

The application of PMCPM in the field of electric vehicles has potential. Compared with traditional permanent magnet synchronous motors, it has a higher torque density and operating efficiency [6–9], and the three-phase structures are independent of each other without coupling. It can independently analyze and improve fault tolerance performance, which is conducive to industrial production and maintenance [10–12]. The unique concentrated winding structure of claw pole motors eliminates the winding ends of traditional permanent magnet synchronous motors and improves the utilization of the axial space of the motor, which is crucial for further reducing the volume and weight of the electric vehicle. Soft magnetic composite (SMC) material is a new type of soft magnetic material manufactured using powder metallurgy technology. Its main component is iron-based particles wrapped in insulating materials on the surface, with a particle diameter of usually about 0.1mm. It has isotropic magnetic properties and low eddy current losses [13]. SMC materials can be used to manufacture complex-shaped iron core structures through compression molding, making them suitable for use in structures with complex three-dimensional magnetic circuits. Currently, SMC materials are commonly used to manufacture the stator core of claw pole motors with complex spatial structures.

Torque is one of the important performances of electric motors. The design of a double stator structure is an effective method to improve the torque density and power density of permanent magnet motors. It has been widely used in various motor types such as DC motors, permanent magnet motors, and stepper motors. A double-stator structure motor consists of two stators and one rotor. According to the different relative positions of the stator and rotor, the double-stator structure can be divided into concentric double-stator structure and parallel double-stator structure. The concentric double-stator structure is used in radial flux motors, which can effectively utilize the internal space of the motor and improve the torque density [14–16]. The parallel double-stator structure is used in the axial flux motor. The two stator structures are identical. By setting different initial phases, the Cogging torque and electromagnetic torque generated between the stator and rotor on both sides will produce phase difference, reducing the Cogging torque and torque ripple [17–21]. At present, research on PMCPM mainly focuses on the traditional structure of single stator and single rotor, while research on double-stator PMCPM is still blank.

PMCPM can be used as a main drive motor in pure electric vehicles or hybrid electric vehicles. PMCPM does not have winding ends, and the same axial space can achieve a higher torque. At the same time, PMCPM is a special type of transverse flux motor which has the advantages of a high torque density, high power density, and easy speed control compared to traditional permanent magnet synchronous motors. Therefore, it can be used as the main drive motor for electric vehicles.

In Section 2 of this article, two concentric double-stator PMCPMs with different rotor structures (PMCPM1 and PMCPM2) are designed. The magnetic flux paths and working principles of the two motors are analyzed, and the equivalent magnetic circuit and equivalent circuit are designed. Section 3 uses three-dimensional finite element analysis to analyze the electromagnetic performance of PMCPM1 and PMCPM2 and compares them with the traditional single-stator single-rotor PMCPM (TPMCPM), proving that the double-stator structure can achieve a high torque performance. Section 4 analyzes the rotor stress of PMCPM1 and PMCPM2 and the stress analysis of the stator core with interference fitting. In order to solve the problem of excessive force on the stator in interference assembly, PMCPM1 with a hybrid material core is proposed, and multiphysics simulation analysis is carried out. Section 5 outlines the production of a low-cost TPMCPM to verify the correctness of the hybrid material magnetic core design and claw pole motor. Section 6 draws together the conclusions of this study.

2. Structural Design and Principle Analysis

2.1. Structural Design

Figure 1 shows the structure of a single-stator and single-rotor PMCPM. The internal rotor PMCPM structure with a single stator and single rotor usually achieves a good performance when the crack ratio is between 0.75 and 0.8, which leads to serious internal space waste when designing a large-sized PMCPM with larger stator outer diameters.

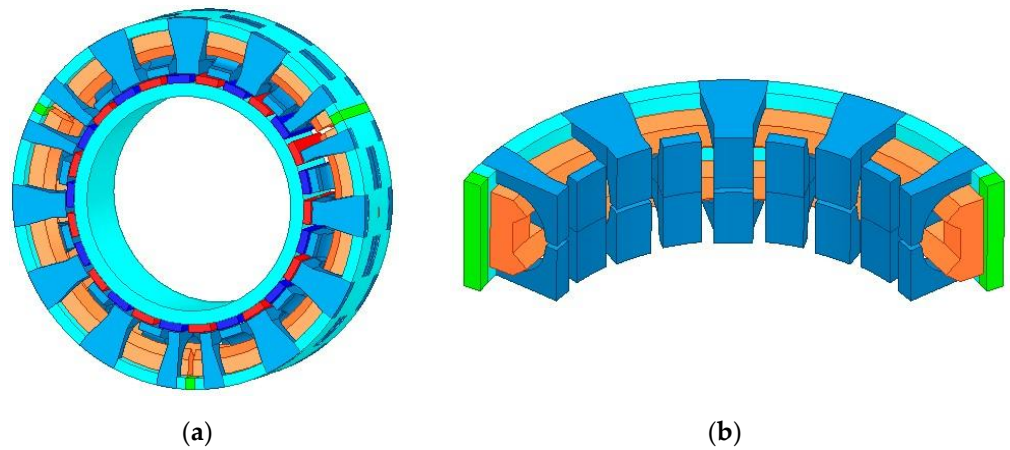


Figure 1. TPMCPM structure diagram. (a) Overall structure diagram; (b) A-phase stator structure diagram.

Figure 2 shows the structural diagrams of a concentric double-stator PMCPM with two rotor structures. Figure 2a shows a concentric double-stator PMCPM with a doublelayer permanent magnet rotor structure (PMCPM1), and Figure 2b shows a concentric double-stator PMCPM with a single-layer permanent magnet rotor structure (PMCPM2). PMCPM1 and PMCPM2 are composed of three parts: the outer stator, the middle rotor, and the inner stator. The outer stator structure is the same as the single-stator and single-rotor structure.

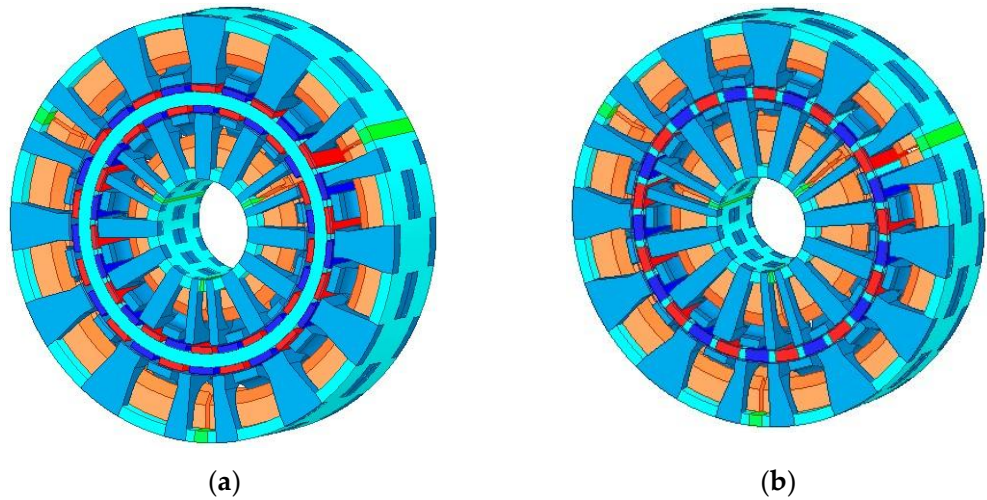


Figure 2. Concentric double-stator PMCPM. (a) PMCPM1; (b) PMCPM2.

The inner and outer main magnetic circuits of PMCPM1 are shown in Figure 3. The outer stator, outer permanent magnet of the rotor, and rotor yoke form a single-stator and single-rotor inner-rotor PMCPM, while the inner stator, inner permanent magnet of the rotor, and rotor yoke form a single-stator and single-rotor outer-rotor PMCPM. The inner and outer windings of PMCPM1 are complementary and independent of each other. The inner and outer main magnetic circuits of PMCPM2 are shown in Figure 4, with the outer stator, middle rotor permanent magnet, and inner stator flux paths coupled. The rotor structure of PMCPM2 is thinner, and the actual inner stator structure can be designed to be larger than PMCPM1. The usage of permanent magnets in PMCPM2 is smaller than that in PMCPM1.

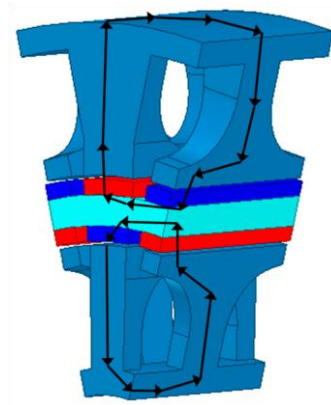


Figure 3. Main magnetic flux path of PMCPM1.

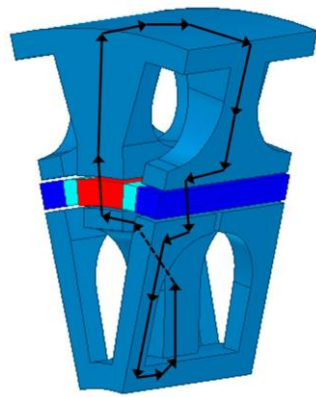


Figure 4. Main magnetic flux path of PMCPM2.

The four parameters of crack ratio, pole arc coefficient, stator claw pole wall thickness, and stator tooth top width have a significant impact on the performance of the motor. By optimizing the four parameters of the three motors, the optimal structure was obtained. The rated operating parameters of the three motors are shown in Table 1.

Table 1. Rated operating parameters of three PMCPMs.

Parameter	Units	TPMCPM	PMCPM1	PMCPM2
Rated speed	rpm	1500	1500	1500
Maximum speed	rpm	6000	6000	6000
Rated frequency	Hz	325	325	325
Maximum frequency	Hz	1300	1300	1300
Rated current	A/mm ²	6	6	6
Maximum current	A/mm ²	10	10	10
Rated output power	kW	4.36	6.52	7.37
Maximum output power	kW	26.4	36.7	40.6
Rated torque	Nm	27.8	41.5	46.9
Maximum torque	Nm	42.0	58.4	64.7

2.2. Equivalent Circuit and Equivalent Magnetic Circuit

The double-stator claw pole permanent magnet synchronous motor has a six-phase winding structure. The three-phase winding of the outer stator is fed with a current difference of 120 degrees, while the three-phase winding of the inner stator is fed with a current difference of 120 degrees. The three-phase circuits of the inner stator and the outer stator are completely independent, and the three-phase windings of the outer stator and the inner stator are completely independent in space, without any coupling relationship. The three-phase winding of the outer

stator and the three-phase winding of the inner stator are, respectively, connected in a Y-shape. According to the operating principle, the equivalent circuit diagram is shown in Figure 5.

