Feasibility analysis and optimization design of PMSM with 120° phase belts toroidal windings for electric vehicles

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Abstract
A permanent magnet synchronous motor (PMSM) is introduced with 120° phase belts toroidal windings (PBTWs) (120°PBTWPMSM), in which its armature reaction field principle is elaborated. Then, the experiment concerning the 120°PBTWPMSM is conducted to verify the validity of the related analysis and the feasibility of the 120°PBTWPMSM. In addition, a method of shifting the magnetic poles (SMP) is adopted to suppress the cogging torque and the torque ripple. After this, the 120°PBTWPMSM after SMP is further optimised by the Taguchi method to obtain the structural parameters of the motor with optimal comprehensive performance. Finally, the performance of the original motor, the 120°PBTWPMSM after SMP and the optimal motor are compared, which verify the effectiveness of the optimization methods.

1 | INTRODUCTION
Because of the rising trends of global energy sustainability and environment protection, electric vehicles (EVs) attract much attention and funding from various governments and individuals all over the world [1–3]. In EVs, owing to the merits of high-power density, high efficiency and low acoustic noise, permanent magnet synchronous motors have gained a lot of concern [4]. Therefore, research into permanent magnet synchronous motors for EVs has drawn much attention from scholars and many novel topologies of the motor are proposed. For example, a permanent magnet synchronous motor (PMSM) with 120° phase belts toroidal windings (PBTWs) (120°PBTWPMSM) is proposed in Gao et al. [5].

In Gao et al. [5], the motor is characterised by low speed and high torque and is suitable for electric vehicles. However, the feasibility of the 120°PBTWPMSM has not been verified experimentally, and the motor has the disadvantage of a large torque ripple. Therefore, to verify the feasibility of the 120°PBTWPMSM, the armature reaction field principle is illuminated here. Moreover, the prototype of the 120°PBTWPMSM is manufactured and tested. Subsequently, some measured parameters including the output torque, output power and current are compared with finite-element results.

In terms of reducing the torque ripple, there are two main approaches: control techniques and motor design. The first uses various control techniques to either eliminate or compensate torque pulsations [6], but control strategies are generally complicated. The second is based on a motor design to reduce the torque ripple. Cogging torque, which is seen as a main components of torque ripple, can be reduced by this approach. Numerous methods have been proposed to suppress cogging torque in the literature, such as axial
segmentation, notching, changing the pole arc to a pole pitch ratio, and so on [7]. Considering the simplification of the optimization method, the cogging torque of the 120° PBTWPMSM is optimised by shifting the magnetic poles (SMP) here.

To satisfy the requirements of industrial applications, it becomes increasingly necessary to the multiojective optimal design of the 120° PBTWPMSM after SMP, particularly with respect to the efficient use of materials and the optimization of geometry [8, 9]. Many optimization algorithms, which include the equivalent magnetic circuit method (EMCM), genetic algorithm, particle swarm optimization, and Taguchi method, are presented to consider the mutual influence among different parameters in direct-drive permanent synchronous motor optimization design [10–14]. Considering magnetic circuit saturation, the non-linearity of the magnetic material and the mutual effect between the permanent magnetic field and the armature reaction magnetic field, the EMCM can effectively balance the calculation time and calculation accuracy. However, this method is more suitable for the initial optimal design of the motor [10, 11]. Genetic algorithms and particle swarm optimization have great advantages in global optimization [12–14]. However, the establishment and solution analysis of the objective function for these methods are complex and it is difficult to realize a fast search of the optimal parameter combination. Therefore, these methods have limitations in the multiojective optimal design. The Taguchi method is not necessary to use sophisticated algorithms and additional programing aside from the finite element method (FEM) of electromagnetic field analysis [15]. It can obtain the optimal combination of parameters with the minimum number of experiments [16]. Song et al. [17] proves that the Taguchi method is more efficient and practical than particle swarm optimization. Therefore, this work uses the magnetic shifting and Taguchi methods to improve the performances of the 120° PBTWPMSM after SMP.

