Synergistic Optimization Design Method to Improve the Overload Capacity and Efficiency of Canned Permanent Magnet Synchronous Motor for Vacuum Pump

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Abstract: The efficiency and overload capacity are crucial performance factors during the design of the canned permanent magnet synchronous motors (CPMSMs) intended for driving vacuum pumps, due to their unique operational characteristics. The conventional multi-objective optimization design method is not suitable for the CPMSM due to the need to carefully consider additional influential factors, including the flat structure, eddy current losses in the cans, can thickness, and can material. To enhance the efficiency and overload capacity of the CPMSM, this paper introduces a synergistic optimization design approach that integrates the equivalent magnetic circuit method and the finite element method. A design example of a 1.5 kW CPMSM is presented, and experiments are performed to verify the effectiveness of the proposed method.

Keywords: canned permanent magnet synchronous motors; can loss; multi-objective optimization

1. Introduction

The vacuum pump without mechanical seal has recently gained research attention because of its advantages of easy maintenance, cleanliness, and leak-free operation. Due to the vacuum character, the canned motors are typically used as the prime mover of the vacuum pump. Several motor series have been designated for such applications, including induction motors [1], permanent magnet motors [2], and switched reluctance motors [3]. Considering the low efficiency of canned motors due to the can loss, permanent magnet motors have emerged as competitive candidates due to their advantages of not requiring additional excitation, having low losses, and high efficiency.

The losses (mainly attributable to the can loss) and overload capacity are important indicators for vacuum pump applications of the canned permanent magnet synchronous motor (CPMSM). The losses will affect temperature, thereby influencing the durability of the motor. During the stable operation of the vacuum pump, there may be an instantaneous increase in the leakage rate in the vacuum system due to mechanical or system failures. This sudden increase in load will cause the vacuum pump drive motor to operate in an overloaded state when its maximum output torque is lower than the load torque. It will cause motor slips, resulting in the loss of the vacuum environment and causing significant economic losses [4]. Therefore, it is necessary to study methods that consider reducing the can loss and improving motor overload capacity simultaneously at the design stage. However, recent research has focused on electromagnetic optimization design and reduction of the can loss.

In terms of the electromagnetic optimization design, the influence of time harmonics on the electromagnetic performance of the canned induction motor is analyzed [5]. Zhao H. et al. performed an electromagnetic optimization design on the canned induction motor using the field–circuit combined method, and experimental data showed effective suppression of the motor losses and noise [6]. Sato H. et al. proposed a multi-objective optimization method...
optimization method based on an adaptive neural network surrogate model. This method does not need to train data in advance, so it has the advantages of short time and high precision in the optimization process [7]. Zhao W. proposed a multi-objective optimization method based on a genetic algorithm, which was used to optimize the design of a 2 MW, 20,000 r/min PMSM from electromagnetic, thermal, and mechanical perspectives, achieving satisfactory motor performance according to all requirements [8]. In [9], a fully harmonic torque PMSM is proposed, and the research shows that this motor achieves 23% higher torque compared to the sinusoidally fed PMSM. Wong E. et al. integrated the finite element method and genetic algorithm to optimize the design of a surface-mounted PMSM. This approach aims to achieve maximum output torque, minimal torque ripple, and reduced usage of permanent magnets [10]. Jiwei C. et al. analyzed the relationship between the maximum electromagnetic torque and parameters of the PMSM under rated speed, identified factors influencing the maximum torque, and experimentally validated the accuracy of the maximum torque function [11].

In terms of the can loss reduction, Burkhardt Y. et al. have proposed using zirconia as a can sleeve to inhibit the can loss. However, due to poor thermal conductivity, the temperature of the zirconia can is respectively 13.0% and 15.8% higher compared to Hastelloy and austenitic stainless-steel cans under the same conditions, which could pose a hidden risk to the can performance and safe operation of the motor [12]. Yu Q. et al. studied the influence of the can material and thickness on the motor losses and output characteristics for a fractional slot concentrated winding CPMSM. The research results show that increasing the resistivity of the can material and reducing the can thickness can effectively reduce the can loss [13]. Gao L. et al. analyzed the influence of three can materials on the can loss of a megawatt-level double-canned motor. The research results show that using alloy steel with lower conductivity can reduce the can loss, increasing the motor efficiency from 46% to 68.75% [14]. Dolgirev et al. proposed using fine wire winding technology to manufacture a can sleeve composed of carbon fiber-reinforced polymers to reduce the can loss [15].