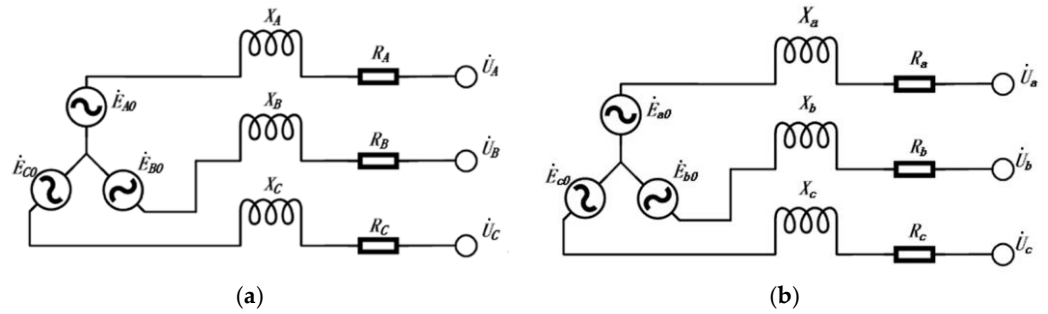


Figure 5. Equivalent circuit of double-stator PMCPM. (a) External stator equivalent circuit; (b) internal stator equivalent circuit.

In Figure 5a, E_{A0} , E_{B0} , and E_{C0} represent the induced electromotive force of the three-phase winding A, B, and C of the outer stator, X_A , X_B , and X_C represent the equivalent synchronous reactance of the three-phase winding A, B, and C of the outer stator, and R_A , R_B , and R_C represent the equivalent resistance of the three-phase winding A, B, and

C of the outer stator, respectively. In Figure 5b, E_{a0} , E_{b0} , and E_{c0} represent the induced electromotive force of the three-phase winding of the inner stator a, b, and c, X_a , X_b , and X_c represent the equivalent synchronous reactance of the three-phase winding of the inner stator a, b, and c, respectively, and R_a , R_b , and R_c represent the equivalent resistance of the three-phase winding of the inner stator a, b, and c.

$$\begin{cases} \dot{E}_{A0} = E_M \angle 0^\circ \\ \dot{E}_{B0} = E_M \angle 120^\circ \\ \dot{E}_{C0} = E_M \angle 240^\circ \end{cases} ; \begin{cases} \dot{E}_{a0} = E_m \angle 0^\circ \\ \dot{E}_{b0} = E_m \angle 120^\circ \\ \dot{E}_{c0} = E_m \angle 240^\circ \end{cases} \quad (1)$$

where E_M represents the amplitude of the induced electromotive force of the three-phase winding of the outer stator, and E_m represents the amplitude of the induced electromotive force of the inner-stator three-phase winding.

In an ideal situation, the three-phase winding structure is identical, and the equivalent synchronous reactance and equivalent resistance are the same, which can be expressed as:

$$X_A = X_B = X_C = X_{ABC}; X_a = X_b = X_c = X_{abc} \quad (2)$$

$$R_A = R_B = R_C = R_{ABC}; R_a = R_b = R_c = R_{abc} \quad (3)$$

where X_{ABC} and R_{ABC} , respectively, represent the equivalent synchronous reactance and equivalent resistance of the three-phase winding of the outer stator, and X_{abc} and R_{abc} represent the equivalent synchronous reactance and equivalent resistance of the three-phase winding of the inner stator, respectively.

U_a , U_b , and U_c , respectively, represent the three-phase voltage of the new radial flux claw pole motor. It can be seen from the figure that under ideal conditions, the three-phase voltage can be expressed as:

$$\begin{cases} \dot{U}_A = U_M \angle 0^\circ \\ \dot{U}_B = U_M \angle 120^\circ \end{cases} ; \begin{cases} \dot{U}_a = U_m \angle 0^\circ \\ \dot{U}_b = U_m \angle 120^\circ \end{cases} \quad (4)$$

$$U_C = U_M \angle 240^\circ \quad U_c = U_m \angle 240^\circ$$

where U_M represents the amplitude of the voltage at the three-phase winding end of the outer stator, and U_m represents the amplitude of the voltage at the three-phase winding end of the inner stator.

Based on the main magnetic flux path and operating principle of the double-stator claw pole motor shown in Figures 3 and 4, PMCPM1 can construct an equivalent magnetic circuit model, as shown in Figure 6. The paths of the inner and outer magnetic circuits are the same, so the topology of the equivalent magnetic circuit model on the inner and outer sides is the same, but the magnetic resistance is different.

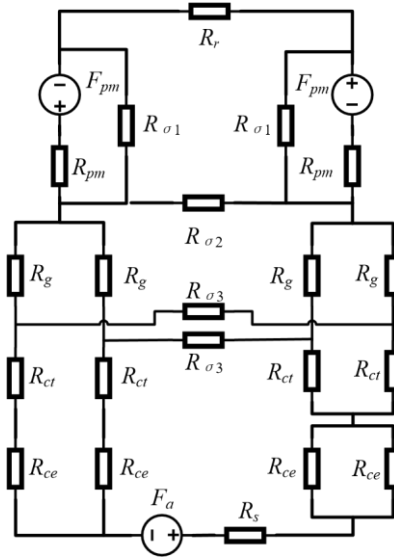


Figure 6. Equivalent magnetic circuit model of PMCPM1.

In Figure 6, R_r represents the magnetic resistance of the rotor core, R_{pm} represents the magnetic resistance of the permanent magnet, and $R_{\sigma 1}$ is the leakage resistance between permanent magnets. $R_{\sigma 2}$ is the leakage reluctance between the permanent magnet and the rotor core, R_g is the air gap reluctance, R_{ct} is the reluctance of the claw pole teeth, $R_{\sigma 3}$ is the leakage magnetic resistance between the claw pole teeth, R_{ce} is the wall magnetic resistance of the claw pole, R_s is the equivalent magnetic resistance of the stator yoke, F_a is the equivalent magnetic electromotive force of the armature winding, and F_{pm} is the excitation magnetic electromotive force of the permanent magnet.

PMCPM2 can construct an equivalent magnetic circuit model, as shown in Figure 7. Due to the mutual coupling of the inner and outer magnetic circuits of PMCPM2, the equivalent magnetic circuit model constructed needs to consider the inner and outer stators.

In Figure 7, R_{pm} in the figure are the permanent magnet reluctance, $R_{\sigma 1}$ are the leakage resistance between permanent magnets, $R_{\sigma 2}$ and $R'_{\sigma 2}$ are the leakage reluctance between the permanent magnet and the rotor core, R_g and R_g are the segmented air gap reluctance, R_{ct} and R_{ct}^0 are the segmented reluctance of the claw pole teeth, $R_{\sigma 3}$ and $R'_{\sigma 3}$ are the leakage magnetic resistance between the claw pole teeth, R_{ce} and R_{ce}^0 are the wall magnetic resistance of the claw pole, R_s and R_s^0 are the equivalent magnetic resistance of the stator yoke, F_a and F_a^0 are the equivalent magnetic electromotive force of the armature winding, and F_{pm} are the excitation magnetic electromotive force of the permanent magnet.

The combination of an analytical method and magnetic circuit can be used to solve the equivalent systems in Figures 6 and 7. The analytical calculation section is based on the axial center section of the claw pole permanent magnet motor to establish a twodimensional analytical model. Firstly, it is assumed that the model is a slot-less motor model, ignoring the slotting effect. The no-load air gap magnetic density expression is calculated under the slot-less condition. The claw pole gap is equivalent to the stator slot, and the slotting effect is considered through the relative air gap

magnetic permeability function. The saturation correction coefficient that needs to be introduced is calculated through the equivalent magnetic circuit model. By combining these three parts, a complete expression of the no-load air gap magnetic density is obtained. Afterwards, based on the magnetic flux path of the claw pole permanent magnet motor under a pair of poles, and based on the three-dimensional structural parameters of the motor and the B-H curve of the ferromagnetic material, the calculation formula for the magnetic resistance of each part of the motor structure is derived. An equivalent magnetic circuit model under a pair of poles is established, and the air gap leakage coefficient and equivalent magnetic flux flowing through different positions are calculated. Combined with the analytical method, the air gap magnetic flux density amplitude and radial magnetic flux at different times are calculated. The tangential air gap magnetic density waveform is used to calculate the average torque, magnetic core loss, power factor, and operating efficiency of the motor under different current densities to quickly calculate the electromagnetic performance of the claw pole permanent magnet motor.

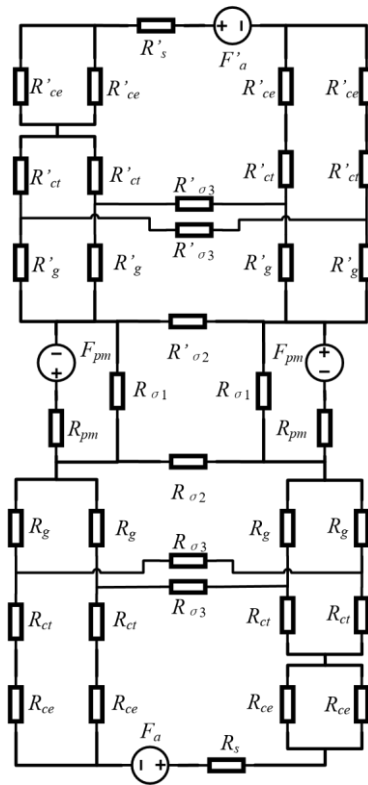


Figure 7. Equivalent magnetic circuit model of PMCPM2.

