

Optimization Design of Permanent Magnet Synchronous Motor Based on Multi-Objective Particle Swarm Optimization Algorithm

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Abstract: Permanent Magnet Synchronous Motors (PMSMs) are characterized by high power density, strong overload capability, high efficiency, and compact size. To enhance the torque performance of PMSMs, an optimization design method combining response surface model with Multi-Objective Particle Swarm Optimization (MOPSO) is proposed. First, the main dimensions of the motor are determined based on the requirements of the motor, followed by the selection of the structural type. The initial structural model of the motor is established using finite element software. Subsequently, sensitivity analysis is performed based on key dimensional parameters. Based on the sensitivity levels of these parameters, a response surface model is developed for highly sensitive parameters, and a multi-objective genetic optimization algorithm is applied for further optimization. Finally, a comparative analysis of the torque performance between the optimized and initial motor is conducted, demonstrating the effectiveness and feasibility of the proposed method.

Keywords: PMSMs; Multi-Objective Particle Swarm Optimization; Response Surface Methodology.

1. Introduction

Permanent Magnet Synchronous Motors (PMSMs), with their high efficiency, high power density, and excellent speed regulation performance, have become a core choice for electric vehicles and high-end industrial drives [1]. Their development aligns closely with the global trends of decarbonization and electrification. Driven by the rapid growth of new energy vehicles and the upgrading of industrial automation, the optimization design of PMSMs has become increasingly critical [2].

Traditional PMSMs design methodologies frequently emphasize singular performance objectives, typically employing parameter-sweeping techniques to maximize torque output or minimize electromagnetic losses [3]. While operationally straightforward, such single-objective approaches exhibit fundamental constraints in addressing interdependent performance characteristics, ultimately yielding suboptimal holistic motor performance.

Illustrative cases demonstrate these limitations: Study [4] prioritized exclusive torque density enhancement through empirical selection of geometric parameters, implementing iterative finite-element analysis via parameter scanning. This methodology proves ineffective in resolving multi-parameter coupling effects and possesses inadequate global exploration capability. Parallel research [5] concentrated on torque ripple attenuation through harmonic current optimization using genetic algorithms, achieving notable reduction in current harmonic amplitudes through phase-angle adjustments. For surface-mounted PMSMs, investigation [6] developed specialized permanent magnet configurations optimized via Taguchi methods, successfully improving operational smoothness while evaluating robustness against manufacturing variances.

Although single-parameter optimization offers implementation simplicity and computational efficiency for specific operational scenarios [7], its inherent inability to

coordinate conflicting performance objectives (e.g., torque density versus ripple suppression, efficiency versus overload capacity) renders it unsuitable for advanced applications. The emerging paradigm consequently shifts toward multi-objective optimization frameworks, enabling balanced consideration of competing performance metrics through systematic design space exploration and Pareto-optimal solution generation. This transition reflects the escalating complexity of contemporary PMSM applications demanding concurrent optimization of multiple performance indices.

This paper proposes a multi-objective particle swarm optimization method incorporating iterative considerations. The approach combines response surface model optimization with multi-objective optimization. Initially, correlation analysis is performed on the parameters to be optimized. Parameters showing high correlation with optimization objectives are then subjected to multi-objective optimization, and motor performance is subsequently validated through experimental tests.

2. Motor Structural Scheme Design

(1) Scheme analysis

Traditional industrial robot joint motors predominantly utilize DC motors or AC induction motors, which struggle to meet the demands of modern robotic joint motors in terms of power density, efficiency, and response speed [8]. To enhance the performance of robotic systems, PMSMs have gradually become the preferred choice in the intelligent era. Notably, surface-mounted permanent motors (SPMSMs) motors are widely adopted in robotic joint applications due to their high power density and reliability. These motors primarily include direct drive and indirect drive configurations. The indirect drive method involving reducers incorporates multiple transmission components such as gears, leading to energy loss, reduced efficiency, and potential compromise in control precision. Therefore, to achieve high-precision control in operational robotic motors, this study adopts a SPMSMs

motor solution capable of rapid response.