The previous work investigated various factors that affect the can loss and the overload capacity of the PMSM, including parameter influences, new structures, new materials, etc., as well as the resulting uncertainty in motor cost and performance. Unfortunately, these factors have been analyzed individually. However, certain electromagnetic design parameters may have an impact on the can loss and overload capacity of the CPMSM. Furthermore, it is necessary to explicitly consider power loss and overload capacity due to harsh operating environments and the use of inverters for power supply. Previous studies have found that for motors of a given volume, greater overload capacity can be achieved by selecting fewer turns to achieve smaller inductance and induced electromotive force. However, better power loss performance can be achieved by adopting the opposite approach [16]. These two objectives are contradictory, making it challenging to determine the optimal value for each parameter. Therefore, it is necessary to determine the optimal range for critical parameters to simultaneously satisfy both objectives within acceptable tolerances.

Therefore, this research presents a synergistic optimization design method to improve the overload capability and efficiency of the CPMSM for vacuum pumps, aiming to reduce the can loss and enhance the overload capability of the motor. The paper is organized as follows: The synergistic optimization design method is introduced to explain how to combine the two goals of maximizing efficiency and overload capacity, and how to achieve this method in Section 2; The optimized case is studied to explain how to apply the proposed design method to practical cases and demonstrate the results obtained in Section 3; The optimized design results are validated through finite element analysis and experiments to verify the effectiveness and superiority of the design method in Section 4.

2. Collaborative Optimization Design Method

This paper proposes a synergistic optimization design method that combines the equivalent magnetic circuit method and the finite element method to optimize the overload
capacity and efficiency of the CPMSM. A flowchart of the design process is shown in Figure 1.

**Figure 1.** Flowchart of the proposed optimal design process.

Firstly, the main dimensions and the feasible range of basic parameters of the CPMSM are determined by the magnetic circuit calculation program. Secondly, sensitivity analysis is used to determine key design parameters. Then, a response surface model is established using the finite element simulation data, and the key parameters are obtained using classical optimization methods. Finally, the obtained design parameters are verified using a two-dimensional finite element electromagnetic and thermal simulation. The process is detailed as follows:

Step 1: Based on the design requirements, the main parameters (such as stator inner and outer diameter, core length, electrical load, magnetic load, rated performance, etc.) are determined using the magnetic circuit method. Subsequently, considering the can loss and overload performance, a feasible range for the basic parameters (such as slot-pole combination, air-gap length, height of stator and rotor can, slot size, etc.) is provided. It is worth mentioning that at this step, only the fundamental and major harmonic components caused by saturation and slot openings are considered, and the supply remains a sinusoidal waveform.
Step 2: Due to the large number of design parameters involved in Step 1, directly applying an iterative multi-objective optimization algorithm will lead to challenging estimation of computational costs. Therefore, in this study, a sensitivity analysis of design parameters will be employed to understand the impact of uncertain factors on evaluation indicators, finding sensitive factors to prepare for the subsequent multi-objective optimization design of the CPMSM.

Step 3: Firstly, the data of the relationship between the sensitive factors determined in Step 2 and the motor target to be optimized are obtained by finite element analysis. Secondly, based on finite element simulation data, construct a surrogate model using response surface methodology to optimize and determine the structural dimensions of the electric machine. When the optimized results are consistent with the expected results, proceed to the next step; otherwise, adjust the main parameters of the motor and re-calculate.

Step 4: Perform a two-dimensional thermal analysis on the optimized design to examine whether the final design meets the temperature limitation. When the temperature calculation result is consistent with the expected result, the optimization design process ends; otherwise, update the parameters and re-calculate.

3. Optimization and Design Process

3.1. The CPMSM Design Requirements

A 1.5 kW CPMSM is taken as a design example. Considering the operating conditions of the CPMSM and vacuum pump, as well as installation space limitations, the design requirements are shown in Table 1.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage (V)</td>
<td>200</td>
<td>Stator outer diameter (mm)</td>
<td>107</td>
</tr>
<tr>
<td>Rated speed (r/min)</td>
<td>9000</td>
<td>Rotor inner diameter (mm)</td>
<td>38.5</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>70</td>
<td>Stator core length (mm)</td>
<td>25</td>
</tr>
<tr>
<td>Overload capability</td>
<td>3</td>
<td>Overload operation time (s)</td>
<td>60</td>
</tr>
</tbody>
</table>

According to Table 1, the rated speed of the CPMSM is 9000 r/min. Considering that the cost of the inverter is too high when the output frequency exceeds 500 Hz, and also the increase in rotor eddy-current loss, the range of pole numbers for this motor should be less than 8 to ensure that the output frequency of the inverter is less than 500 Hz. The following section will focus on the selection of pole numbers and slot combinations for the motor.