Considering the nonlinear characteristics of the silicon steel material used in the rotor magnetic core and the soft magnetic composite material used in the stator magnetic core, iterative calculation is required when calculating the equivalent magnetic resistance. Firstly, set the initial magnetic permeability of the material, insert it into the equivalent magnetic resistance calculation formula, establish an initial equivalent magnetic circuit model, calculate the magnetic flux flowing in the path, obtain the magnetic induction intensity B , insert it into the B-H curve to obtain the magnetic permeability at this time, and calculate its deviation from the initial magnetic permeability. If the deviation is less than 5%, take this magnetic permeability as the final magnetic permeability of the part of the magnetic resistance; if the calculation deviation is greater than 5%, the magnetic permeability at this time will be used as the initial magnetic permeability for iterative calculation again until the error meets the requirements.

2.3. Analysis of Equivalent Power Equation

Claw pole motor is a permanent magnet synchronous motor. The electromagnetic power of a permanent magnet motor can be expressed as:

$$P_{em} = \frac{mZ}{T_0} \int_0^T e(t)i(t)dt \quad (5)$$

where m represents the number of motor phases; T represents the electrical cycle of the motor; and $e(t)$ and $i(t)$ represent the changes in the back electromotive force and current of the motor over time, respectively.

$e(t)$ and $i(t)$ can be expressed as:

$$e(t) = E_m \sin\left(\frac{2\pi}{T}t\right) \quad (6)$$

$$i(t) = I_m \sin\left(\frac{2\pi}{T}t\right) \quad (7)$$

where E_m represents the amplitude of the back electromotive force; I_m represents the amplitude of the current.

By introducing Equations (2) and (3) into Equation (1) and simplifying them, the electromagnetic power of the motor can be obtained as:

$$P_{em} = \frac{mZ}{T_0} \int_0^T E_m I_m \sin\left(\frac{2\pi}{T}t\right) \sin\left(\frac{2\pi}{T}t\right) dt = \frac{mZ}{T_0} E_m I_m \int_0^T \sin^2\left(\frac{2\pi}{T}t\right) dt \quad (8)$$

The amplitude of the back electromotive force can be determined by the magnetic flux ψ . The derivative obtained over time is expressed as:

$$E = - \frac{d\psi}{dt} \quad (9)$$

During the operation of a permanent magnet motor, as the rotor permanent magnet rotates, the permanent magnet flux that intersects with the winding changes over time. The no-load permanent magnet flux of the permanent magnet motor can be expressed as:

$$\psi = N_{coil} \phi_m \cos\left(\frac{2\pi}{T}t\right) \quad (10)$$

where N_{coil} represents the number of winding turns; ϕ_m represents the maximum permanent magnetic flux.

By introducing Equation (9) into Equation (10), the expression for the back electromotive force of a permanent magnet motor can be obtained as follows:

$$E = \frac{2\pi N}{T} \phi_m \sin\left(\frac{2\pi}{T}t\right) \quad (11)$$

The peak current of a permanent magnet motor can be expressed as:

$$I_m = J_c A_{coil} k_{sf} \quad (12)$$

where J_c represents the current density, A_{coil} represents the cross-sectional area of the winding, and k_{sf} represents the slot fill rate.

For permanent magnet synchronous motors using centralized or distributed winding structures, the slot fill ratio is generally between 0.5 and 0.6, while claw pole motors using global winding structures can achieve a slot fill ratio of 0.8.

Introducing Equations (10) and (12) into Equation (8) can obtain the expression for the electromagnetic power of TPMCPM:

$$P_e = \frac{m}{2} \omega_r P_r N_{coil} \phi_m J_c A_{coil} k_s f \quad (13)$$

The electromagnetic torque of TPMCPM can be expressed as:

$$T_e = e \frac{m}{2} P_r N_{coil} \phi_m J_c A_{coil} k_s f \quad (14)$$

The torque performance of the inner and outer stators of PMCPM1 and PMCPM2 on the rotor can be represented by Equation (14). The inner and outer magnetic circuits of PMCPM1 do not interfere with each other, which can be expressed as:

$$T_{PMCPM1} = \frac{m}{2} P_r J_c k_s f (\phi_{m_outer} N_{coil_outer} A_{coil_outer} + \phi_{m_inner} N_{coil_inner} A_{coil_inner}) \quad (15)$$

where ϕ_{m_outer} and ϕ_{m_inner} represent the magnetic flux linkage of the inner and outer windings, N_{m_outer} and N_{m_inner} represent the number of turns of the inner and outer windings, and A_{m_outer} and A_{m_inner} represent the winding area of the inner and outer windings, respectively, P_r represent the number of pole pairs of the motor.

The coupling of the inner and outer magnetic circuits of PMCPM2 can be approximately assumed to be the same as the outer magnetic flux without considering magnetic leakage.

$$T_{PMCPM2} = \frac{m}{2} P_r J_c k_s f \phi_m (N_{coil_outer} A_{coil_outer} + N_{coil_inner} A_{coil_inner}) \quad (16)$$

3. Performance Analysis and Comparison

This section may be divided by subheadings. It should provide a concise and precise description of the FEA analysis results, their interpretation, as well as the conclusions that can be drawn from the FEA analysis.

3.1. No-Load Performance Analysis

The magnetic density clouds of TPMCPM and PMCPM1 and PMCPM2 are shown in Figure 8. As shown in the figure, the maximum magnetic density of PMCPM1 and PMCPM2 occurs at the waist of the stator claw pole, with an average magnetic density of approximately 1.75 T. Then, an average magnetic density of TPMCPM occurs in the rotor core with a maximum magnetic density of approximately 1.9 T.

In Figure 9, the no-load permanent magnet flux comparison of three motors is shown. The outer stator structure of PMCPM1 and PMCPM2 is identical to that of TPMCPM, but the double-stator structure significantly increases the no-load permanent magnet flux amplitude of the outer winding. The no-load permanent magnet flux amplitude of TPMCPM is 41.6 mWb, while the no-load permanent magnet flux amplitude of PMCPM1 and PMCPM2 is 46.3 mWb and 46.7 mWb, which is 11.3% and 12.3% higher than that of TPMCPM. The amplitude of the no-load permanent magnet flux of the inner stator is significantly smaller than that of the outer stator. Due to the cross linkage of the inner and outer stator magnetic circuits, the amplitude of the no-load permanent magnet flux of PMCPM2 is much greater than that of PMCPM1. TPMCPM does not have an inner stator, so it can be seen that the double-stator structure has a relatively high utilization rate for the internal space of the motor.

Figure 10 shows the no-load electromotive force of the outer stator winding of three PMCPMs. The no-load electromotive force amplitude of TPMCPM is 102.2 V, and the no-load electromotive force amplitude of PMCPM1 and PMCPM2 is 109.0 V and 104.7 V. The electromotive force of three motors is similar. However, it can be seen from Figure 10b that the no-load electromotive force fundamental amplitude of TPMCPM is 87.1 V, and the no-load electromotive force fundamental amplitude of PMCPM1 and PMCPM2 is 100.4 V and 99.7 V, which is 15.3% and 14.5% higher than

TPMCPM. The third and seventh harmonics of the no-load electromotive force of PMCPM1 and PMCPM2 are significantly reduced, the total harmonic distortion (THD) of the no-load electromotive force of TPMCPM is 21.7%, and the THDs of the no-load electromotive force of PMCPM1 and PMCPM2 are 17.0% and 12.6%, respectively. The double-stator structure significantly reduces the harmonic content of electromotive force. Figure 11 shows the comparison of the no-load electromotive force of the inner stator of two double-stator PMCPMs. The no-load electromotive force amplitude of the inner stator winding is 70.4 V and 120.7 V, and the no-load electromotive force THDs are 43.5% and 46.1%, respectively. Because the thickness of the rotor of PMCPM2 is thin, the inner rotor structure can be designed to be larger, so the winding electromotive force of the inner stator is larger. Due to the high harmonic content of the no-load electromotive force in the inner stator winding of the two motors, the double-stator structure may have a large cogging torque and torque ripple.

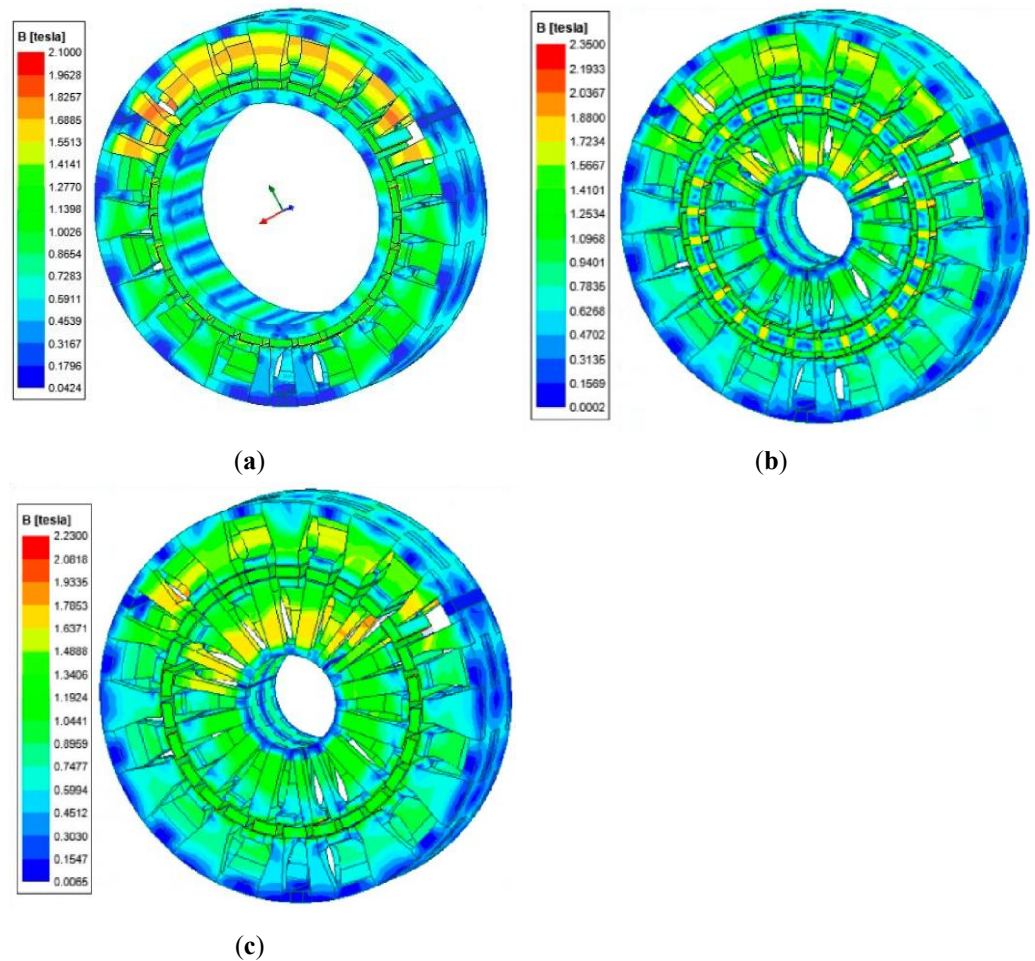


Figure 8. No-load magnetic density cloud diagram. (a) TPMCPM; (b) PMCPM1; (c) PMCPM2.

