



Article Multi-Objective Optimization Design of a New Permanent Magnet Synchronous Motor Based on the Taguchi Method

Chunyu Qu, Ziqi Guo *, Yongzhuang Hu, Xiuping Wang and Fangxu Han

Abstract: To improve the performance and stability of the permanent magnet synchronous motor (PMSM), a new type of built-in permanent magnet synchronous motor (IPMSMB) is proposed. Firstly, the performance indexes of IPMSM, IPMSMA, and IPMSMB are compared by finite element analysis. The results show that the effective harmonic of the air-gap magnetic density of the motor increases when the rotor outer diameter is piecewise eccentric. At the same time, torque ripple and cogging torque decrease. Then the permanent magnet structure of the motor is changed on the basis of IPMSMA to form IPMSMB, which improves the output torque of the motor. Secondly, the Taguchi method is used to optimize the structural parameters of IPMSMB. After optimization, the output torque of IPMSMB is increased by 4.6%. The cogging torque and torque ripple are decreased by 45.5% and 25.7%, respectively. The consumption of permanent magnets is reduced by 7.74%. Finally, the rationality of the motor design is verified by the prototype experiment.

Keywords: permanent magnet synchronous motor; air gap flux density; cogging torque; torque ripple; structure optimization; prototype testing



Citation: Qu, C.; Guo, Z.; Hu, Y.; Wang, X.; Han, F. Multi-Objective Optimization Design of a New Permanent Magnet Synchronous Motor Based on the Taguchi Method. Energies 2022, 15, 7347. https:// doi.org/10.3390/en15197347

Academic Editors: Lorand Szabo and Feng Chai

Received: 10 September 2022 Accepted: 29 September 2022 Published: 6 October 2022

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1. Introduction

With the rapid development of the new energy vehicle industry, the permanent magnet synchronous motor for vehicles stands out among the electric vehicle drive motors due to its advantages of high power, high torque density, simple structure, and high reliability. At present, since pure electric passenger vehicles use permanent magnet synchronous motors as the main technical route, how to further improve their performance has become an important issue in the industry. In general, permanent magnet synchronous motors for electric vehicles need to have large starting torque, high power density, and small cogging torque and torque ripple [1-3]. It brings certain challenges to the structural design and optimization of permanent magnet synchronous motors for electric vehicles.

Reference [4] shows that the harmonic content in the air gap magnetic density can be reduced by optimizing the shape of the permanent magnet and the shape of the rotor surface core respectively, so as to effectively weaken the cogging torque, suppress torque ripple and improve the overall performance of the motor. Reference [5] proposes an asymmetric V-type built-in permanent magnet synchronous motor and carries out multiobjective optimization. The motor structure is shown in Figure 1. The results show that the improved asymmetric rotor structure can reduce torque ripple and improve torque density. In reference [6], the eccentric air gap is obtained by changing the shape of the pole shoe. The simulation results show that the air gap magnetic field waveform of the motor is improved. Reference [7] presents a segmented permanent magnet structure, which improves the electromagnetic torque of the motor. It also achieves a wide constant power speed range and shows good performance at high speed. Reference [8] proposes a method of adding auxiliary slots on the rotor surface to optimize the air-gap magnetic field of PMSM. The iron loss and torque ripple caused by harmonics are reduced. The performance of the motor is greatly improved. In reference [9], an IPMSM motor with a flared-shape rotor

School of Electric Power, Shenyang Institute of Engineering, Shenyang 110136, China * Correspondence: 13028279718@163.com

structure is proposed and compared with the basic IPMSM motor. Simulation results show that the proposed flared-shape IPMSM motor has higher efficiency, lower torque ripple, and higher reliability. In reference [10], each permanent magnet of the surface-mounted PMSM is divided into eight parts, which effectively reduces the cogging torque of this motor. In reference [11], holes are cut on the rotor surface of the IPMSM motor. Then the size, number, and position of holes are optimized. The results show that the cogging torque of the motor is reduced and the average torque is increased.



Figure 1. Schematic diagram of IPMSM.