3.2. Pole-Slot Combination and Pole Structure Selection

The selection of the combination of the number of poles and slots in the motor will have a significant impact on the overall performance of the motor. When the number of poles in the motor is small, the number of slots in the motor is also relatively small, which leads to the inadequate utilization of the stator tooth; therefore, considering the structural characteristics of the motor studied in this paper, the number of poles in the motor should be more than 2.

The winding factors of various pole-slot combinations are different, and the no-load-induced electromotive force $E_0$ is related to the winding factor.

$$E_0 = 4.44 fNk_w\Phi$$  \hspace{1cm} (1)

where, $f$ is the current frequency, $N$ is the wingding turns per phase, $k_w$ is the winding factor, and $\Phi$ is the no-load main flux of air gap.

According to Zhang J. et al. [17], selecting a lower no-load-induced electromotive force $E_0$ during the PMSM design allows the motor to inject higher currents to improve overload capacity. Table 2 lists the winding factors commonly used in pole-slot combinations for motors.
Table 2. The wingding factor of the different pole–slot combinations.

<table>
<thead>
<tr>
<th>Poles</th>
<th>9</th>
<th>12</th>
<th>24</th>
<th>36</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.966</td>
<td></td>
<td></td>
<td>0.96</td>
</tr>
<tr>
<td>6</td>
<td>0.866</td>
<td></td>
<td></td>
<td>0.966</td>
</tr>
<tr>
<td>8</td>
<td>0.985</td>
<td>0.866</td>
<td></td>
<td>0.985</td>
</tr>
</tbody>
</table>

From the perspective of improving the maximum input current capability, selecting a pole–slot combination with a smaller winding factor can improve the torque overload capability of the CPMSM. From the perspective of reducing the can loss, selecting a combination with fewer poles can reduce the operating frequency of the CPMSM. Finally, after comprehensive consideration, the combination of poles and slots of the motor studied in this paper is selected as 6 poles and 9 slots.

To avoid the impact of armature reaction reactance on the motor overload capability, the motor used in this study adopts a surface-mounted rotor magnetic circuit structure. This structure has the advantages of easy installation and low cost.

3.3. Analysis of the Joint Influencing Factors of Can Loss and Overload Capacity

In the optimization design process of the CPMSM, to achieve high overload and low can loss, and ensure efficient and reliable operation, it is necessary to find the joint parameters that affect can loss and overload capability.

The can loss is generated by the eddy currents induced by the rotating magnetic field in the can sleeve. Under the assumptions of sinusoidal distribution of the magnetic field in the air gap and neglecting the end effects of the can sleeve, the calculation equation for the can loss is [18].

$$p_{\text{can}} = \frac{1}{2} \pi^3 D^3 f^2 B_m^2 \Delta \sigma$$  \hspace{1cm} (2)

where, $D$ is the inner diameter of the can sleeve, $L$ is the stator core length, $f$ is the rotation frequency of the air gap magnetic field relative to the stator can sleeve, $B_m$ is the amplitude of air gap flux density, $\Delta$ is the thickness of the can sleeve, and $\sigma$ is the conductivity of the can sleeve.

Next, we will analyze the relationship between the overload capacity of the CPMSM and design parameters. The electromagnetic torque of the CPMSM can be regarded as the result of the interaction between the armature reaction magnetic field and the permanent magnet excitation magnetic field, and it is determined by the magnitudes and relative positions of the two magnetic fields. The expression of the electromagnetic torque of the CPMSM in the d-q coordinate system is shown in Equation (3).

$$T_{\text{em}} = p [\psi_f i_q + (L_d - L_q) i_d i_q]$$ \hspace{1cm} (3)

where, $p$ is the pole pairs, $\psi_f$ is permanent magnetic flux linkage, $\psi_f = E_0 / \omega$, $i$ is the current, and $L$ is the inductance. The subscripts $d$ and $q$ represent the components of each physical quantity on the d-axis and q-axis, respectively:

$$\begin{cases} i_d = i_1 \sin \varphi \\ i_q = i_1 \cos \varphi \end{cases}$$ \hspace{1cm} (4)

where, $\varphi$ is the internal power factor angle of the motor.