(2) Design requirements for permanent magnet synchronous motors in robotic applications

The project specifies the parameters of the permanent magnet synchronous motor as shown in Table 1,

Table 1. Main specifications of the PMSMs

Parameter	Value
voltage	24
rated speed	100
rated torque	14.5
rated current	14.3
stator outer diameter	208
rotor inner diameter	115

(3) Dimensions preliminary sizing of key dimensions

The key dimensions of a permanent magnet synchronous motor (PMSM), such as the stator inner diameter D_{il} and the stacked core length l_{ef} , significantly influence the motor's weight and torque output density. Thus, selecting appropriate key dimensions is critical. The preliminary sizing formula for these dimensions is given as follow[13]:

$$\frac{D_{il}^2 l_{ef} n}{P'} = \frac{60}{\pi^2 a_p' K_{Nm} K_{\omega} A B_{\delta}} = \frac{6.1}{a_p' K_{Nm} K_{\omega} A B_{\delta}} \quad (1)$$

n represents the rotor speed, P' represents the power, a_p' represents the pole arc coefficient, K_{Nm} represents the waveform coefficient, K_{ω} represents the winding coefficient, A represents the line load, and B_{δ} represents the air-gap magnetic flux density. By selecting the appropriate line load A and air-gap magnetic flux density B_{δ} , the main dimensions of the motor can be calculated using Equation (1).

(4) Pole-Slot combination design

Given the stringent requirement for stator yoke thickness in this design project, which must not exceed 6.85 mm, a 20-pole configuration is determined to be appropriate based on design experience. Concentrated windings exhibit shorter end-winding lengths and lower armature resistance compared to distributed windings, thereby enhancing the motor's overload capability. Furthermore, a near pole-slot combination is more effective in suppressing torque ripple. Consequently, a 20-pole/18-slot configuration is selected for the pole-slot combination.

(5) Basic parameters

The basic parameters of the PMSM prototype are shown in Table 2. The structural schematic of PMSMs is shown in Figure 1.

Table 2. Main specifications of the PMSMs

Parameter	Value
Outer diameter of stator /mm	208
Outer diameter of rotor/mm	143
Permanent magnet thickness /mm	5
Air gap length/mm	1
Slot opening width/mm	10
Slot wedge maximum width/mm	13
Slot bottom width/mm	21.2
Slot opening height/mm	1
Slot depth/mm	23
Rated speed/mm	400
Number of poles	20
Number of slots	18

3. The Application Value of Traditional Embroidery in Modern Fashion Design

To further enhance the motor's performance, this section

focuses on parametric optimization of the designed motor. Traditional single-parameter scanning methods are inadequate for accurately identifying the optimal solution that meets design requirements, and they suffer from drawbacks such as high computational load and low optimization efficiency. Therefore, this study integrates a response surface model with a multi-objective particle swarm optimization algorithm to rapidly optimize the motor and improve its overall performance. The optimization flowchart is illustrated in Figure 2.

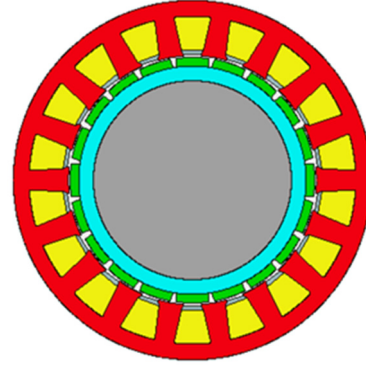


Fig 1. Structure of PMSM

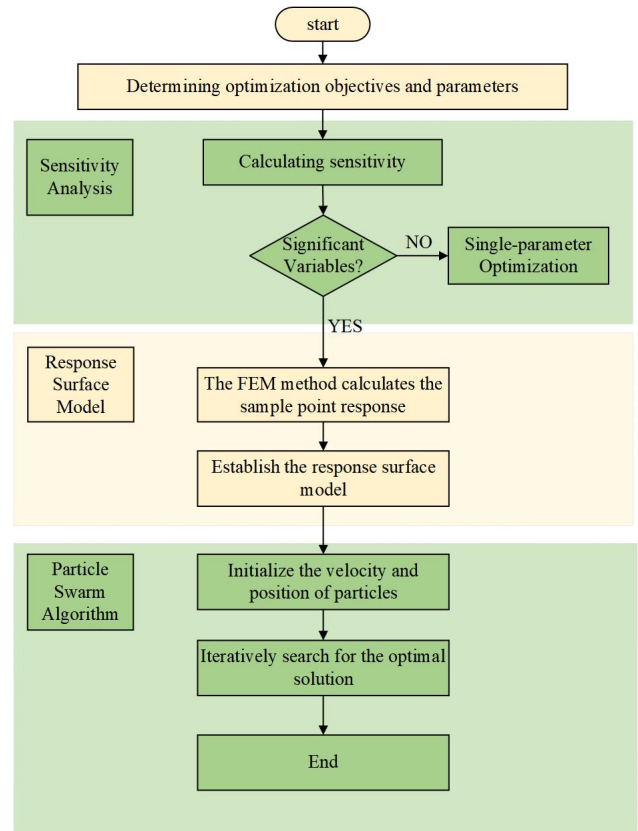


Fig 2. Multi-objective optimization design process

(1) Optimization parameters

To attain superior torque characteristics, the optimization objectives are defined as torque ripple and output torque (T_a). As summarized in Table 2, eight parameters associated with the stator and permanent magnets were identified as design variables to systematically analyze their influences on the target performance metrics. The predetermined feasible ranges of these parameters are specified in Table 2. Accordingly, the multi-objective optimization problem with its constraints is formulated as follows:

$$\min\{Tr, -T_a\}$$

$$\text{s. t. } \begin{cases} \text{Tr} \leq 0.02 \\ \text{Ta} \geq 10 \end{cases} \quad (2)$$