In recent years, the Taguchi method proposed by Dr. Genichi Taguchi from Japan has been widely used in the field of motor optimization design. Although the Taguchi method is a local optimization method, its objective function is relatively simple to establish, the calculation period is short, and the optimal combination parameters for multi-objective optimization can be quickly and effectively searched. The optimization efficiency is high [12]. Reference [13] uses the Taguchi method to optimize the design of the magnetic pole parameters by taking the ratio of the electromagnetic torque pulsation of the motor to the average torque value and the levitation force pulsation and the average value of the levitation force as evaluation criteria.

To solve the problems of torque ripple and large cogging torque currently existing in the permanent magnet synchronous motor of electric vehicles and improve the running stability of electric cars. We propose a permanent magnet synchronous motor (IPMSMB) with a novel rotor structure and a novel permanent magnet topology. Compared with the basic IPMSM, IPMSMB increases the output torque of the motor and reduces the cogging torque and torque fluctuation of the motor under rated conditions. Finally, the rationality and feasibility of the motor structure design are verified by the experimental test of the prototype.

2. The Structure of the Motor

In this paper, an IPMSM with 3 phases, 8 poles, and 48 slots is selected as the research object, as shown in Figure 2. The basic design parameters of the IPMSMB designed in this paper are shown in Table 1.



Figure 2. Schematic diagram of IPMSM.

Table 1. The basic parameters of IPMSM.

Parameter	Symbol	Unit	Value
Rated power	Р	Kw	20
Rated voltage	U	V	380
Rated current	Ι	А	20
Frequency	f	Hz	100
Rotating speed	n	r/min	1500
Number of pole pairs	Р	-	4
Outer diameter of the stator	R_g	mm	185
Inner diameter of the stator	R_s	mm	132.6
Rotor outside diameter	R_o	mm	130.6
Inner diameter of the rotor	R_i	mm	40
Axial length of the iron core	La	mm	160
Length of single permanent magnet	h	mm	12.4
Thickness of single permanent magnet	d_1	mm	6

First, we eccentric the rotor outer diameter of the IPMSM in Figure 2 with an eccentricity of 9 mm, thus obtaining IPMSMA. Figure 3 shows the schematic diagram of the IPMSM and IPMSMA rotor structure. Figure 4 shows IPMSMA. Table 2 shows the basic parameters of IPMSMA.



Figure 3. (a) Rotor structure diagram of IPMSM; (b) rotor structure diagram of IPMSMA.



Figure 4. Schematic diagram of IPMSMA.

Table 2. The basic parameters of IPMSMA.

Parameter	Symbol	Unit	Value
Rated power	Р	Kw	20
Rated voltage	U	V	380
Rated current	Ι	А	20
Frequency	f	Hz	100
Rotating speed	n	r/min	1500
Number of pole pairs	р	-	4
Outer diameter of the stator	R_g	mm	185
Inner diameter of the stator	R_s	mm	132.6
Maximum value of rotor outer diameter	Romax	mm	131.5
Minimum value of rotor outer diameter	R _{omin}	mm	130.6
Inner diameter of the rotor	R_i	mm	40
Axial length of the iron core	La	mm	160
Length of single permanent magnet	h	mm	12.4
Thickness of single permanent magnet	d_1	mm	6

Then, we disassemble each integral permanent magnet of IPMSMA into two small permanent magnets of equal size. The width of each adjacent small permanent magnet becomes half of the original whole permanent magnet, which results in IPMSMB. The dotted line in Figure 5 is a single permanent magnet in IPMSMA. IPMSMB is formed by dividing a single permanent magnet equally at a certain angle on its wide side [14,15]. To provide a fair and reasonable comparison, all motor key parameters other than the air gap (inner and outer diameter, axial length, and stator slot width) are set equal. Figure 6 shows the structure of IPMSMB. Table 3 shows the basic parameters of IPMSMB.



Figure 5. Structure diagram of a single permanent magnet for IPMSMB.



Figure 6. Schematic diagram of IPMSMB.

Table 3. The basic parameters of IPMSMB.