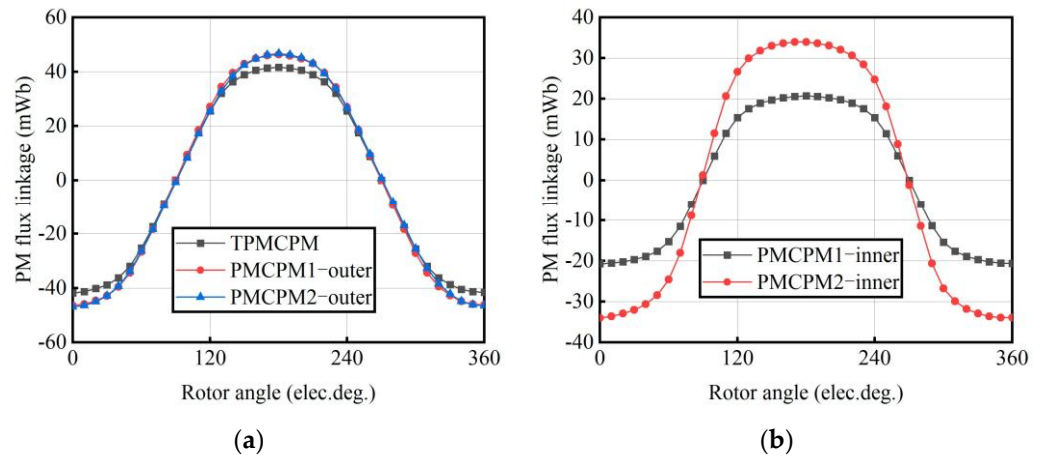


Figure 9. Comparison of no-load permanent magnet flux linkage. (a) Outer stator winding; (b) inner stator winding.

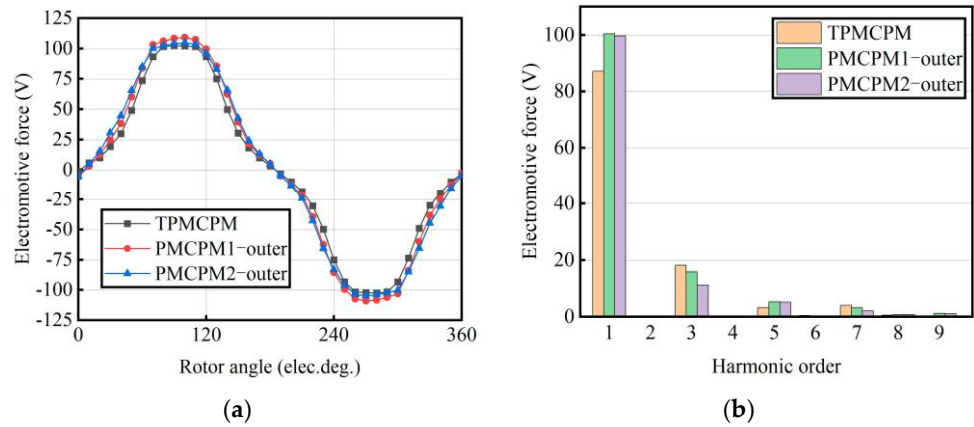


Figure 10. Comparison of no-load electromotive force between the outer stator coil of PMCPM1 and PMCPM2. (a) No-load electromotive force; (b) FFT of no-load electromotive force.

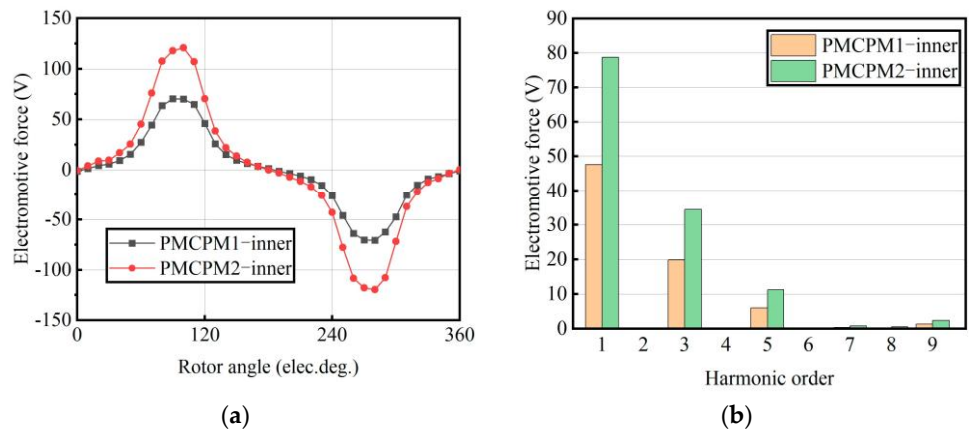


Figure 11. Comparison of no-load electromotive force between the inner stator coil of PMCPM1 and PMCPM2. (a) No-load electromotive force; (b) FFT of no-load electromotive force.

Figure 12 shows the self-inductance of the inner and outer windings of a PMCPM1 structure double-stator claw pole motor. It can be seen that the average self-inductance of the outer winding is 1334 μ H. The average self-inductance of the inner winding is 887 μ H. The average self-inductance of the outer winding is greater than that of the inner winding because the magnetic circuits between the inner and outer windings of PMCPM1 are not coupled. The outer permanent magnet of the outer winding and rotor can be regarded as an inner rotor claw pole motor, and the inner permanent magnet of the inner winding and rotor can be regarded as an outer rotor claw

pole motor. Due to the short magnetic circuit and fewer permanent magnets in the external rotor claw pole motor, the self-inductance is low.

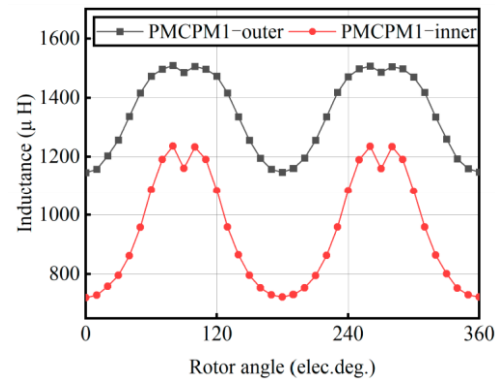


Figure 12. Self-inductance of the inner and outer stators of PMCPM1.

Figure 13 shows the self-inductance of the inner and outer windings of a PMCPM2 structure double-stator claw pole motor. It can be seen that the average self-inductance of the outer winding is 1344 μ H. The average self-inductance of the inner winding is 2455 μ H. The average self-inductance of the outer winding is the same as that of the outer winding of PMCPM1, while the inner winding is much greater than the average self-inductance of the inner winding of PMCPM1. This is because the rotor thickness of PMCPM2 is relatively thin, so the inner winding can be designed to be relatively large. At the same time, the rotor has only a single layer, and the inner and outer magnetic circuits are mutually exclusive. Therefore, the inner winding of PMCPM2 has a higher self-inductance.

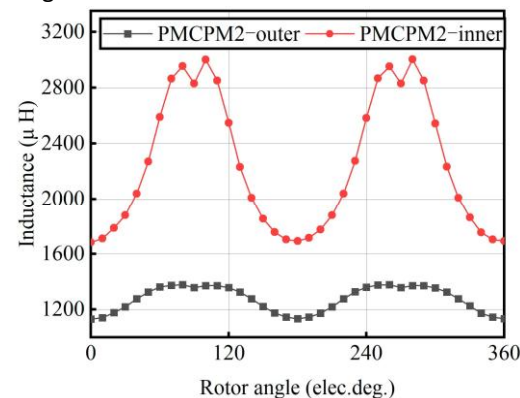


Figure 13. Self-inductance of the inner and outer stators of PMCPM2.

The self-inductance of TPMCPM is 83.3 μ H. The self-inductance of PMCPM1 and PMCPM2 is far greater than that of TPMCPM, which is conducive to sensorless vector control and the direct torque control of motors. The inner and outer windings of PMCPM2 are interconnected, resulting in significant mutual inductance between the inner and outer windings. The mutual inductance between the windings corresponding to the inner and outer sides is the maximum, that is, the mutual inductance between A and a, B and b, and C and c. In Figure 14a, the mutual inductance of these three sets of corresponding windings is shown. Figure 14b–d show the mutual inductance between the outer A, B, and C windings and the inner three-phase winding. It can be seen that the mutual inductance between phase A and a is 32.8 μ H. The mutual inductance between A and b is 19.4 μ H. The mutual inductance between A and c is 24.6 μ H. The inductance between the three-phase windings of the inner and outer windings is shown in Table 2.

Table 2. Self-inductance and mutual inductance of inner and outer windings of PMCPM2.