Table 3. Design variables definition of the PMSM

Description	Parameter	Range
Stator inner Diameter	D_1	140-148
Air gap length	D_2	0.5-1.5
Slot opening width	B_{s0}	7-12
Slot wedge maximum width	B_{s1}	11-15.5
Slot bottom width	B_{s2}	18.24-24.2
Slot opening height	H_{s0}	0.3-1.5
Slot depth	H_{s2}	18-27
Permanent magnet thickness	H_{pm}	3-7

(2) Sensitivity analysis

Given the initial set of eight optimization parameters for the motor, the multi-objective optimization space expands considerably. To streamline the design process, sensitivity analysis is first conducted to identify critical parameters. The sensitivity index of the optimization parameters is defined as follows:

$$\bar{S}_{ni}^m = \frac{\partial f}{\partial z_i} \Big|_{NOP} \frac{z_i}{f} \approx \frac{\frac{\Delta f}{f}}{\frac{\Delta z_i}{z_i}} \quad (3)$$

In the equation: Z_i represents the optimization parameters; f is the function of the optimization objective.

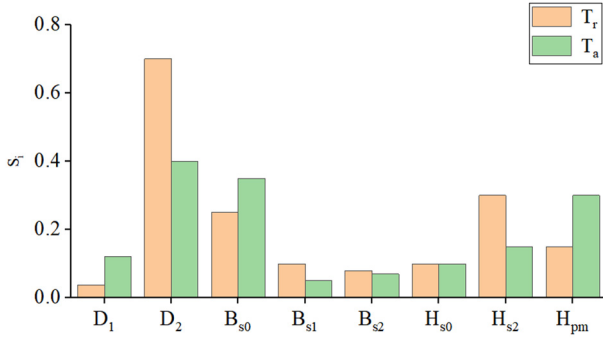


Fig 3. Sensitivity indices of the design variables

For enhanced comparability of parameter sensitivity indices, the sensitivity calculation results were normalized. As illustrated in Figure 3, parameters D_2 , B_{s0} , H_{s2} and H_{pm} demonstrate significantly higher sensitivity compared to other variables. It should be emphasized that this analysis represents local sensitivity characterization and cannot be extrapolated to the entire global design space.

(3) Response surface model

To enhance optimization efficiency, this study introduces a surrogate modeling approach—the response surface methodology. The Box-Behnken Design (BBD) method has gained widespread adoption in constructing response surface models due to its advantage of maintaining sampling points within specified boundaries. Essentially, BBD constitutes a three-level experimental design that integrates two-level fractional factorial components with one or more center points [14].

In this study, the BBD method enables the construction of response surface models for both optimization objectives with respect to the four design variables using merely 21 sampling points, substantially reducing computational requirements. Upon completion of data sampling, a second-order polynomial fitting function with appropriate accuracy and complexity is selected, yielding response surface models with determination coefficients all exceeding 0.9.

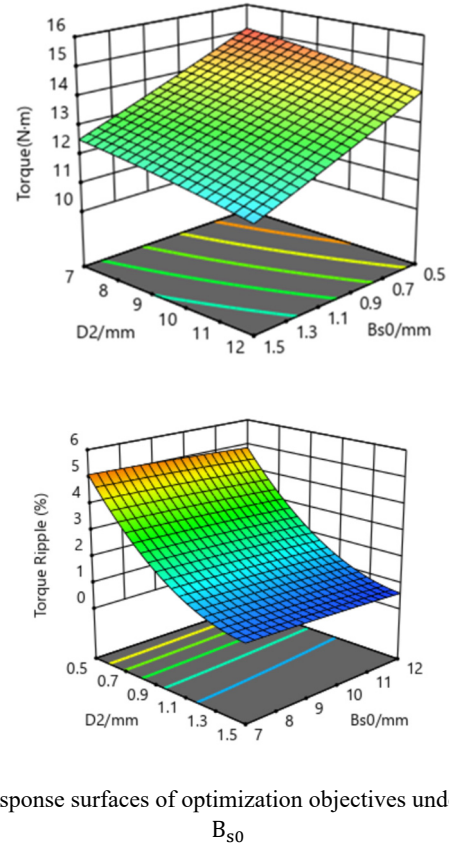


Fig 4. Response surfaces of optimization objectives under D_2 and B_{s0}

(4) Response surface model

Currently, numerous multi-objective optimization algorithms are extensively employed to address optimization challenges in engineering and scientific research [15]. The core principle involves achieving enhanced global optimization performance within a defined design space without degrading any objective function value. Among these approaches, the multi-objective particle swarm optimization algorithm has gained widespread application in engineering optimization due to its rapid convergence and high solution accuracy [16]. Consequently, this study employs this algorithm for motor optimization.