Parameter	Symbol	Unit	Value
Rated power	Р	Kw	20
Rated voltage	U	V	380
Rated current	Ι	А	20
Frequency	f	Hz	100
Rotating speed	n	r/min	1500
Number of pole pairs	р	-	4
Outer diameter of the stator	R_g	mm	185
Inner diameter of the stator	R_s°	mm	132.6
Maximum value of rotor outer diameter	Romax	mm	131.5
Minimum value of rotor outer diameter	R _{omin}	mm	130.6
Inner diameter of the rotor	R_i	mm	40
Axial length of the iron core	L_a	mm	160
Length of single permanent magnet	h	mm	12.4
Thickness of single permanent magnet	d_2	mm	3

3. Electromagnetic Characteristic Analysis and Structural Parameter Optimization

Firstly, the structure of the IPMSM is optimized in this paper, and the outer diameter of the rotor of the IPMSM is designed by segmental eccentricity to form an uneven air gap. The structure of the non-uniform air gap can reduce the harmonic content of the air gap magnetic density, increase the effective harmonic content, and improve the performance of the motor. When designing the rotor structure with an uneven air gap, as shown in Figure 7, the rotor is divided into 2p parts. The *LL'* part of the outer circle of the rotor of each region is eccentric to the same degree while the rest of the elements remain unchanged. Thus, a motor rotor with a segmented abnormal structure is formed. The black dotted line in Figure 7 is the outer surface of the rotor before eccentricity. *r* is the outer diameter of the rotor before eccentricity and *r'* is the radius of the eccentric circle. The position of the extreme circle center of the rotor under the non-uniform air gap structure is different from the axial center of the rotor axis. In this paper, the eccentric distance a = 9 mm, the maximum air gap length $\delta_{max} = 1$ mm, and the minimum air gap length $\delta_{min} = 0.54$ mm.



Figure 7. Rotor structure with an uneven air gap.

Secondly, this paper optimizes the permanent magnets of the rotor and divides each permanent magnet of the IPMSMA into two equal parts. The two small permanent magnets are arranged at an angle α . The optimized magnetic pole structure is shown in Figure 8. In this paper, the length of a single permanent magnet is h = 12.4 mm, the width of the permanent magnet is d = 3 mm, the angle between the permanent magnets is $\alpha = 9.8^{\circ}$, and the distance between the two small permanent magnets outside each pole is the V-shaped angle $\beta = 63^{\circ}$.



Figure 8. Optimized permanent magnet structure.

3.1. Magnetic Flux Density Analysis

The magnetic field density of the motor at no-load is shown in Figure 9, where Figure 9a represents PMSM, Figure 9b is IPMSMA, and Figure 9c is IPMSMB. By comparison, it is found that the amplitudes of the magnetic flux density at the stator teeth and the magnetic poles of IPMSMB are the largest, and the IPMSMB has the largest average magnetic flux density.



Figure 9. Comparison of magnetic flux density of three types of motors. (**a**) IPMSM; (**b**) IPMSMA; (**c**) IPMSMB. T is the unit of magnetic induction, that is, tesla.

3.2. No-Load Air Gap Flux Density Harmonic Analysis

Figure 10 shows the harmonic analysis diagram of the no-load air-gap flux density of the motor before and after optimization. It can be seen from the figure that the amplitude of the 4th harmonic component is the highest. This is because the number of pole pairs of the permanent magnets of the motor designed in this chapter is four. The uneven air gap is formed between the stator and the rotor by decentering the rotor section by section, which improves the air gap flux density of the motor at no-load. The 4th harmonic component is decreased to a certain extent, while the higher harmonic component is decreased. The wave components have decreased. After the optimization of the permanent magnet structure, the fourth harmonic of IPMSMB is further enhanced, but the higher harmonic components are not significantly improved. In this paper, the IPMSM adopts a uniform air gap. IPMSMA and IPMSMB employ non-uniform air gaps. We need to be careful that the greater the eccentricity is not the better.





3.3. No-Load Air Gap Flux Density Harmonic Analysis

The no-load back EMFs of IPMSM, IPMSMA, and IPMSMB are shown in Figure 11.



Figure 11. No-load back EMF of three types of motors.

Under the rated conditions, as shown in Figure 12, when the air gap is uniform, the amplitude of the cogging torque is 1210 mNm. When there is an uneven air gap for the motor, the amplitude of the cogging torque is 480 mNm. The amplitude of the cogging torque is reduced by 60.3%, the cogging torque is weakened to a certain extent. This is because the non-uniform air gap changes the air gap magnetic density of the motor, which affects the size of the cogging torque [16–19]. At the same time, after optimizing its magnetic pole structure based on IPMSMA, the amplitude of cogging torque of IPMSMB has been further reduced to 330 mNm.