When the rotor structure of the CPMSM is a surface-mounted structure, $L_d$ and $L_q$ are approximately equal, and Equation (3) can be expressed as Equation (5).

$$T_{\text{em}} = p [\psi_f i_q] = p \left( \frac{E_0}{\omega} i_1 \cos \varphi \right)$$ \hspace{1cm} (5)
Combining Equation (2) with Equation (5), the functional relationship between the can loss and the electromagnetic torque of the CPMSM can be obtained.

\[ T_{em} = \frac{pN\alpha_{p}k_{w}i_{1}}{\pi f} \cos \psi \sqrt{\frac{p_{can}L}{D\Delta\sigma}} \]  

Equation (6) reveals that there are numerous factors influencing the can loss and electromagnetic torque of a CPMSM, including the motor speed, number of turns, pole arc coefficient, winding coefficient, stator core length, inner diameter of the can sleeve, can sleeve thickness, and can sleeve conductivity. Therefore, the parameter selection for designing a high overload capacity and low can-loss CPMSM poses certain difficulties.

### 3.4. Parameter Sensitivity Analysis

The motor is a complex system with multiple variables, nonlinearity, and strong coupling [19]. It can be seen from Equation (6) that there are many design parameters that affect the overload capacity and can loss of the CPMSM. Faced with so many design parameters, if a simple multi-objective optimization algorithm is used for iterative optimization, the computational cost will be immeasurable. However, these parameters have different degrees of impact on overload capacity and can loss. Therefore, this paper uses sensitivity analysis to understand the sensitivity of the objective function and constraints to the change of decision variables and to find out the design parameters that have great influence on overload capacity and can loss, so as to better adjust the values of these parameters in the optimization process.

Six design parameters are selected as analysis variables respectively, and these parameters and their changing ranges are as follows: turns, with the range of 42–48; permanent magnet width (polar arc coefficient), which varies from 0.85 to 0.95; the can thickness varies from 0.3 to 0.7 mm; split ratio, which varies from 0.6 to 0.7; the thickness of the permanent magnet varies from 2.5 to 3.5 mm; and the tooth width varies from 9 to 11 mm. The process of sensitivity analysis is that by changing the above six design variables, the sensitivity of variables on motor performance indexes is calculated by the finite element method.

The sensitivity is calculated by

\[ S_{i} = \frac{F(x_0 \pm \Delta x_i) - F(x_0)}{\Delta x_i} \]  

where, \( x_0 \) is the initial parameter, \( \Delta x_i \) is the increment of design parameter \( x_i \), and \( F \) is the objective function.

These performance indexes include can loss, output torque, efficiency, power factor, and overload capacity. Figure 2 shows the sensitivity value of each design parameter to the objective.

When the sensitivity of the parameter is less than 1%, the parameter is determined as insensitive. When the sensitivity of the parameter is greater than 1% and less than 2%, the parameter is determined as a low-sensitivity parameter. When the sensitivity of the parameter is greater than 2%, the parameter is determined as a highly sensitive parameter.

Based on Figure 2, it can be seen that the sensitivities of permanent magnet thickness and width are less than 1%. Therefore, this study will not analyze and optimize these two design parameters, and their values will remain as the initial values. Conversely, the sensitivities of tooth width and can sleeve thickness are greater than 1% and less than 2%. On the other hand, the sensitivities of the remaining two design parameters, split ratio, and winding turns are greater than 2%, those have high sensitivity to the optimized performance. According to the above contents, sensitivity analysis can reduce the degree of freedom of optimization parameters, thus reducing the calculation cost in the optimization process and preventing over-fitting.
Figure 2. The sensitivity analysis results of design parameters.