Coil	A	B	C
a	32.8 μ H	19.4 μ H	24.6 μ H

b	19.4 μ H	32.8 μ H	19.4 μ H
c	24.6 μ H	19.4 μ H	32.8 μ H

Figure 15 shows the cogging torque of three PMCPMs. It can be seen from the figure that the peak-to-peak cogging torque of TPMCPM is 1.2 Nm, and the peak-to-peak cogging torques of PMCPM1 and PMCPM2 are 2.2 Nm and 3.1 Nm, increasing by 83.3% and 158.3% compared with TPMCPM. The cogging torque of the double-stator structure is larger than that of the single-stator structure. For the PMCPM1, the cogging torque and torque generated by the inner and outer windings can generate a phase difference by changing the position of the inner and outer permanent magnets and the current phase of the inner and outer windings, thus reducing the cogging torque and torque ripple.

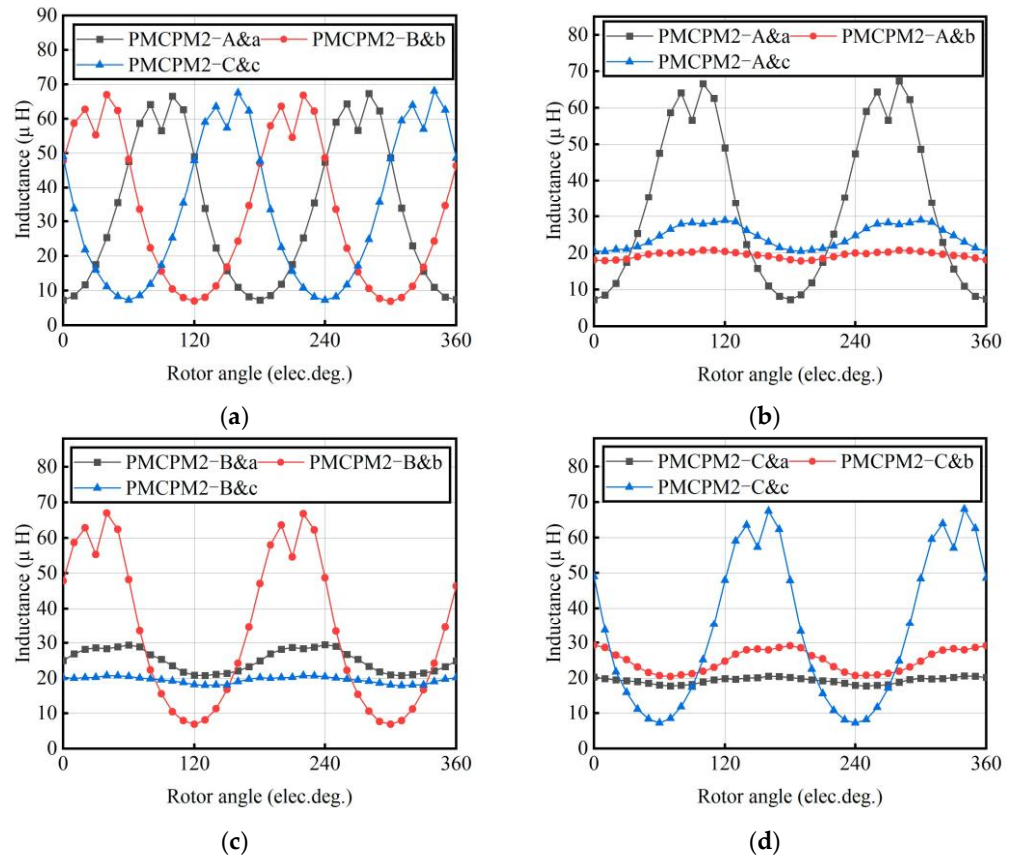


Figure 14. Mutual inductance of inner and outer windings of PMCPM2. (a) Inner and outer mutual inductance; (b) external A-phase and internal three-phase mutual inductance; (c) external B-phase and internal three-phase mutual inductance; (d) external C-phase and internal three-phase mutual inductance.

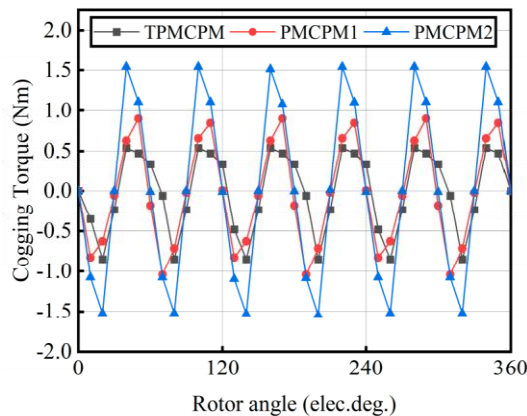


Figure 15. Comparison of cogging torque of three PMCPMs.

3.2. Load Performance Analysis

Figure 16 shows the average torque of three types of PMCPMs under different current densities, and Figure 17 shows the torque waveforms of three types of PMCPMs under 6 A/mm² operating conditions. It can be seen that the torque of the two types of doublestator structure motors is significantly higher than that of TPMCPM. At 6 A/mm², the average torque of TPMCPM was 27.8 Nm, and the average torques of PMCPM1 and PMCPM2 were 41.5 Nm and 46.9 Nm, respectively, which increased by 49.3% and 68.7% compared to TPMCPM. However, under the working condition of 6 A/mm², the torque ripple of TPMCPM is 14.8%, and the torque ripples of PMCPM1 and PMCPM2 are 16.9% and 22.7%, respectively. The torque ripple increased by 14.2% and 53.4% compared to TPMCPM. As the current density increases, the slope of the change in the torque gradually decreases, which is caused by the large leakage of the stator core of the PMCPM. As shown in Figure 16, the slopes of PMCPM1 and PMCPM2 at different positions are greater than those of TPMCPM, indicating that the overall magnetic leakage of the double-stator motor is smaller than that of TPMCPM.

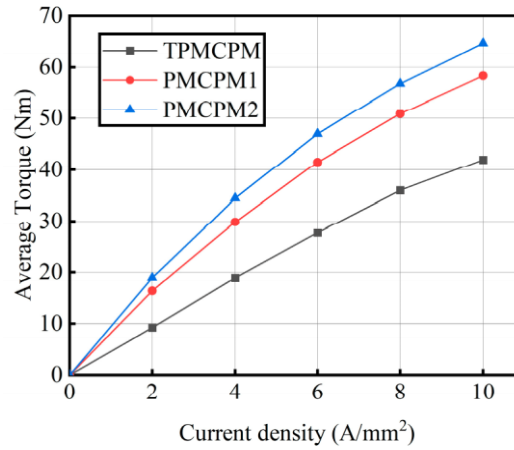


Figure 16. Comparison of torque under different current densities.

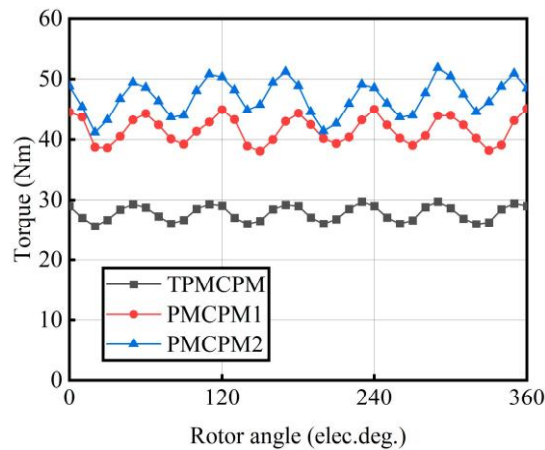


Figure 17. The torque waveforms under 6 A/mm² operating conditions.

In Figure 18, the power factor comparison between two double-stator PMCPMs and TPMCPM is presented. It can be seen that the power factor of the outer stator windings of PMCPM1 and PMCPM2 is slightly higher than that of TPMCPM. However, the power factor of the inner stator winding is low, which is caused by the large no-load electromotive force harmonics of the inner-stator windings of the double-stator structure. Since the no-load electromotive force harmonic content of the inner-stator winding of the PMCPM2 is greater than that of the PMCPM1, the power factor of the inner-stator winding of the PMCPM2 is lower.

The iron loss of TPMCPM, PMCPM1, and PMCPM2 is a function of speed and torque.

In Figure 19, as the speed increases, the iron loss gradually increases. When the speed is 1500 rpm and the current density is 6 A/mm², the iron losses of TPMCPM, PMCPM1, and PMCPM2 are 69.6 W, 126.7 W, and 144.1 W, respectively. Due to the addition of an inner stator in the double-stator structure, the inner stator significantly increases the motor's iron loss. The inner space of PMCPM2 is larger, and the inner stator is much larger than PMCPM1, resulting in a 13.7% increase in motor iron loss compared to PMCPM2.

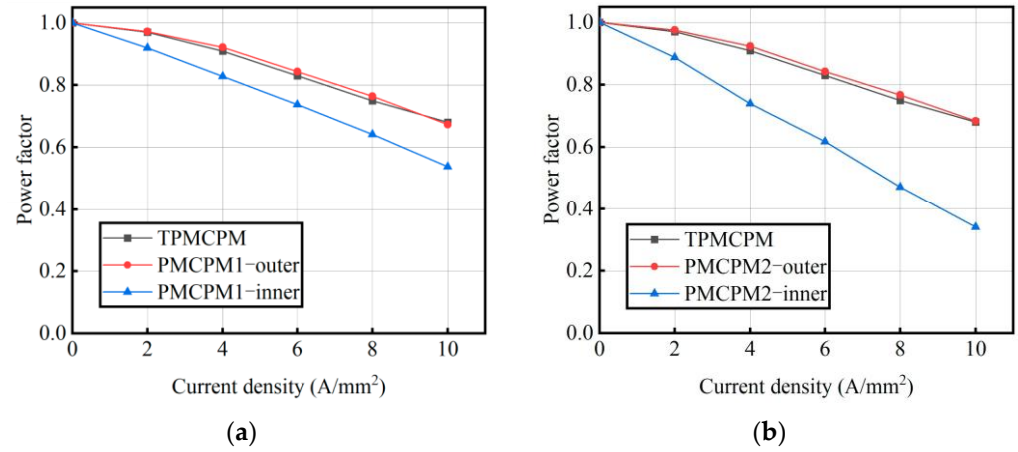


Figure 18. Power factor comparison of two double-stator claw pole motors. (a) PMCPM1; (b) PMCPM2.