Figure 12. Cogging torque of three types of motors.

3.4. Analysis of Load Torque

Under the rated conditions, the output torque of the motor is shown in Figure 13. By comparing IPMSM and IPMSMA, it is shown that the amplitude of the output torque of the motor has been improved after the non-uniform air gap is adopted. Meanwhile, the torque ripple is changed from 8.72–6.5%. This is due to the uneven air gap between the stator and rotor. Therefore, the waveform of the air-gap magnetic field is sinusoidal, and the effective harmonic content of the air-gap magnetic density is improved [20–22]. Compared with IPMSMA, the average output torque of IPMSMB is increased by 4.36 Nm, while the

torque ripple is reduced to 6.19%. This is because this arrangement of permanent magnets improves the magnetic field distribution on the stator and rotor. At the same time, the output torque of the motor is improved.



Figure 13. Output torque of three types of motors.

Table 4 shows the performance comparison of the three kinds of motors under rated conditions.

Parameter	IPMSM	IPMSMA	IPMSMB
Amplitude of no-load back potential/V	319.97	341.38	355.80
Output torque/Nm	112.90	120.32	124.98
Cogging torque/Nm	1.21	0.48	0.33
Torque ripple/%	8.72	6.50	6.19

Table 4. Performance comparison of three kinds of motors under rated conditions.

4. Multi-Objective Optimization of Rotor Structure Based on the Taguchi Method

In this paper, we use the Taguchi method for multi-objective optimization of the motor. The flowchart is shown in Figure 14.



Figure 14. Flow chart of optimization design of Taguchi method.

4.1. Determining Optimization Goals and Optimization Factors

Since the PMSM of electric vehicles needs to meet its performance requirements of high torque density and power density, stable operation, and low noise, the average output torque T_{av} , cogging torque T_c , and torque ripple K are selected as the optimization objectives in this paper. Larger is better for the first indicator and smaller is better for the last two indicators. Due to the eccentricity of the rotor outer diameter, the structure size of the permanent magnet and the position of the permanent magnet in the rotor have a great influence on the motor. Based on the above factors, we choose five parameter variables as optimization factors: the eccentricity *a*, the length *d* of the permanent magnet, the thickness *h* of the permanent magnet, the Angle α of the permanent magnet, and the Angle β of the V-shape.

4.2. Determining the Optimal Value Range and Level Value of the Optimization Factor

In this paper, we use Ansys Maxwell finite element analysis software to adjust the optimization factor parameters many times and a large number of simulation calculations. As a result, the optimal value range of the optimization factor is obtained, as shown in Table 5. We select four influence levels equidistant within the optimal value range of each factor. Then we arrange the four-level values according to the ordering principle from small to large and named them as level values 1, 2, 3, and 4, respectively. The values of each level are shown in Table 6.

Table 5. Selection range of optimization parameters.

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Optimization Factor	Preferred Range
Eccentricity/a	8–11
Length of permanent magnet/ d	12–13.2
Thickness of permanent magnet/h	2.6–3.8
Angle of permanent magnet/ α	8.8-11.8
V-shaped angle/ β	61–67

Table 6. Number of levels for the optimization factor.

Optimization Factor	Level 1	Level 2	Level 3	Level 4
Eccentricity/a	8	9	10	11.80
Length of permanent magnet/ d	12	12.4	12.8	13.22
Thickness of permanent magnet/ h	2.6	3	3.4	3.8
Angle of permanent magnet/ α	8.8	9.8	10.8	11.8
V-shaped angle/ β	61	63	65	67

4.3. Determining the Optimal Value Range and Level Value of the Optimization Factor

According to the five optimization factors selected in Table 6 and the four level values determined by each optimization factor, we establish the orthogonal table by using the construction principle of the orthogonal table and the experimental design principle of the Taguchi method. In this way, we only need $4^2 = 16$ experiments to realize the multi-objective optimization of the motor, which greatly reduces the simulation times and time. Then we use Ansys simulation software to establish 16 motor models and their finite element analysis calculation. The solution results are shown in Table 7.