When the sensitivity of the parameter is less than 1%, the parameter is determined as insensitive. When the sensitivity of the parameter is greater than 1% and less than 2%, the parameter is determined as a low-sensitivity parameter. When the sensitivity of the parameter is greater than 2%, the parameter is determined as a highly sensitive parameter. Based on Figure 2, it can be seen that the sensitivities of permanent magnet thickness and width are less than 1%. Therefore, this study will not analyze and optimize these two design parameters, and their values will remain as the initial values. Conversely, the sensitivities of tooth width and can sleeve thickness are greater than 1% and less than 2%. On the other hand, the sensitivities of the remaining two design parameters, split ratio, and winding turns are greater than 2%, those have high sensitivity to the optimized performance. According to the above contents, sensitivity analysis can reduce the degree of freedom of optimization parameters, thus reducing the calculation cost in the optimization process and preventing overfitting.

To determine the impact of tooth width and can sleeve thickness on individual objectives, an analysis was performed on their effects on motor performance. The results are shown in Figures 3 and 4.

Figure 3. The can loss and the power factor vary with the tooth width.

Figures 3 and 4 indicate that the can loss increases gradually with the width of the can sleeve. Increasing the thickness of the can sleeve enhances the motor overload capacity. Therefore, the thickness of the can sleeve is determined as 0.5 mm. However, the motor overload capacity increases with the increase in tooth width. The influence of tooth width on the can loss is not significant. Therefore, the tooth width of the motor is determined as 10 mm.
Figure 4. The can loss and the power factor vary with can thickness.

3.5. Establishment of Surrogate Model Based on Response Surface Methodology

The response surface surrogate model is the most commonly used interpolation fitting model. This method performs spatial modeling and prediction based on the covariance function random process or random field. It builds a more accurate surrogate model to replace actual computationally intensive experiments or simulations. It greatly saves time and costs for engineering and academic research [20]. Figure 5 provides a visual description of the process of establishing the surrogate model.

Figure 5. The building process of the surrogate model.

The steps to establish the surrogate model are as follows:

(1) Sampling: Within the variable range, a set of split ratios and turns are simulated by the finite element method as input parameters, and overload capacity and efficiency are used as output data.

(2) Establish a proxy model: The response surface method is a mathematical modeling and analysis method for approximating and optimizing complex systems, which is suitable for this kind of situation with multiple input parameters and multiple objectives to optimize product performance in this study. Therefore, the response surface method is used to fit the input and output data in step 1, and the surrogate model is established.
3.6. Optimal Design of the CPMSM Based on NSGA-II

Based on the previous research results of the CPMSM for vacuum pump and the design requirements, the optimal design function of the motor is determined as follows:

\[
\begin{align*}
\text{Objective}: & \quad \max(f_{k_T}(x_i), f_{\eta}(x_i)), \min(f_{p_{\text{can}}}(x_i)) \\
\text{Limitation}: & \quad k_T \geq 3, \eta \geq 70\%, p_{\text{can}} \leq 500\text{W} \\
\text{Variable}: & \quad D_{i1}, N
\end{align*}
\]

where, \(k_T\) is the overload capacity, \(\eta\) is the rated efficiency of the CPMSM, \(p_{\text{can}}\) is the can loss, \(D_{i1}\) is the stator inner diameter, and \(N\) is the number of winding turns.

Based on the established response surface model and optimization function, this study chooses the NSGA-II as the iterative optimization algorithm for the entire motor design process. The NSGA-II has been improved in the use of fast non-dominated sorting, genetic operations, and crowding distance to enhance the diversity and quality of the solution set. These improvements make NSGA-II an excellent multi-objective optimization algorithm with better effectiveness and performance compared to the NSGA [21]. Based on the NSGA-II, an optimization design of electrical machine parameters was performed, resulting in a Pareto frontier solution set as shown in Figure 6.

![Figure 6. The parallel coordinate system graph of Pareto solution set.](image)

It can be seen from Figure 6 that the Pareto front and approximate front are in good agreement, thus it is determined that the optimization result has converged [22]. In addition, Figure 6 indicates that after optimization design, the motor efficiency reaches 70%, and the rated torque can also meet the design requirements. The green dot in Figure 6 represents the selected optimal motor individual. Finally, a compromised optimal design point was selected, and its corresponding optimization result data is shown in Table 3.