4. Experimental Results

The values of the motor optimization variables before and after optimization are given in Table 5. After obtaining the Pareto front, the optimal solution was selected corresponding to a torque ripple of 0.82% and an output torque of 15.52 N · m to achieve minimal torque ripple while maintaining satisfactory torque performance. The Pareto front is illustrated in Figure 6. The optimized motor demonstrates significant performance improvements compared to the initial design. Torque ripple decreases from 1.44% to 0.82%, representing a 43.1% reduction, while average torque increases from 13.24 N · m to 15.52 N · m, achieving a 17.22% enhancement. The values of the motor optimization variables before and after optimization are given in Table 2. Figure 5 illustrates the comparative torque performance before and after optimization.

Table 4. Design variables of initial and optimal designs

Parameter	Before Optimization	After Optimization
D_1	144	143
D_2	1	1.47
B_{s0}	10	7
B_{s1}	13	12.5
B_{s2}	21.2	21
H_{s0}	1	1
H_{s2}	23	22.9
H_{pm}	5	7

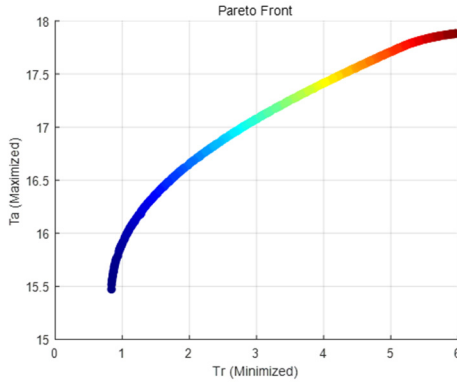
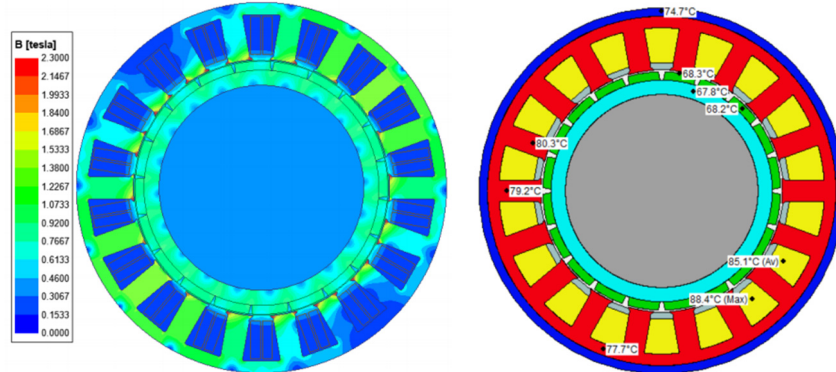
**Figure 5.** Pareto front

Figure 6 displays the magnetic flux density contour and

**Figure 6.** Magnetic flux density contour and temperature distribution under no-load conditions

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temperature distribution under no-load conditions. The results indicate that the maximum magnetic density in the stator teeth reaches approximately 1.4 T. Thermal analysis was performed for rated operation lasting 10 seconds at an ambient temperature of 40°C. Utilizing Class A insulation with a maximum allowable temperature of 105°C, the winding temperature remains within the safe operational limit.

5. Conclusion

The escalating requirements for high-performance motors have intensified the need for sophisticated design methodologies for permanent magnet synchronous machines, particularly regarding torque ripple mitigation and output torque enhancement. This investigation presents a novel two-stage optimization architecture tailored for robotic joint motor applications, combining sensitivity screening, response surface approximation, and multi-objective evolutionary algorithms. Comparative finite element simulations reveal substantial performance gains in the optimized configuration, with the final interior permanent magnet synchronous motor design exhibiting 43.1% lower torque ripple alongside 17.2% higher torque output relative to the baseline. These findings validate the proposed framework's efficacy in generating optimal electromagnetic designs, simultaneously advancing torque characteristics and optimization productivity for permanent magnet motor development, indicating strong industrial applicability.