The rest of the research is organised as follows. In addition to the structure of the 120° PBTWPMSM, the armature reaction field principle of the motor is elaborated upon. Then, the simulation and experiments are conducted on the 120° PBTWPMSM to verify its feasibility. Subsequently, the method of SMP is adopted to minimise the cogging torque of the 120° PBTWPMSM. After this, the 120° PBTWPMSM after SMP is further optimised by the Taguchi method, in which the detailed optimization process is described and optimal structural parameters of the motor are obtained. Finally, the characteristics of the three motors before and after optimization are compared.

2 | STRUCTURE AND PRINCIPLE

2.1 | Motor structure

The object is a surface-mounted PMSM with 24 slots, eight poles and toroidal windings (Figure 1). The main parameters of the 120° PBTWPMSM are reported in Table 1. Figure 1(a) shows that 24 armature coils are located in the stator slots by striding the stator yoke; the inlet end of all coils is on the outer side of the stator and the outlet end is on the inner side. In addition, each phase armature winding includes eight toroidal armature coils connected in series. Owing to the characteristics of the novel toroidal windings, each stator winding keeps the same size and the stator coils in each slot are independent of each other, which improves the insulation and fault tolerance of the motor windings. Furthermore, the cooling area of stator is increased and the heat dissipation performance of the motor is improved, because the back-side windings of the stator yoke are directly exposed to the air and the remaining space of the stator can be used as a ventilation channel.

According to the structural characteristics of the novel toroidal windings, the motor can be made into a double-rotor motor, in which the back-side windings of the stator yoke are separated by the stator teeth. As a result, the fault tolerance between windings is further improved, the use of the windings and stator blade is increased, and the copper loss of the stator is reduced. As shown in Figure 1(b), the rotor of the 120° PBTWPMSM consists of silicon steel sheets and eight arc-shaped permanent magnets, in which the permanent magnets are evenly distributed in the circumferential direction and the magnetic field directions excited by adjacent permanent magnets are opposite.

![Figure 1](image-url) Structure of the motor.
(a) stator, (b) rotor
2.2 | Armature reaction field principle

The topology of the toroidal windings in the proposed motor has changed greatly compared with conventional windings. When only one toroidal winding in the stator slot is energised, the generated magnetic field completely passes through the stator core and separately forms a closed loop. When each toroidal winding is symmetrically distributed in the stator slot, the magnetic field generated by each toroidal winding passes through the path of maximum magnetic permeability to form a closed loop. Therefore, when toroidal windings are excited by a three-phase alternating current, the magnetic field generated by the adjacent two-phase winding coil meets the magnetic field generated by the coil of the other phase winding, and both attempt to pass through the stator core. The magnetic field lines of the magnetic fields are opposite in direction and resist each other, which makes the magnetic field of each pole look for a path closed loop with a smaller reluctance and a shorter path. Then, the magnetic field is interlinked with the rotor side of the motor through the air gap. For example, the armature reaction fields produced by phase A and phase C exhibit the same direction in the stator yoke, whereas the field direction of phase B is opposite, as shown in Figure 2(a).

The variation in the armature magnet field for the three-slot unit motor is described to illustrate the armature reaction field principle, as shown in Figure 2. The armature magnetic field of the three-slot unit motor forms a pair of poles and changes periodically. The poles of the armature magnetic field of the 120°PBTWPMSM have increased and are twice those of conventional motors.

| TABLE 1 | Parameters of the motor |
|-----------------|------------------------|
| Items           | Values | Units |
| Rated power     | 1.5    | kW    |
| Rated current   | 6.26   | A     |
| Number of pole pairs | 4 | / |
| Outer diameter of rotor | 202 | mm |
| Outer diameter of stator | 168 | mm |
| Inner diameter of stator | 100 | mm |
| Axial length    | 68     | mm    |
| Air gap length  | 1      | mm    |
| Permanent magnet thickness | 3 | mm |
| Polar arc coefficient | 0.75 | / |
| Wire diameter   | 0.73   | mm    |
| Number of parallel branches | 2 | / |
| Number of turns per phase | 55 | / |

