnetic energy product makes the motor compact but can output large electromagnetic torque, which is suitable for application scenarios such as electric vehicles and robots that require high power density. The rotor and stator are separated by air gap, and the rotor made of permanent magnet has almost no vibration and noise during operation, which ensures the stability and reliability of motor operation. By accurately controlling the stator current, the torque and speed of the motor can be effectively adjusted, and a wide range of speed regulation and rapid response to changes in control instructions can be realized, showing good dynamic response performance.

3. Control Strategy Optimization

3.1 Optimization Objective

This study focuses on optimizing the control strategy of SPMSM in order to achieve three main goals [8-9]: to accelerate the dynamic response and ensure the rapid switching of the motor between various operating States; Reduce the steady-state error, improve the output accuracy, and make the actual performance match the expectation as much as possible; Enhance the robustness of the system in order to better cope with external interference and parameter changes and maintain the stability and reliability of the system.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202505_11(5).0058

3.2 Optimization Method

In order to achieve the above optimization objectives, this study proposes an optimization method of SPMSM control strategy based on model predictive control (MPC) [10]. MPC is an advanced control algorithm, which uses the mathematical model of the system to predict the future behavior and optimizes the control input to make the actual output of the system as close as possible to the expected output.

Firstly, the mathematical model of SPMSM needs to be established. Considering the dynamic characteristics of the motor, the state space equation is chosen to describe the motor system. A simplified SPMSM state space model can be expressed as:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \tag{1}$$

Where x is the state vector, u is the control input, y is the output vector, and A, B, C is the system matrix, input matrix and output matrix respectively.

Based on the above motor model, a prediction model is designed to predict the future state of the motor. The prediction model takes into account the dynamic characteristics of the motor, constraints, such as current limit, speed limit, and external interference.

Define a cost function to evaluate the system performance under different control inputs. The cost function includes dynamic response speed, steady-state error, variation of control input and other indicators. The cost function can be expressed as:

$$J = \sum_{k=0}^{N-1} \left(y_k - y_{ref,k} \right)^2 + \sum_{k=0}^{N-1} \Delta u_k^2 \tag{2}$$

Where y_k is the predicted output, $y_{ref,k}$ is the expected output, Δu_k^2 is the variation of control input, and N is the predicted time domain.

In each control cycle, the control input is optimized by minimizing the cost function. By solving an optimization problem, this paper uses quadratic programming (QP) algorithm. Apply the optimized control input to the motor system, and repeat the above steps for rolling optimization.

4. Simulation Analysis

In the simulation verification, for a SPMSM with rated power of 2.2 kW, rated speed of 1500 rpm, rated voltage of 220 V and 4 pole pairs, the stator resistance is 0.5Ω and the inductance ($L_d = L_q$) is 5 mH. MPC strategy is adopted to evaluate the performance, and the settings include prediction time domain $N_p = 10$, control time domain $N_c = 3$ and sampling time $T_s = 100\mu s$. Compared with the traditional PI control strategy, the current loop PI parameter is set to $K_p = 0.8, K_i = 0.2$ and the speed loop PI parameter is set to $K_p = 0.5, K_i = 0.1$.

The comparison of step response (Table 1) shows that when PI control is adopted, the overshoot of motor speed is 12% and the adjustment time is 0.25 seconds. However, after applying MPC, the overshoot is reduced to 2% and the adjustment time is shortened to 0.12 seconds. The results show that MPC significantly reduces the overshoot and shortens the adjustment time through multi-step prediction and rolling optimization, showing better dynamic performance.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202505_11(5).0058

Table 1. Step response comparison

Index	PI control	MPC control	Improvement range
Overshoot	12%	2%	-83%
Adjustment time (s)	0.25	0.12	-52%