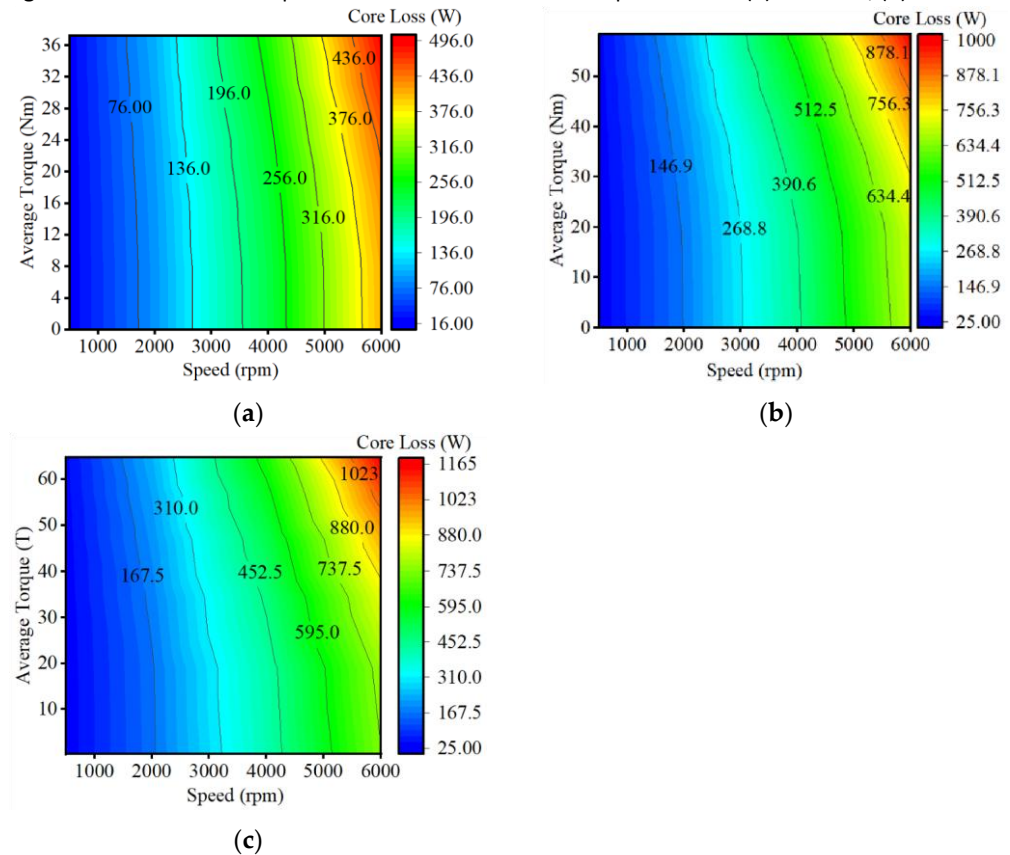


Figure 19. Cloud chart of iron core loss. (a) TPMCPM; (b) PMCPM1; (c) PMCPM2.

Figure 20 shows a cloud plot of the efficiency of TPMCPM, PMCPM1, and PMCPM2 as a function of speed and torque. As shown in the figure, at a speed of 1500 rpm and a current density of 6 A/mm², the efficiencies of TPMCPM, PMCPM1, and PMCPM2 are 0.971, 0.970, and 0.969, respectively. The efficiency of the three different structures of PMCPMs is not significantly different. The double-stator structure has little effect on the efficiency of PMCPMs.

Table 3 shows the core loss and efficiency of three claw pole motors under different operating conditions. It can be seen that the iron loss of PMCPM2 is greater than that of PMCPM1 under the three operating conditions, while the iron loss of TPMCPM is the smallest. This is because TPMCPM does not have an inner stator core. Under three operating conditions, the efficiency of PMCPM1 and PMCPM2 is lower than that of TPMCPM due to the lower power factor of the inner stator of the dual-stator structure and the higher

harmonic content of the back electromotive force, resulting in a higher copper loss of the inner winding.

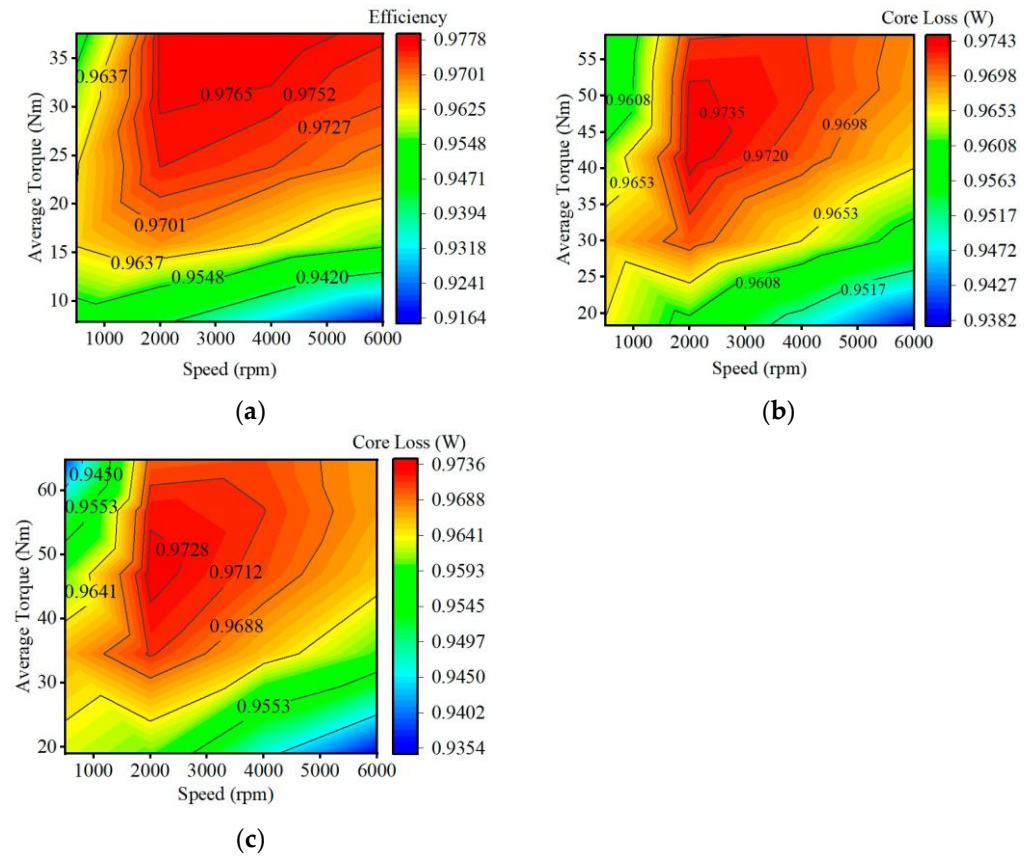


Figure 20. Efficiency cloud chart. (a) TPMCPM; (b) PMCPM1; (c) PMCPM2.

Table 3. Mechanical properties of four materials.

Performance	Operating Conditions	TPMCPM	PMCPM1	PMCPM2
Core loss	1500 rpm 6 A/mm ²	72 W	137 W	157 W
	3000 rpm 6 A/mm ²	13 W	278 W	289 W
	6000 rpm 6 A/mm ²	379 W	765 W	784 W
Efficiency	1500 rpm 6 A/mm ²	0.702	0.693	0.697
	3000 rpm 6 A/mm ²	0.745	0.729	0.725
	6000 rpm 6 A/mm ²	0.725	0.695	0.683

4. Interference Assembly Analysis

4.1. Stress Analysis of Interference Assembly

SMC materials are made by pressing and molding SMC material powders that are insulated from each other. SMC material powders are pure-iron powder particles manufactured by powder metallurgy technology and coated with surface insulation. The average diameter of these material particles is about 0.1 mm. The steps of SMC material production include material pretreatment, iron core forming, and heat treatment. The type of SMC material powder, material proportion, pressing stress, and heat treatment process all affect the mechanical strength and magnetic properties of SMC. By manufacturing molds with different shapes, various shapes of iron cores can be made, making them suitable for use in transverse and axial motors with three-dimensional

complex magnetic circuits. However, within the SMC iron core formed by pressing, the number of particles on the indirect contact surface that can reach the range of atomic gravity is limited, so the mechanical strength of the iron core is poor. Increasing the pressing pressure and improving the sintering process can improve the mechanical strength of the motor, but the resulting manufacturing costs also increase sharply.

Interference assembly is often used between the motor stator and casing, but interference assembly can cause significant compressive stress on the motor stator core. When the compressive stress on the stator core exceeds the yield stress, the core will undergo plastic deformation, which affects the electromagnetic performance of the material. Therefore, in motor design, the design criterion should be that the compressive stress of the motor stator core does not exceed the yield strength of the stator material. The stator cores of PMCPM1 and PMCPM2 analyzed in Section 2 are all made of SMC material through direct compression molding. During the interference assembly of the stator and casing, the interference assembly force is mainly concentrated near the interface between the stator yoke and the casing. Therefore, only the interference assembly of PMCPM1 can be analyzed. When using a 0.02 mm interference amount for the interference assembly of the stator core and casing, the force and deformation of the outer and inner stators of PMCPM1 are shown in Figure 21.