Simulation and experiments are conducted on a three-phase 120°PBTWPMSM based on the parameters in Table 1. The prototype of the 120°PBTWPMSM is shown in Figure 3. The windings of the motor are wound annularly from the stator slot to the back of the stator yoke, and the incoming direction is the same. Then, the lead wire of each coil is sleeved by a white sleeve, and 24 coils are divided into four groups and taken out from the four holes of the pedestal. Finally, the two terminals of each coil are led to make a connection. The windings connection can be seen in Figure 3. Different from the

![Image of armature field distributions versus different times](image-url)

**Figure 2** Armature field distributions versus different times. (a) $\omega t = 30^\circ$, (b) $\omega t = 90^\circ$, (c) $\omega t = 150^\circ$, (d) $\omega t = 210^\circ$, (e) $\omega t = 270^\circ$, (f) $\omega t = 330^\circ$
traditional motor, the back-side windings of the stator yoke of the prototype are directly exposed to the air. If the prototype is immersed in the liquid, the rise in temperature generated by copper consumption can be effectively removed by direct contact between the liquid and the back-side windings of the stator yoke. Therefore, the prototype can also be used in a submersible pump. Furthermore, according to the structural characteristics of the toroidal windings, it can be made into a dual-rotor motor. The windings at the back of the stator yoke are separated by stator teeth to avoid contact with each other. Therefore, the fault tolerance between the windings is further improved, and the usage rate of the motor windings and the stator punching is improved simultaneously.

The test platform for the 120°PBTWPMSM prototype is shown in Figure 4, which includes the prototype, the torque-speed sensor, the magnetic particle brake, the supply power, the controller, the digital oscilloscope and the actuating device.

The structure of the prototype and the distribution of the coils are the same as the FEM model in Magnet. The windings are charged with three-phase AC source supplied by the actuating device. The induced voltages can be measured by a digital oscilloscope from the induction coils. The controller could adjust the output load of the magnetic powder brake by controlling the input current. The torque of the prototype can be controlled by adjusting the load supply and acquired from the upper computer through the torque-speed sensor. The current on the motor can also be measured by the digital oscilloscope. Considering the safety of the experiment, the current of the 120°PBTWPMSM prototype is set between 0.2\(I_N\) and 1.1\(I_N\), where the peak value of \(I_N\) is 6.26 A.

When the prototype is excited by the current from 0.2\(I_N\) and 1.1\(I_N\), the output torque is tested by the high-precision torque-speed sensor in Figure 4. The output torque and output power versus current are described in Figure 5.

The output torque is approximately proportional to the current, and the output torque and output power have almost the same trend as the current. Moreover, the finite element results are basically the same as the output torque and power.
measured by the experiment under different conditions. The deviation is 5%, which is a controllable range under the conditions of the existing equipment and platform.

When the prototype is operating at a rated condition, the current is measured, as shown in Figure 6. The simulated and measured currents in Figure 6 are 6.26 and 5.94 A, respectively, so the measured current is reduced by 5.11%.

The deviation between experimental results and the finite element results is within the allowable range of engineering. Therefore, the principle presented is correct, the finite-element model is reasonable, and the application of the 120°PBTWPMSM to electric vehicles is feasible. Nevertheless, it is necessary to optimise the 120°PBTWPMSM, because the torque ripple of the motor is large [5].

4 | COGGING TORQUE OPTIMIZATION

4.1 | Optimization design process

The existence of cогging torque will cause output electromagnetic torque fluctuations, motor vibration and noise, and so on, which affect the accuracy of control of the system [18].

Therefore, the cогging torque of the 120°PBTWPMSM is optimised by SMP in this section.

The shifted angles of the permanent magnets mounted on the rotor are the deviation angles of the permanent magnets relative to the uniformly distributed position, which can be obtained by Equation (1) [19]:

\[
\theta_k = \frac{2\pi}{2pN_pZ} (k-1) \quad 1 \leq k \leq 2p
\]

where \( \theta_k \) is the angle between a stator tooth centreline and a permanent magnet pole centreline, \( p \) represents the number of pole pairs, \( Z \) means the number of slots, and \( N_p = \frac{2p}{CD_i(\lambda_{w},2p)} \).