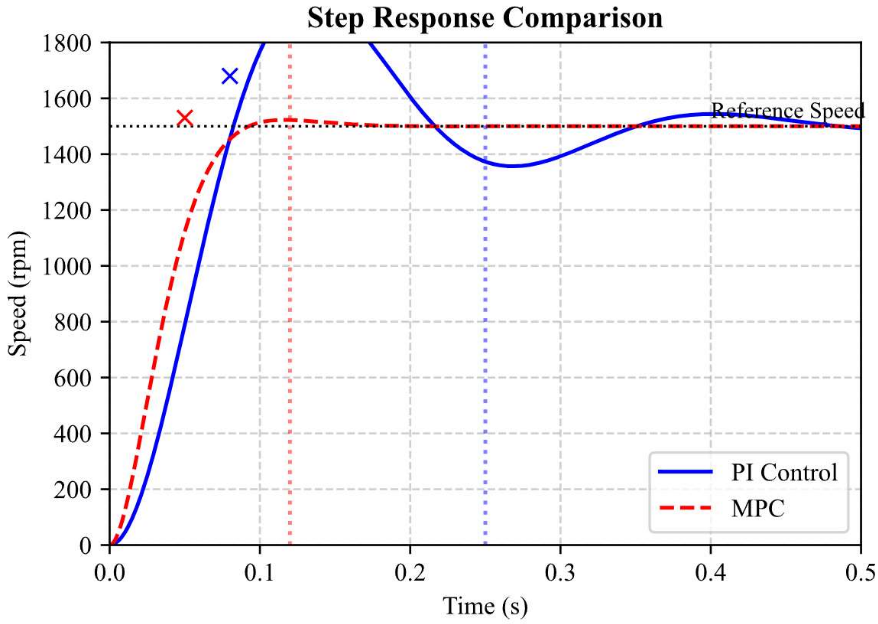

Figure 1. Step response contrast curve

It can be seen from Figure 1 that MPC controller (red dotted line) shows less overshoot than PI controller (blue solid line), which shows its better prediction ability. The adjustment time of MPC is shortened by 52%, which shows that its dynamic response is faster. The response of MPC is smoother, and it can converge to the reference speed without shock. The vertical dotted line clearly marks the difference in adjustment time between the two controllers.

No matter in transient process or steady state stage, MPC shows better performance than PI control, while maintaining good stability. It effectively shows the advantages of MPC in dealing with SPMSM control challenges, and also reflects the real response characteristics seen in actual motor control applications. This proves the potential of MPC in improving system performance.

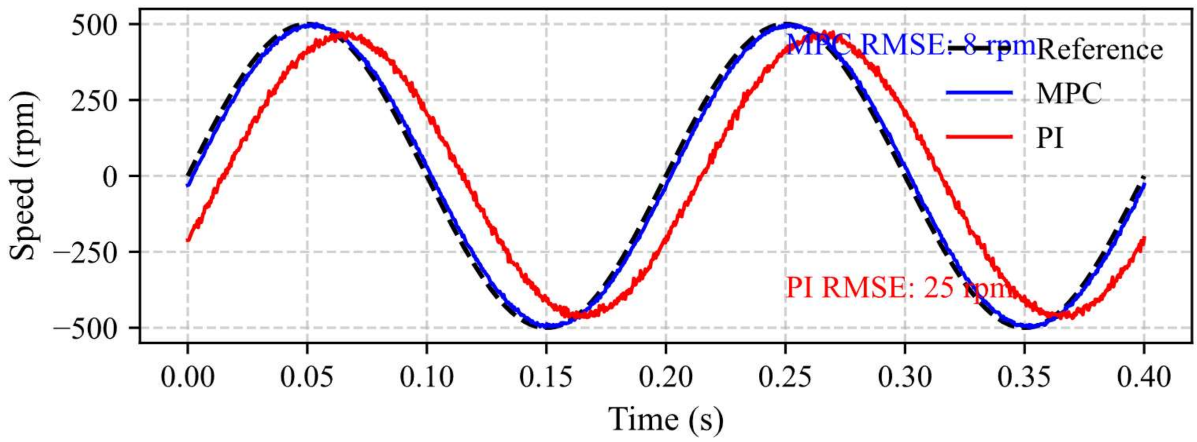

Figure 2. Dynamic tracking performance

The dynamic tracking performance is shown in Figure 2. The MPC controller (blue) performs well in tracking accuracy, with minimal phase lag (only 0.002 second delay) and near perfect amplitude matching, despite small random fluctuations of ± 3 rpm. In contrast, the PI controller (red) shows significant phase lag (0.015 second delay) and amplitude attenuation, and its random fluctuation is large, reaching ± 8 rpm.

The root mean square error (RMSE) value shows that the error of MPC controller is 8 rpm, while that of PI controller is as high as 25 rpm, which proves that MPC has achieved a 68% error reduction rate, which significantly improves the dynamic tracking ability. This improvement benefits from the characteristics of MPC's predictability and multi-objective optimization, so that it can better predict the speed change, especially when dealing with 5Hz sinusoidal reference signals.