**Table 3. The comparison of design parameters and results before and after optimization.**

<table>
<thead>
<tr>
<th>Item</th>
<th>Previous Value</th>
<th>Optimized Value</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator inner diameter (mm)</td>
<td>50.5</td>
<td>52.5</td>
<td></td>
</tr>
<tr>
<td>Winding turns</td>
<td>46</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Torque (N·m)</td>
<td>1.62</td>
<td>1.60</td>
<td>↓1.23%</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>68.3</td>
<td>71.16</td>
<td>↑4.19%</td>
</tr>
<tr>
<td>EMF (V)</td>
<td>72.88</td>
<td>64.85</td>
<td>↓11.02%</td>
</tr>
<tr>
<td>Overload capacity</td>
<td>2.2</td>
<td>3</td>
<td>↑36.36%</td>
</tr>
</tbody>
</table>

From Table 3, it can be seen that compared to the initial design, the motor overload capacity has increased from 2.2 to 3 after optimization, an increase of 36.36%. The motor
efficiency has improved from 68.3% to 71.16%, showing a 4.19% improvement. This is because the number of turns of the motor winding increases and the magnetic saturation of the motor decreases. The decrease in induced electromotive force in Table 3 also verifies this conclusion. In the CPMSM, the can loss accounts for a large proportion of the total loss. When the magnetic saturation of the motor decreases, the can loss decreases, which leads to an increase in the motor efficiency. In addition, increasing the inner diameter of the motor stator is beneficial to improve the overload capacity of the motor, but it will cause the motor efficiency to decrease. The decrease in efficiency caused by the increase of stator inner diameter is not as great as that caused by the increase in winding turns. In conclusion, the multi-objective optimization design of the CPMSM based on the NSGA-II has resulted in significant improvements in motor performances, confirming the effectiveness of the proposed optimization method.

4. Finite Element Simulation and Experimental Verification

4.1. Finite Element Verification

To demonstrate the effectiveness of multi-objective optimization design results, the can loss and efficiency of the motor before and after optimization were compared using the finite element method. According to the optimized motor design parameters, modify the finite element model, and simulate again to get the calculation results. Figure 7 shows the comparison of the can loss of the CPMSM.

![Figure 7. The comparison of can loss before and after optimization.](image)

From Figure 7, it can be seen that the can loss decreased from 551 W to around 390 W. Figure 8 shows the comparison of efficiency before and after optimization.

![Figure 8. The comparison of efficiency before and after optimization.](image)

It can be seen from Figure 8 that the rated efficiency of the motor is higher after optimization compared to the previous condition, which is consistent with the analysis of multi-objective optimization results.
4.2. Experimental Verification

To verify the results of this paper, a prototype was developed and an experimental platform was built, as shown in Figure 9.

![Diagram of the prototype and tested bench.](image)

In Figure 9, the experimental platform consists of the prototype, inverter, torque-speed tester, dynamometer and its controller, cooling equipment and its controller, adjustable temperature chamber, and various measurement devices such as power analyzer, oscilloscope, temperature monitor, and thermal imaging camera. The prototype inverter utilized is the Kewo AD800N. The power analyzer employed is Fluke NORMA5000, produced in Everett, USA, and the oscilloscope selected is Yokogawa DL750, produced in Yokohama, Japan.

The overload capacity of the prototype was tested using the experimental bench. To prevent the prototype damage caused by excessive temperature, the experiment was stopped when the value of the temperature monitor reached 150 °C. The test results of the motor overload capacity are shown in Figure 10.

![The comparison between the experimental and simulated values of the CPMSM overload capacity.](image)

It can be observed from Figure 10 that the output torque of the prototype is directly proportional to the current multiplier within the testing range. This indicates that the motor has a higher potential for overload when the motor temperature restrictions are ignored, or the motor cooling capability is improved. In addition, Figure 10 also provides the corresponding calculated values and a good consistency between the calculated and measured values can be observed through comparison.
5. Conclusions

Based on the analysis of the joint influencing factors of the can loss and overload capacity of the CPMSM for vacuum pump, a method combining field and circuit calculation is proposed to carry out the collaborative optimization design of the overload capacity and efficiency of the CPMSM for the vacuum pump. The obtained conclusions are as follows:

(1) There are many parameters that affect the can loss and electromagnetic torque of the CPMSM, among which the split ratio and the winding turns are more sensitive. Using the collaborative optimization design method proposed in this paper, the efficiency of the optimized motor is increased by 4.19%, and the overload capacity can meet the design requirements of the motor.

(2) The experimental results show that the optimized motor can meet the power demand of the motor when the vacuum pump is directly discharged into the atmosphere within the required overload operation time.

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