As shown in Table 2, \( \theta_1 \sim \theta_2 \) are the shifted angles of the permanent magnets relative to the uniform distribution position. Figure 7 shows the rotor of the 120°PBTWPMSM after SMP. When the 120°PBTWPMSM after SMP is manufactured, the permanent magnets are assembled on the rotor by a fixed frame. There are protruding fixed blocks on the fixed frame, where the arc length of the fixed block is equal to the distance between adjacent permanent magnets. A mounting slot matching the shape of the permanent magnet block is formed.

**FIGURE 5** Output torque, power versus current. (a) output torque, (b) output power

**FIGURE 6** Currents of the motor by test and finite element method at rated conditions. (a) finite element result, (b) experiment result
between adjacent fixed blocks; it is used to place the magnet block in its stable position. When the method of SMP is used, the distribution of \( B_s^2(\theta) \) is unevenly distributed along the circumferential direction, assuming the flux per pole is changed. The Fourier expansion of \( B_s^2(\theta) \) on the interval \([-\pi, \pi]\) can be expressed as \([19]\):

\[
B^2_s(\theta) = B^0_s + \sum_{n=1}^{\infty} (B^\text{ran}_n \cos n\theta + B^\text{shn}_n \sin n\theta)
\tag{2}
\]

where \( B^0_s, B^\text{ran}_n, \text{and } B^\text{shn}_n \) are the Fourier expansion coefficients \( B^\text{ran}_n \) and \( B^\text{shn}_n \) are derived as:

\[
B^\text{ran}_n = \frac{2B^2_s}{n\pi} \sin \frac{n\pi a_p}{2p} \sum_{k=1}^{2p} \cos \left( \frac{\pi}{p} (k - 1 + \theta_k) \right)
\tag{3}
\]

\[
B^\text{shn}_n = \frac{2B^2_s}{n\pi} \sin \frac{n\pi a_p}{2p} \sum_{k=1}^{2p} \sin \left( \frac{\pi}{p} (k - 1 + \theta_k) \right)
\tag{4}
\]

when the slots distribute uniformly, the Fourier transform of \( G^2(\theta, \gamma) \) can be performed within a slot pitch as:

\[
\left( \frac{b_m(\theta)}{b_m(\theta) + \delta(\theta, \gamma)} \right)^2 = G^0_n + \sum_{n=1}^{\infty} G_n \cos n\theta
\tag{5}
\]

Because the energy stored in iron can be negligible, the magnetic energy stored in the machine can be taken as that stored in the air gap and permanent magnets (PMs) \([20]\):

\[
W \approx W^\text{gap} + W^\text{PM} = \frac{1}{2\mu_r} \int_V B^2_s(\theta) \left( \frac{b_m(\theta)}{b_m(\theta) + \delta(\theta, \gamma)} \right)^2 dV
\]

\[
= \frac{1}{2\mu_r} \int_V B^2_s(\theta) G^2(\theta, \gamma) dV
\tag{6}
\]

According to Equations (2), (5) and (6), the magnetic energy in the 120°PBTWPMSM after SMP can be derived using integration. Then, the expression of coggging torque can be obtained as:

\[
T_{\text{cog}}(\gamma) = -\frac{\partial W}{\partial \gamma}
\]

\[
= \frac{\pi L_d}{4\mu_0} (R_1^2 - R_2^2) \sum_{n=1}^{\infty} nG_n (B^\text{ran}_n \cos n\gamma + B^\text{shn}_n \sin n\gamma)
\tag{7}
\]

where \( L_d \) is the axial length of the armature, \( R_1 \) the outer radius of the armature, \( R_2 \) the inner radius of stator yoke, \( z \) the number of slots, \( \mu_0 \) the permeability of air, and \( \gamma \) the rotor position. The expressions of Fourier expansion coefficients \( B^\text{ran}_n \) and \( B^\text{shn}_n \) are shown in Equations (3) and (4). Based on the orthogonality of trigonometric function, not all orders of \( B^\text{ran}_n \) and \( B^\text{shn}_n \), but only those of the order that is the multiple of \( nz \) (\( n = 1, 2, 3 \)), have effects on coggging torque.