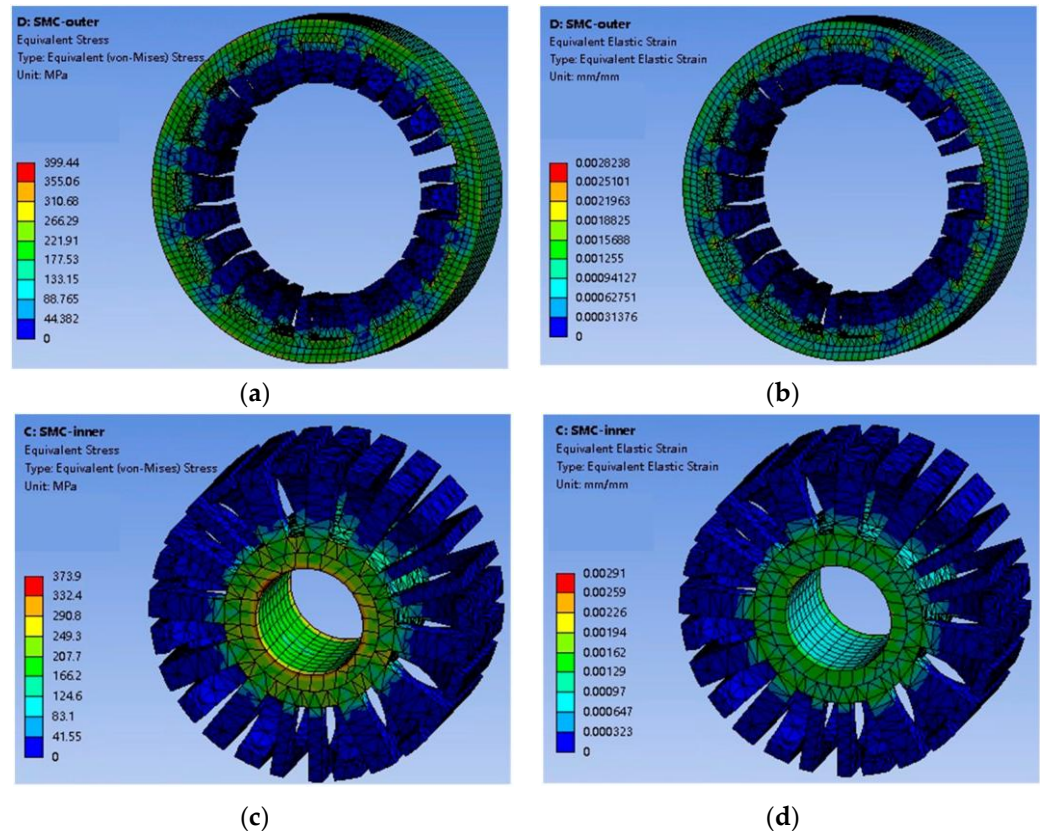


Figure 21. Stress and deformation of PMCPM1 stator. (a) Stress on the outer stator of PMCPM1; (b) strain of the outer stator of PMCPM1; (c) stress on the inner stator of PMCPM1; (d) strain of inner stator of PMCPM1.

From Figure 21, it can be seen that during the interference assembly of PMCPM1 stator and casing, the maximum stresses of the outer stator and inner stator are 399.0 Mpa and 374.0 Mpa, respectively. The compressive yield stress of Somaloy700HR5P grade SMC material is between 100 Mpa and 250 Mpa, and the maximum compressive stress of the stator exceeds the maximum compressive yield stress of SMC material. Therefore, using SMC material to make the stator core does not meet the mechanical strength requirements for interference assembly. When assembling the stator core and casing, the selection of interference amount and whether to perform

interference assembly need to be carefully selected as it is easy to damage the stator core during the assembly process.

4.2. Hybrid Material Magnetic Core Design

We propose a hybrid material magnetic core, where the yoke is made by silicon steel sheets and the poles are made by SMC. Silicon steel material is a common electrical material that has been widely used in transformers, motors, and other electromagnetic equipment. Adding 3.25–5% silicon to ordinary carbon steel forms a silicon carbon soft magnetic alloy, and the motor iron core can be manufactured through iron core punching and lamination pressing. Silicon steel sheet punching also requires processes such as burr removal, insulation treatment, and annealing, resulting in a complex manufacturing process. There is difficulty in ensuring coaxiality during the lamination of silicon steel sheets. At the same time, the magnetic permeability of the silicon steel sheet iron core in the stacking direction of the silicon steel sheet is very low, making it difficult to manufacture motor components with three-dimensional magnetic circuits. Table 4 compares the mechanical properties of SMC materials and silicon steel materials.

Table 4. Mechanical properties of SMC and silicon steel sheet.

Attribute	Units	Somaloy700HR5P	B27AHV1400
Yield strength	Mpa	15	410
Vickers hardness	Hv	160	181
Density	g/cm ³	7.5	7.65
Young's modulus	Mpa	1.5×10^5	1.87×10^5
Poisson's ratio	—	0.23	0.25–0.27

The silicon steel sheet is rolled and welded to form the stator yoke. The stator claw pole is directly molded using SMC, and the thickness of the stator yoke is slightly greater than the thickness of the connecting part between the stator claw pole and the stator yoke. For interference assembly, 1 mm is left at the top. The stator claw pole is assembled with silicon steel at the stator yoke by bonding. Due to the fact that the interference amount for interference assembly is usually selected below 0.02 mm and there is friction between the stator claw pole and the stator yoke assembly groove, it can be considered that interference assembly will not affect the stator claw pole of SMC material. Only the interference assembly between the stator yoke and the casing of silicon steel material can be analyzed. Figure 22 shows the stress and strain of the stator yoke silicon steel during PMCPM1 interference assembly of a hybrid material magnetic core.

In Figure 22, it can be seen that when the PMCPM1 stator designed with a hybrid material magnetic core is assembled with a casing interference, the maximum stresses of the outer and inner stators are 358.5 Mpa and 339.1 Mpa, respectively. Compared with the PMCPM1 stator made entirely of SMC material, the maximum stresses of the outer and inner stators are reduced by 10.2% and 9.33%. The compressive yield stress of silicon steel material is between 450 Mpa and 500 Mpa, so the stator core of claw pole motors designed with hybrid material magnetic cores can be safely assembled with interference, and there is a large stress margin, which can improve the success rate of interference assembly and the overall mechanical strength of the stator core.

In Figure 23, the magnetic permeability and loss densities of silicon steel and SMC materials at 400 Hz and 800 Hz are shown. It can be seen that the magnetic permeability of silicon steel material is higher than that of SMC when the magnetic field strength is less than 4775 A/m, and lower than that of SMC material when the magnetic field strength is greater than 4775 A/m.

The magnetic density of PMCPMs is usually below 1.8 T. At this magnetic flux density, the permeability of silicon steel material is greater than that of SMC material. Therefore, hybrid material magnetic core PMCPMs can achieve greater torque compared to PMCPMs that use SMC material to make stator cores. The eddy current loss of SMC material is relatively low, and replacing it with silicon steel material reduces the stator core loss. There will be additional eddy current loss at the junction of silicon steel material and SMC material, further increasing the loss of PMCPMs. We analyzed the electromagnetic performance of two types of concentric double-stator claw pole

motors using the threedimensional finite element method. Figure 24 shows the curve of no-load permanent magnet flux linkage and the cogging torque and average torque of PMCPM1 and PMCPM2 under a current density of 6 A/mm^2 . From Figure 24, it can be seen that the design of the hybrid material magnetic core can slightly improve the electromagnetic performance of the motor, but the improvement is about 1%.

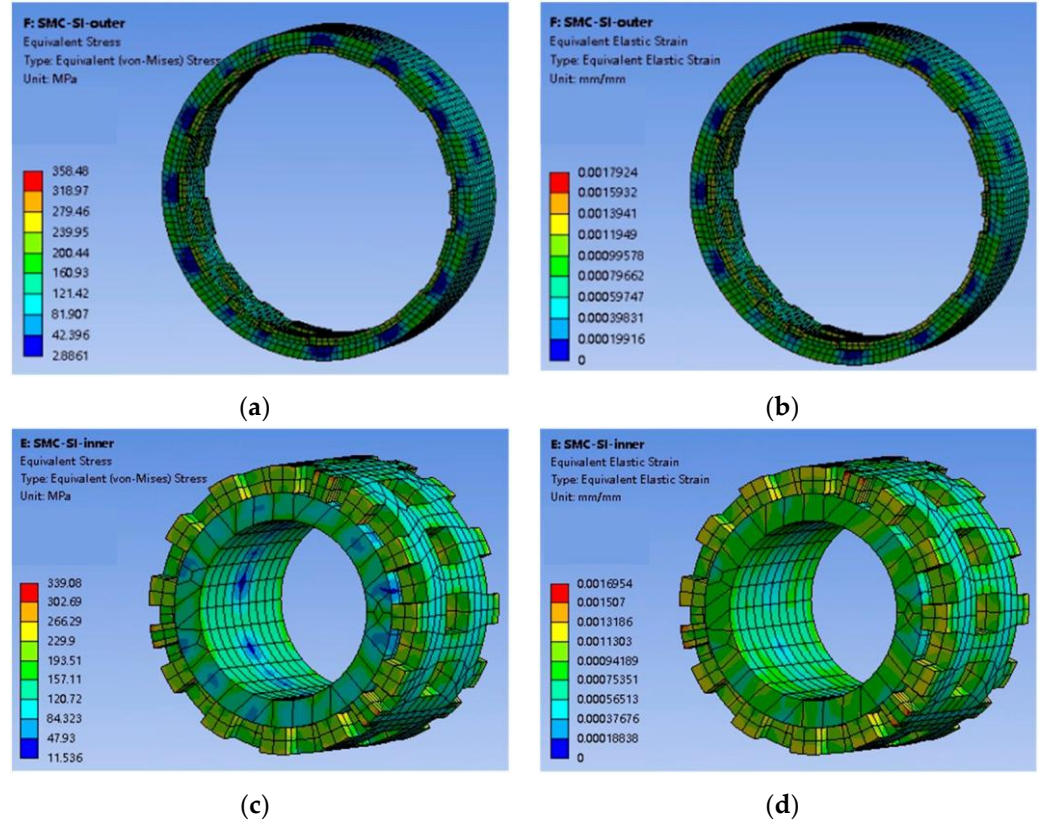


Figure 22. Stress and strain of hybrid material core PMCPM1. (a) Stress on the outer stator of hybrid material core PMCPM1; (b) strain of the outer stator of hybrid material core PMCPM1; (c) stress on the inner stator of hybrid material core PMCPM1; (d) strain of inner stator of hybrid material core PMCPM1.