Test Number	Experiment Matrix			T _{em} /Nm	T./Nm	K/%		
itst itumber -	а	d	h	α	β	1 40/1 111	1,0111	10/70
1	1	1	1	1	1	118.35	0.14	11.10
2	1	2	2	2	2	123.52	0.20	6.56
3	1	3	3	3	3	126.83	0.93	9.82
4	1	4	4	4	4	132.17	2.13	8.06
5	2	1	2	3	4	123.83	0.67	6.20
6	2	2	1	4	3	121.92	0.54	5.30
7	2	3	4	1	2	126.82	1.02	8.85
8	2	4	3	2	1	128.94	0.68	5.12
9	3	1	3	4	2	124.25	0.58	4.43
10	3	2	4	3	1	127.78	0.28	2.58
11	3	3	1	2	4	125.11	0.54	6.17
12	3	4	2	1	3	129.92	0.67	4.64
13	4	1	4	2	3	124.80	0.84	10.45
14	4	2	3	1	4	128.70	0.62	4.05
15	4	3	2	4	1	128.75	0.14	5.59
16	4	4	1	3	2	126.86	0.31	8.62

Table 7. Orthogonal table and finite element simulation results.

4.4. Mean Analysis

To obtain the influence of all optimization factors on the optimization target and the proportion of the parameter changes of each factor, we carry out the proportion of the influence on the optimization target according to the above orthogonal experiment table and finite element analysis results. Firstly, the average value is analyzed. Then the variance is analyzed. Finally, the optimization result is obtained.

According to Formula (1), we calculate the average value of the finite element simulation results of all optimization objectives. The results are shown in Table 8.

$$m = \frac{1}{n} \sum_{i=1}^{n} S_i \tag{1}$$

Table 8. Average results for each optimization objective.

-	T_{av}/Nm	T_c/Nm	K/%
т	126.16	0.67	6.72

In the formula, *m* is the average result of each optimization objective in Table 7; *n* is the number of trials, n = 16 in this paper; S_i is the *i*-th optimization objective value. (*i* is one of 1–16).

Secondly, the average value of the optimization factor at different levels is analyzed. According to Formula (2), when all the optimization factors matter at different levels, the average calculation results of the average output torque T_{av} , cogging torque T_c , and torque ripple *K* are shown in Table 9.

$$m_{ij}(f) = \frac{1}{4}[f(1) + f(2) + f(3) + f(4)]$$
⁽²⁾

Optimization Factor	Number of Levels	T_{av}/Nm	T_c/Nm	K/%
	1	125.22	0.85	8.89
	2	125.38	0.73	6.37
u	3	126.77	0.52	4.46
	4	127.28	0.48	7.18
	1	122.80	0.56	8.05
1	2	125.48	0.41	4.62
a	3	126.88	0.66	7.61
	4	129.47	0.95	6.61
h	1	122.81	0.38	7.80
	2	126.51	0.54	5.75
	3	127.18	0.70	5.86
	4	127.89	1.07	7.49
	1	125.95	0.61	7.16
<i>a</i>	2	125.59	0.57	7.08
α	3	126.33	0.55	6.81
	4	126.77	0.85	5.85
P	1	125.96	0.43	6.10
	2	125.36	0.53	7.12
P	3	125.87	0.75	7.55
	4	127.45	0.99	6.12

Table 9. The average value of motor performance indexes of various optimization factors at different levels.

In Formula (2), *i* is one of the optimization factors *a*, *d*, *h*, α , and β . *j* is the number of levels. *f* is one of the optimization objectives *T*_{*av*}, *T*_{*c*}, and *K*.

4.5. Variance Analysis

According to Table 8 of the average value of each optimization target and Table 9 of the average value of each optimization factor under different levels of motor performance indicators, the variance of each optimization factor under each motor performance indicator and its impact proportion on each motor performance can be calculated according to Formula (3). Table 10 shows the influence of each optimization factor on different motor performance indicators.

$$D = \frac{1}{4} \sum_{j=1}^{4} \left[m_{ij}(f) - m(f) \right]^2$$
(3)

Outimization Factor	T_{c}	T_{av}/Nm		T_c/Nm		K/%	
Optimization Factor	D	Proportion/%	D	Proportion/%	D	Proportion/%	
а	0.78	7	0.02	10	2.54	44	
d	5.81	52	0.04	20	1.75	29	
h	3.84	34	0.07	35	0.86	15	
α	0.19	2	0.02	10	0.27	5	
β	0.61	5	0.05	25	0.40	7	
In total	11.23	100	0.2	100	24.77	100	

Table 10. Performance comparison of three motors.