### 4.2 Optimization result analysis

#### (1) Coggging torque

Figure 8 compares the coggging torque waveforms of the motor before and after SMP. It shows that the amplitudes of the coggging torque for two motors are 6.22 and 0.49 Nm, respectively. Compared with the original motor, the coggging torque of 120°PBTWPMSM after SMP has been reduced by 92.12%. Thus, the method of SMP can effectively reduce the coggging torque of 120°PBTWPMSM.

#### (2) No-load air-gap magnetic density

As shown in Figure 9, the no-load air-gap magnetic density before and after SMP is analysed. Figure 9(a) describes the waveforms of the no-load air-gap magnetic density, and Figure 9(b) compares the harmonics of motors. Figure 9(a) indicates that the fundamental values of the no-load air-gap magnetic density for the motors are 0.975 and 1.04 T,
successively. Compared with the original motor, the fundamental values of the no-load air-gap magnetic density in the 120°PBTWPMSM after SMP increased by 6.67%.

Furthermore, the total harmonic distortion (THD) of the no-load air-gap magnetic density in the motors are respectively 22.96% and 29.25%. The reason for the increase in the THD is that the third and fifth harmonic values of the no-load air-gap magnetic density for the motor increase after SMP. However, the seventh and ninth harmonic values of the no-load air-gap magnetic density have decreased.

(3) No-load back electromotive force (EMF)

Figure 10 analyzes the no-load back EMF before and after optimising the 120°PBTWPMSM. Figure 10(a) reveals that the no-load back EMF waveform is more sinusoidal compared with the ones of the original motor. Figure 10(b) shows that the fundamental values of no-load back EMF in motors are 161.074 and 154.115 V, and the corresponding THDs in the 120°PBTWPMSM and 120°PBTWPMSM after SMP are 4.67% and 2.74%. Compared with the original motor, the fundamental value of no-load back EMF in the 120°PBTWPMSM after SMP has improved by 4.32% and its THD has reduced by 41.33%. Moreover, Figure 10(b) indicates that
the harmonic contents in the 120°PBTWPMSM after SMP have been effectively suppressed.

(4) Output torque

Figure 11 depicts the output torque waveforms of the original motor and the 120°PBTWPMSM after SMP. Figure 11 demonstrates that the average values of the output torque in the motors are 19.10 and 18.16 Nm. Also, the torque ripples of two motors are 67.31% and 9.9%. Therefore, the torque ripple of the 120°PBTWPMSM obviously decreased after optimization.

The method of SMP can suppress the cogging torque and reduce the output torque ripple. However, the average torque is also decreased. Hence, the 120°PBTWPMSM after SMP needs further optimization.

5 | MULTIOBJECTIVE OPTIMIZED DESIGN

5.1 | Design method and optimization objective

In this section, the 120°PBTWPMSM after SMP is further optimised by the Taguchi method. A flowchart of the Taguchi method is shown in Figure 12.

Because polar arc coefficient \( a_p \), thickness of permanent magnet \( b_p \), and air-gap length \( b \) affect the magnetic field distribution, and slot opening width \( b_s \) affects the torque fluctuation, the four structural parameters mentioned are selected as optimization variables A, B, C and D. Through repeated adjustment and simulation calculation of optimization parameters by Magnet, the optimal value range of each optimization parameter can be preliminarily determined as A (0.7~0.85 mm), B (3~4.5 mm), C (0.5~2 mm), and D (1.6~2.2 mm). Generally, three to five levels are selected for optimization parameters. Here, each parameter takes four factor levels, which are close to the initial design parameters. The optimization variables and their factor levels are listed in Table 3.

In the orthogonal experiment, the torque, torque ripple \( T_{\text{ripple}} \), efficiency and THD of back EMF \( \text{THD}_{\text{emf}} \) are selected as optimization objectives. The \( T_{\text{ripple}} \) and \( \text{THD}_{\text{emf}} \) can be calculated by:

\[
T_{\text{ripple}} = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{ave}}} \tag{8}
\]

\[
\text{THD}_{\text{emf}} = \sqrt{\sum_{n=2}^{\infty} \left( \frac{U_n}{U_1} \right)^2} \tag{9}
\]

where \( T_{\text{max}} \) is the maximum value of torque, \( T_{\text{min}} \) is the minimum value of torque and \( T_{\text{ave}} \) is average torque. \( U_n \) is the amplitude of the \( n \)-th harmonic of the back EMF.