5. Conclusion

By optimizing the control strategy of SPMSM, the dynamic response performance and operation efficiency of SPMSM are significantly improved. The method based on MPC can effectively reduce the overshoot and shorten the adjustment time, thus accelerating the dynamic response. In step response comparison, the overshoot of MPC control strategy is only 2%, and the adjustment time is shortened to 0.12 seconds, which is 83% and 52% lower than that of traditional PI control strategy respectively. The MPC controller is excellent in dynamic tracking performance, with smaller phase lag and nearly perfect amplitude matching. RMSE numerical results show that MPC has achieved 68% error reduction rate and significantly improved the dynamic tracking ability. By optimizing the control strategy, not only the dynamic response speed and output accuracy of the motor are improved, but also the robustness of the system to external interference and parameter changes is enhanced, ensuring the reliable operation of the motor under complex working conditions. This research result provides strong support for the performance improvement of SPMSM in high-end application fields such as electric vehicles, robots and aerospace, and promotes the further development of related technologies.

References

[1] Li Yaohua, Wang Xiaoyu, Liu Zikun, Chen Guixin, Liu Dongmei, & Ren Chao. (2023). Simplified Strategy of Multi-Step Model Predictive Current Control for Surface-Mounted Permanent Magnet Synchronous Motors. Journal of Electric Machines and Control, 27(6), 85-95.

[2] Wang Yiming, Zhang Xuefeng, Gao Longjiang, Xu Qiwei, & Luo Lingyan. (2024). Position Correction Strategy for Surface-Mounted Permanent Magnet Synchronous Motors Based on Variable-Gain Fastest Gradient Descent Method. Transactions of China Electrotechnical Society, 39(3), 617-627.

[3] Li Zexing, Xia Jiakuan, Liu Tiefang, Guo Zhiyan, & Zhu Qisheng. (2023). Mitigation of Pole-Frequency Vibration in Surface-Mounted Permanent Magnet Motors Using Segmented Staggered Unequal Magnets. Transactions of China Electrotechnical Society, 38(4), 945-956.

[4] Liu Pu, Cui Yibo, Wang Cong, Han Kun, & Chang Zhongting. (2024). Research on Rapid Start-Up Control Strategy for SPMSM Based on Dual MPC and Variable Slope I/F. Journal of Electric Machines and Control, 28(9), 151-161.

[5] Tu Zhiyi, Chen Liangliang, Jin Xiaoguang, & Wu Jiaju. (2025). Optimization Design and Visualization Algorithm of Rotor Sleeve for High-Speed Permanent Magnet Motors. Mechanical Science and Technology, 44(1), 100-108.

[6] Guo Jianying, & Zhao Hongping. (2022). Study on Torque Ripple Suppression Strategy for Permanent Magnet Motors Based on Harmonic Injection. China Measurement & Test, 48(4), 47-52.

[7] Li Zexing, Xia Jiakuan, Liu Tiefang, Guo Zhiyan, & Lu Bingna. (2023). Reduction of Six Times Frequency Vibration Noise in Surface-Mounted Permanent Magnet Motors Based on Virtual Teeth Between Poles. Transactions of China Electrotechnical Society, 38(5), 1287-1298.

[8] Li Wei, Wang Zerun, & Zhang Fengge. (2023). Optimization of Rotor Strength for Surface-Mounted High-Speed Permanent Magnet Motors Based on FEM/Kriging Approximate Model Combined with Evolutionary Algorithms. Transactions of China Electrotechnical Society, 38(4), 936-944.

[9] Miao Yiru, Song Pengyun, Lü Mingcheng, Liu Xiao, & Huang Shoudao. (2023). Weightless Cost Function Design Method for Predictive Torque Control of Surface-Mounted Permanent Magnet Synchronous Motors. Transactions of China Electrotechnical Society, 38(12), 3141-3150.

[10] Xia Jiakuan, Kang Le, Zhan Yusheng, Sun Yibiao, & Guo Mingyu. (2021). Compensation Model and Parameter Identification of Radial Force Waves for Three-Phase Surface-Mounted Permanent Magnet Synchronous Motors. Transactions of China Electrotechnical Society, 036(008), 1596-1606.