In Formula (3), *D* is the variance, *j* is the number of levels, *i* is one of the optimization factors *a*, *d*, *h*, α , and β , and *f* is one of the optimization targets T_{av} , T_c , and *K*.

According to the data in Table 10, eccentricity *a* has the greatest impact on torque ripple *K*, so we chose a = 10 mm; The permanent magnet length *d* has a relatively important influence on T_{av} and T_c , and its influence on T_{av} is the most obvious, so we chose d = 13.2 mm; the thickness of the permanent magnet *h* has a great influence on T_c . According to the calculation results in the table, we should choose the scheme with the smallest thickness, so we chose h = 2.6 mm; the influence of the angle α of the permanent magnet on

the parameters is not particularly large, mainly affecting T_c . We chose $\alpha = 9.8^{\circ}$ or $\alpha = 10.8^{\circ}$ to obtain a relatively optimal value. From the perspective of improving the output torque and reducing the cogging torque, we finally chose $\alpha = 10.8^{\circ}$; the included angle β has the greatest impact on T_c , so $\beta = 61^{\circ}$ is selected [23–25]. The final best combination of motor main parameters is shown in Table 11. The comparison results of performance indexes before and after optimization are shown in Table 12.

 Table 11. Optimization factor parameters before and after optimization.

Parameter	a/mm	d/mm	<i>h</i> /mm	α/ °	$eta l^\circ$
Before optimization	9	12.4	3	9.8	63
After optimization	10	13.2	2.6	10.8	61

 Table 12. Comparison of various performance indexes before and after optimization.

Parameter	T_{av}/Nm	T_c/Nm	K/%
Before optimization	124.98	0.33	6.19
After optimization	130.67	0.18	4.84

4.6. Comparative Analysis of Motor Performance Simulation

Under the rated conditions, the above-optimized motor model is simulated by finite element analysis, including the simulation analysis of torque characteristics and efficiency. The comparison of performance indexes before and after optimization is shown in Table 12. According to Table 12, the output torque of the motor before the optimization is 124.98 Nm, the cogging torque is 0.33 Nm, and the torque ripple is 6.19%. The optimized performance indexes are: output torque is 130.67 Nm, cogging torque is 0.18 Nm, and torque ripple is 4.84%. After optimization, the average output torque of the motor increases by 4.6%, the cogging torque decreases by 45.5%, and the torque ripple decreases by 25.7%. After optimization, the output torque of the motor increases, and the cogging torque and torque ripple decrease to a certain extent, which improves the operational performance and stability of the motor. The output torque comparison diagram and cogging torque comparison diagram of the motor before and after optimization are shown in Figures 15 and 16, respectively.



Figure 15. Comparison of motor output torque before and after optimization.



Figure 16. Comparison of cogging torque of motor before and after optimization.

4.7. On Load Performance Analysis of Optimized Motor

Figure 17 shows the relationship between the output torque and the current of the motor. According to the figure, the output torque of the motor gradually increases with the increase in the load current of the motor.



Figure 17. Influence of current on torque.

The relationship between the electromagnetic torque of the motor and the current angle is shown in Figure 18. Given the current of the motor of 30 A, the set current angle varies from -90° to 90° , and the current angle of the motor gradually increases. With the increase in the current angle of the motor, the electromagnetic torque of the motor gradually increases first and then decreases. It can be seen from the curve that when the current angle of the motor is 0° , the electromagnetic torque of the motor reaches the maximum value.



Figure 18. Influence of current angle on torque.

The comparison of the economic indicators of the motor before and after optimization is shown in Table 13. After optimization, the consumption of permanent magnets of the motor is reduced by 7.74%, the utilization rate of permanent magnets is increased by 13.3%, and the comprehensive economy is improved to a certain extent.

Parameter	Volume of	Utilization of	Cost of Permanent
	Permanent	Permanent	Magnets/RMB
	Magnet/mm ³	Magnets/Nm/mm ³	(yuan)
Before optimization	190,464.00	$6.562 imes 10^{-4}$	539.29
	175 718 40	7 436 imes 10^{-4}	497 54
Alter optimization	175,710.40	7.430 × 10	477.54

Table 13. Comparison of economic indexes of the motor before and after optimization.