5.2 | Optimization process

Because there are four optimization variables and each has four factor levels in the experiment, the experimental orthogonal matrix is established and expressed as \( L_{16} \). \( L \) is the code of the

**TABLE 3** Optimization variables and factor levels

| Variables/factor level | A/mm | B/mm | C/mm | D/mm |
|------------------------|------|------|------|------|
| 1                      | 0.7  | 3    | 0.5  | 1.6  |
| 2                      | 0.75 | 3.5  | 1    | 1.8  |
| 3                      | 0.8  | 4    | 1.5  | 2    |
| 4                      | 0.85 | 4.5  | 2    | 2.2  |
orthogonal table. There are 16 rows in the orthogonal table. The orthogonal matrix is solved by the FEM. The experimental orthogonal matrix and result analysis are shown in Table 4.

According to the data in Table 4, the average of each optimization objective in overall experiments is calculated by:

\[
M = \frac{1}{n} \sum_{i=1}^{n} p_i \tag{10}
\]

where \(M\) is equal to the number of experiments and \(p_i\) is the value of optimization objective in the \(i\)-th experiment. The averages of optimization objectives are listed in Table 5.

The average value of optimization objective at each factor level of each optimization variables are obtained by:

\[
E_{xi} = \frac{1}{4} [E_x(j) + E_x(k) + E_x(l) + E_x(m)] \tag{11}
\]

where \(E_{xi}\) is the optimization objective average when the optimization variable \(x\) is at the \(i\)-th factor level and \(E_x(j)\) is the value of the optimization objective with the experimental sequence number \(j\) when the optimization variable \(X\) is at a specific factor level. For example, when variable \(A\) is at level factor 1, average torque is expressed by:

\[
E_A^1 = \frac{1}{4} [E_A(1) + E_A(2) + E_A(3) + E_A(4)] \tag{12}
\]

Therefore, the averages of all optimization objectives at all level factors can be obtained in a similar way, as reported in Table 6. The effect of structural parameters on performance is shown in Figure 13.

According to the value in Table 5 and the average of optimization objectives in Figure 13, the proportion of influence of the optimization variable on the optimization objectives can be obtained by:

\[
D_x = 4 \sum_{i=1}^{4} (E_{xi} - E) \tag{13}
\]

The results obtained by Equation (13) are compared in Table 7 in which the proportion of influence of the optimization variable to the optimization objectives is obtained.

### Table 4 Experimental orthogonal matrix and result analysis

| No. | A    | B | C | D | Torque (Nm) | Efficiency (%) | T_ripple (%) | THD\textsubscript{emf} (%) |
|-----|------|---|---|---|-------------|----------------|--------------|--------------------------|
| 1   | 0.7  | 3 | 0.5| 1.6| 19.245      | 87.64          | 11.69        | 3.60                     |
| 2   | 0.7  | 3.5| 1  | 1.8| 17.906      | 86.81          | 168.48       | 3.58                     |
| 3   | 0.7  | 4  | 1.5| 2  | 17.829      | 86.76          | 12.05        | 3.77                     |
| 4   | 0.7  | 4.5| 2  | 2.2| 17.297      | 86.39          | 12.10        | 3.82                     |
| 5   | 0.75 | 3  | 1  | 2  | 18.391      | 87.12          | 9.03         | 2.79                     |
| 6   | 0.75 | 3.5| 0.5| 2.2| 20.170      | 88.15          | 9.64         | 4.25                     |
| 7   | 0.75 | 4  | 2  | 1.6| 17.249      | 86.36          | 10.08        | 2.84                     |
| 8   | 0.75 | 4.5| 1.5| 1.8| 18.839      | 87.40          | 8.62         | 2.74                     |
| 9   | 0.8  | 3  | 1.5| 2.2| 17.442      | 86.49          | 7.53         | 2.49                     |
| 10  | 0.8  | 3.5| 2  | 2  | 16.972      | 86.16          | 7.34         | 2.45                     |
| 11  | 0.8  | 0.5| 1.8| 20.061  | 88.09        | 9.20         | 4.28                     |
| 12  | 0.8  | 4.5| 1  | 1.6| 20.092      | 88.11          | 7.02         | 2.63                     |
| 13  | 0.85 | 3  | 2  | 1.8| 16.438      | 85.76          | 7.21         | 2.62                     |
| 14  | 0.85 | 3.5| 1.5| 1.6| 18.443      | 87.15          | 9.21         | 3.17                     |
| 15  | 0.85 | 4  | 1  | 2.2| 20.040      | 88.08          | 9.79         | 3.82                     |
| 16  | 0.85 | 4.5| 0.5| 2  | 21.10       | 88.63          | 12.49        | 4.47                     |

Abbreviation: THD, Total harmonic distortion.

### Table 5 Average of each optimization objective

| Optimization Objective | Torque (Nm) | Efficiency (%) | T_ripple (%) | THD\textsubscript{emf} (%) |
|------------------------|-------------|----------------|--------------|--------------------------|
| M                      | 18.60       | 87.19          | 19.47        | 3.33                     |

Abbreviation: THD, Total harmonic distortion.

### Table 6 Averages of all optimization objective at all level factors

| Variable | Level factor | Torque (Nm) | Efficiency (%) | T_ripple (%) | THD\textsubscript{emf} (%) |
|----------|--------------|-------------|----------------|--------------|--------------------------|
| A        | 1            | 18.07       | 86.90          | 51.08        | 3.69                     |
| B        | 2            | 18.66       | 87.26          | 9.34         | 3.15                     |
| C        | 3            | 18.64       | 87.21          | 7.77         | 2.96                     |
| D        | 4            | 19.01       | 87.40          | 9.67         | 3.52                     |
| A        | 1            | 17.88       | 86.75          | 8.87         | 2.88                     |
| B        | 2            | 18.37       | 87.07          | 48.67        | 3.36                     |
| C        | 3            | 18.79       | 87.32          | 10.28        | 3.68                     |
| D        | 4            | 19.33       | 87.63          | 10.06        | 3.41                     |
| A        | 1            | 20.14       | 88.13          | 10.75        | 4.15                     |
| B        | 2            | 19.11       | 87.53          | 48.58        | 3.20                     |
| C        | 3            | 18.14       | 86.95          | 9.35         | 3.04                     |
| D        | 4            | 16.99       | 86.17          | 9.18         | 2.93                     |
| A        | 1            | 18.76       | 87.31          | 9.50         | 3.06                     |
| B        | 2            | 18.31       | 87.01          | 48.38        | 3.30                     |
| C        | 3            | 18.57       | 87.17          | 10.23        | 3.37                     |
| D        | 4            | 18.74       | 87.28          | 9.76         | 3.59                     |

Abbreviation: THD, Total harmonic distortion.
5.3 | Optimization result analysis

According to the comparisons in Figure 13 and Table 7, the influence of the optimization variable on the optimization objective is different. Therefore, the three optimization schemes of objective performance are formulated.

(1) Optimization scheme 1: Torque and efficiency optimization

When the torque and efficiency are selected as the optimization objective, the factor levels of four optimization variables, A, B, C and D, can be selected as 4, 4, 1 and 3, successively. As shown in Table 8, the optimization results are compared with results from the 120°PBTWPMSM after SMP and the original motor, in which the permanent magnets in the original motor are evenly distributed along the circumferential direction.

Table 8 demonstrates that the torque increased by 10.47% and 16.19% compared with results obtained from the original motor and 120°PBTWPMSM after SMP. Furthermore, efficiency is improved by 1.23% and 1.90%, respectively.

(2) Optimization scheme 2: THD of back EMF

When the factor levels of four optimization variables, A, B, C and D, are successively equal to 3, 1, 4 and 1, the THD of back EMF is optimal. The results before and after

| Variable | A       | B       | C       | D       |
|----------|---------|---------|---------|---------|
| Torque (Nm) | $D_1$ | 1.81    | 4.58    | 21.8    | 0.51 |
| Proportion (%) | 6.29  | 15.97   | 75.96   | 1.78    |
| Efficiency (%) | $D_2$ | 5.46E-5 | 1.67E-4 | 8.37E-4 | 2.19E-5 |
| Proportion (%) | 5.05  | 15.47   | 77.45   | 2.03    |
| $T_{\text{ripple}}$ (%) | $D_3$ | 0.534   | 0.456   | 0.453   | 0.446 |
| Proportion (%) | 28.28 | 24.12   | 23.98   | 23.62   |
| THD$_{\text{emf}}$ (%) | $D_4$ | 0.000133 | 0.000133 | 0.000371 | 0.000058 |
| Proportion (%) | 19.16 | 19.12   | 53.38   | 8.34    |