5. Experimental Platform and Experimental Research

5.1. Prototype and Experimental Platform

To verify the rationality of the above motor design and finite element simulation analysis, we use the prototype to carry out experimental tests. The main parameters of the prototype are shown in Table 14.

Table 14. Main parameters of the prototype.

Parameter	Value
Rated power/Kw	20
Rated voltage/V	380
Rated current/A	20
Rated frequency/ f	100
Rated power factor	0.96
Wiring mode	Y
Number of motor poles	8

The prototype experimental platform is shown in Figure 19, mainly composed of a permanent magnet motor system, speed and torque instrument, power analyzer, and frequency converter.



Figure 19. Prototype experiment platform.

5.2. Prototype Experiment Platform

In order to test the rationality and feasibility of the motor designed by us, we use the load experiment to test the load capacity of the prototype. First, we run the motor no-load at rated conditions. Then, we continuously increase the load of the motor until the rated load. Second, we record the power, output torque, and other electrical parameters of the motor with different sizes of load. Finally, we calculate the efficiency of the motor under different conditions to judge the load capacity of the motor.

We measure the output power and efficiency after changing the load. The results are shown in Table 15. According to Figure 20, to show the difference between the calculated value and the actual value of efficiency more intuitively, we import the experimental results into the line chart.

-	Measured Value		Calculated Value	
Adjusting Torque/Nm	Output Power/Kw	Efficiency/%	Output Power/Kw	Efficiency/%
0	0.305	26.5	0.305	22.4
27	2.782	76.9	2.781	74.2
54	5.451	86.1	5.508	84.0
81	8.244	88.4	8.243	87.2
108	11.008	89.0	10.954	88.7
135	13.728	90.9	13.638	90.2
162	16.324	91.8	16.324	91.2
189	18.917	92.9	18.916	91.3

Table 15. Load power and efficiency.



Figure 20. Variation of efficiency with adjusting torque.

The simulation results in Figure 20 show that the actual efficiency of the prototype test is slightly lower, which may be caused by the increase in the core loss of the motor caused by the temperature rise during the operation of the motor.

6. Conclusions

To improve the performance and reliability of a permanent magnet synchronous motor for a vehicle, we have designed a new type of permanent magnet synchronous motor for a vehicle, IPMSMB, and carried out multi-objective optimization by the Taguchi method. Finally, we have used the prototype experiment platform to verify the rationality of the design. The research conclusions are as follows:

- (1) Through finite element analysis, we have compared the air-gap magnetic field, back potential, and torque characteristics of three structural motors. The results show that the waveform of air-gap magnetic density can be effectively improved and the coat-torque of the motor can be reduced by adopting a piecewise eccentric design on the external surface of the motor rotor under the rated conditions. The optimization of permanent magnet structure can improve the electromagnetic torque of the motor to a certain extent.
- (2) The Taguchi method has been used to optimize the key parameters affecting the performance of the motor, and the simulation verification has been carried out. The results show that the permanent magnet consumption of the optimized IPMSMB has been reduced by 7.74% under the rated conditions. Meanwhile, the output torque has been increased by 4.6%, the cogging torque has been reduced by 45.5%, and the torque ripple has been reduced by 25.7%.
- (3) The experimental measurement results of the prototype are very close to the simulation calculation values, which verifies the rationality of the motor design.
- (4) In future work, we will strive to reduce the loss of the motor and improve the efficiency of the motor by using low-loss magnetic materials or trying to make the iron core into a laminar structure.

Author Contributions: Investigation, Z.G. and F.H.; Methodology, C.Q. and Z.G.; Project administration, C.Q. and X.W.; Software, Y.H.; Writing—original draft, C.Q. and Z.G.; Writing—review & editing, Z.G. and X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported in part by the Liaoning Natural Science Foundation under Grant 2020-MS-240 and 2020-MS-242, Shenyang Young and Middle-aged Scientific and Technological Innovation Talents under Grant RC200192, Liaoning Provincial Department of Education Scientific Research Project under Grant LJKZ1085.

Conflicts of Interest: The authors declare no conflict of interest.

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