Abbreviation: THD, Total harmonic distortion.
optimization are reported in Table 9. Compared with results obtained from the original motor and 120°PBTWPMSM after SMP, the value of \( \text{THD}_{\text{emf}} \) decreased by 48.82% and 12.77%.

(3) Optimization scheme 3: Torque ripple optimization and comprehensive performance optimization

When the optimization objective is only the torque ripple, the factor levels of optimization variables A, B, C and D should be 3, 4, 2 and 1, respectively. The torque ripple of the motor is the smallest with this parameter combination. The results in Table 10 show that compared with the original motor and 120°PBTWPMSM after SMP, the torque ripple is reduced by 89.57% and 29.09%.

With the same parameter combination, the comprehensive performances of the three motors are also optimal. The structural parameters of the three motors are compared in Table 11. Table 10 shows that the comprehensive performances improved significantly, especially compared with the original motor.

Figure 14(a) describes the waveforms of the magnetic flux density. Figure 14(b) shows the Fourier analysis of the magnetic flux density. The fundamental component of the air-gap magnetic density in the three motors are 0.97, 1.04 and 1.10 T, respectively. With the original motor and 120°PBTWPMSM after SMP, the fundamental component of the air-gap magnetic density in the optimal motor increased by 13.40% and 5.77%.

The no-load back EMF of the three motors is compared in Figure 15. The no-load back EMF waveforms in Figure 15(a) indicates that the waveforms of the 120°PBTWPMSM after SMP and the optimal motor tends to be more sinusoidal compared with the waveforms of original motor, which is because the permanent magnets in the 120°PBTWPMSM after SMP and the optimal motor have a magnetic pole offset. In addition, the amplitude of the optimal motor is the biggest of the three motors. Figure 15(b) shows the harmonics of the no-load back EMF in the motors mentioned earlier. The fundamental component of the no-load back EMF in the original motor, 120°PBTWPMSM after SMP and the optimal motor are 161.07, 154.12 and 170.01 V, successively. Compared with the results before optimization, the value of the no-load back EMF in the optimal motor increased by 5.55% and 10.31%. Furthermore, the THDs of the no-load back EMF in the three motors are 4.67%, 2.74% and 2.63%.

Figure 16 describes the torque waveforms of the original motor, 120°PBTWPMSM after SMP and the optimal motor when they are excited by rated current and operating at the rated speed. The average torques of the three motor are 19.10, 18.16 and 20.09 Nm. Compared with the original motor and 120°PBTWPMSM after SMP, the average torque of the optimal motor has improved by 5.18% and 10.63%. Furthermore, the ripple of torque is significantly improvement. The values of \( T_{\text{ripple}} \) of the motors are 67.31%, 9.9% and 7.02%, respectively.
6 | CONCLUSION

The structure of the 120°PBTWPMSM is introduced and its armature reaction field principle is illustrated. Then, its prototype is manufactured to measure the dynamic performance. In addition, the cogging torque of the 120°PBTWPMSM is optimised using the SMP method. Then, the Taguchi method is adopted to optimise the 120°PBTWPMSM further after SMP to realize comprehensive performances of the optimal motor. Thus, these conclusions can be made:

(1) The experimental results show good agreement with the finite element results, which verify the feasibility of the 120°PBTWPMSM.

(2) The cogging torque and the torque ripple of the 120°PBTWPMSM are greatly reduced by the SMP method.
By the SMP method and the Taguchi method, the structural parameters of the motor with optimal comprehensive performance are obtained.

Although the comprehensive performance of the 120° PBTWPMsM is greatly improved, there is still room to optimize the torque ripple. Control strategies such as the current compensation method will be adopted to reduce the torque ripple in the future.

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