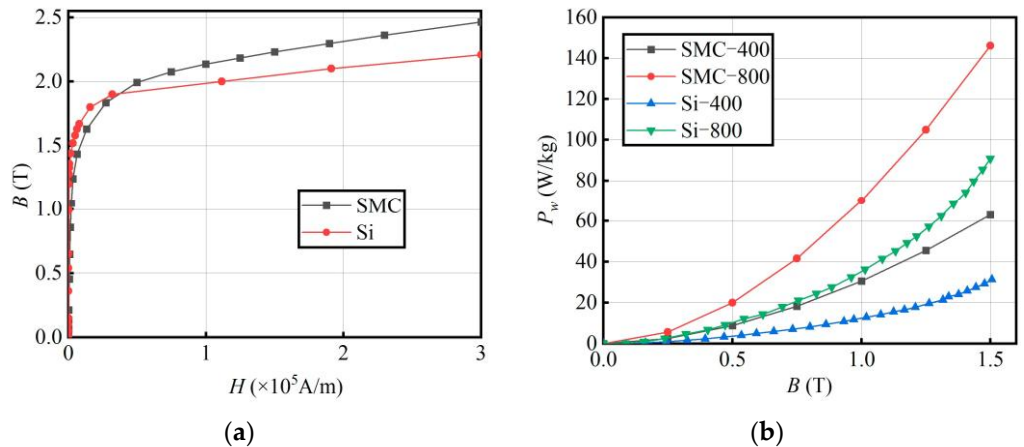


Figure 23. BH curve and loss curve of silicon steel and SMC materials. (a) BH curves of two materials; (b) loss curves of two materials.

In summary, using a mixed-material magnetic core design can improve the mechanical strength of the stator during interference assembly, avoid stator damage, and at the same time slightly increase the torque of the motor.

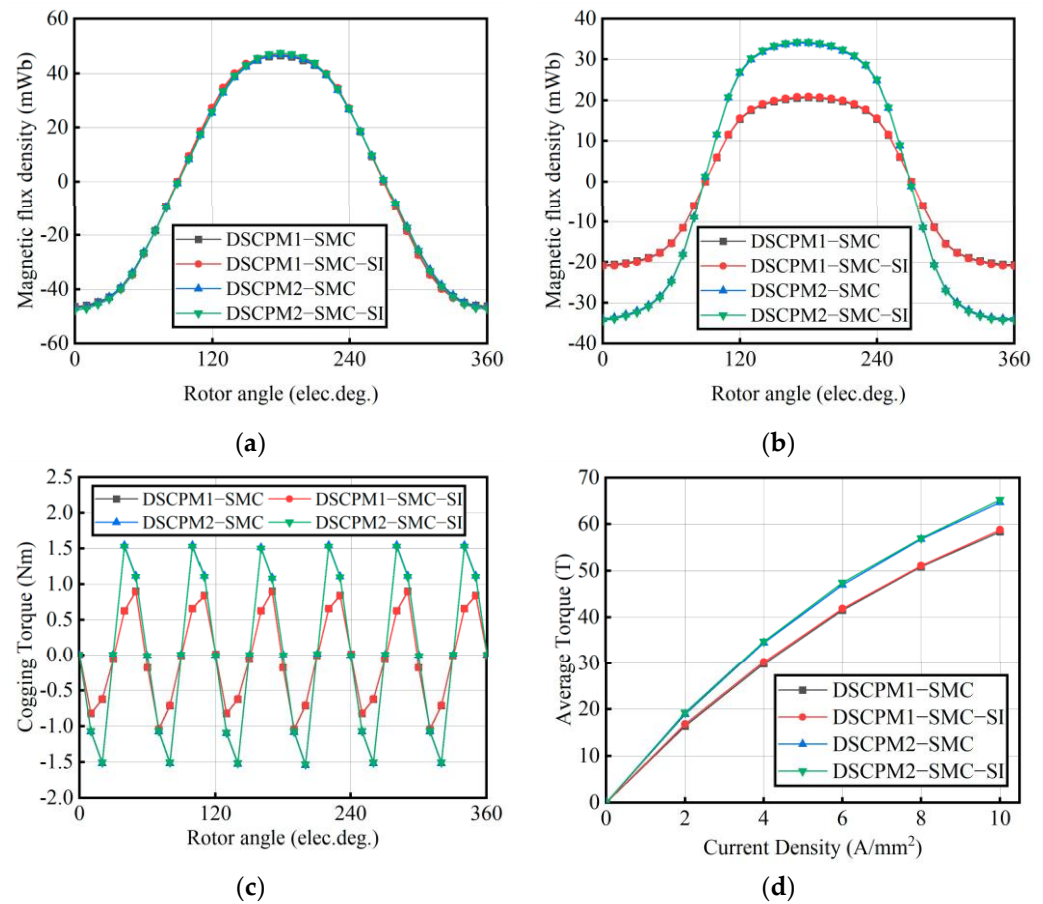


Figure 24. Performance comparison and analysis of hybrid material magnetic core structure motors. (a) Comparison of magnetic flux linkage of outer stator winding; (b) comparison of inner stator winding flux linkage; (c) cogging torque; (d) torque at different current densities.

5. Experimental Verification

There are the following difficulties in the production of the dual stator claw pole motor proposed in this article.

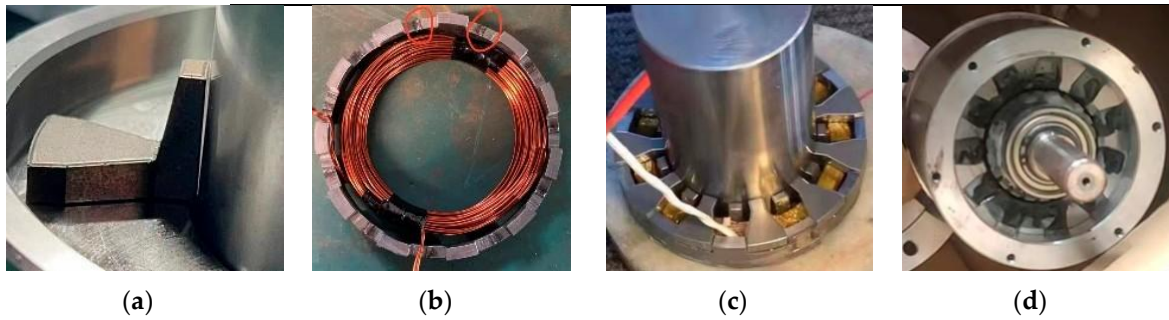
1. The SMC material pressing molding requires the production of a mold, and both the inner and outer layers of claw poles require separate molds, while the auxiliary claw poles also require separate molds.
2. The procurement of SMC materials is subject to import and export restrictions, and the procurement of SMC materials has been completed.
3. The double stator usually adopts a cup rotor structure, and overseas manufacturers with this manufacturing process need a long time to produce it.
4. Neodymium iron boron permanent magnets in permanent magnet motors are expensive, and the claw pole motor studied in this article has a larger size, resulting in a higher cost of neodymium iron boron. Therefore, relevant research funding is being applied for.
5. Convenient control. Unlike traditional permanent magnet synchronous motors, claw pole motors cannot use the $i_d=0$ control method and require reprogramming and the production of controllers.

To verify the correctness of the hybrid material magnetic core and claw pole motor proposed in this article, we conducted experiments on low-cost small-scale traditional claw pole motors with distributed winding. Table 5 shows the dimensional and operational parameters of the prototype.

Figure 25a,b show the key parts of the prototype, including the stator claw pole, winding, and stator yoke made by using silicon steel sheets. Figure 25c,d show the single phase stator assembly diagram and the complete motor assembly diagram.

Table 5. Structure parameters.

Symbol	Describe	Unit	TCPM
R_{so}	Stator outer diameter	mm	50
R_{si}	Stator inner diameter	mm	30
L_{gap}	Air gap length	mm	0.85
H_{pm}	PM radial length	mm	3
A_{pm}	PM circumferential width	deg	8.5
L_{pm}	PM axial length	mm	15
L_{ry}	Rotor yoke thickness	mm	9
L_{tall}	Shaft length	mm	15
$Speed$	Rated speed	rpm	1500
$Speed_m$	Maximum speed	rpm	6000
f_r	Rated frequency	Hz	325
f_m	Maximum frequency	Hz	1300
J_{cr}	Rated current	A/mm ²	6
J_{cm}	Maximum current	A/mm ²	10
P_r	Rated output power	W	471
P_m	Maximum output power	kW	3.14
T_r	Rated torque	Nm	3
T_m	Maximum torque	Nm	5

**Figure 25.** Prototype structure diagram. (a) stator claw pole; (b) windings and stator yoke silicon steel laminations; (c) single-phase stator assembly diagram; (d) complete motor assembly diagram.

The performance of the prototype was tested by using the experimental platform shown in Figure 26. The experimental platform includes a dynamometer system, the signal acquisition system, a torque sensor, an oscilloscope, and a liftable prototype stand. The dynamometer system can output constant speed, the torque sensor has a range of 0–50 Nm, and the four-channel oscilloscope can display three-phase waveforms simultaneously. The signal acquisition system can collect the data output from the speed sensor, torque sensor, and oscilloscope for analysis and processing.

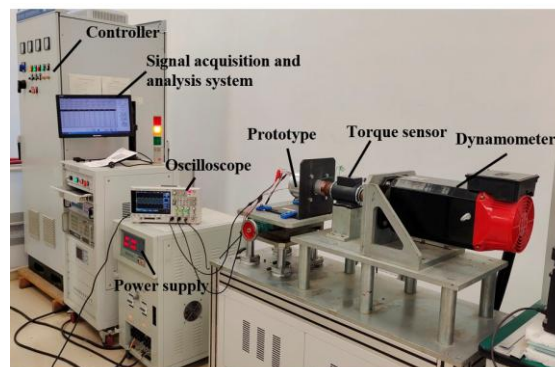
**Figure 26.** Experimental test platform.

Figure 27 shows the comparison of the tested and calculated no-load back EMF of the prototype under the rotor speed of 200 rpm. As shown, the back EMF of the prototype differ from each other by 120 degrees in phase, and the calculated no-load back EMF of the machine is about 1.53 V, and the magnitude of the measured back EMF is about 1.5 V, which may be caused by the increase in the air gap length of the main magnetic circuit and the decrease in the magnetic conductivity due to the small air gap between the stator claw pole and the stator yoke during the manufacturing process. Based on the calculated and measured no-load back EMF comparison, the basic concept of the TCPM made by using hybrid silicon sheets and SMC cores is verified.

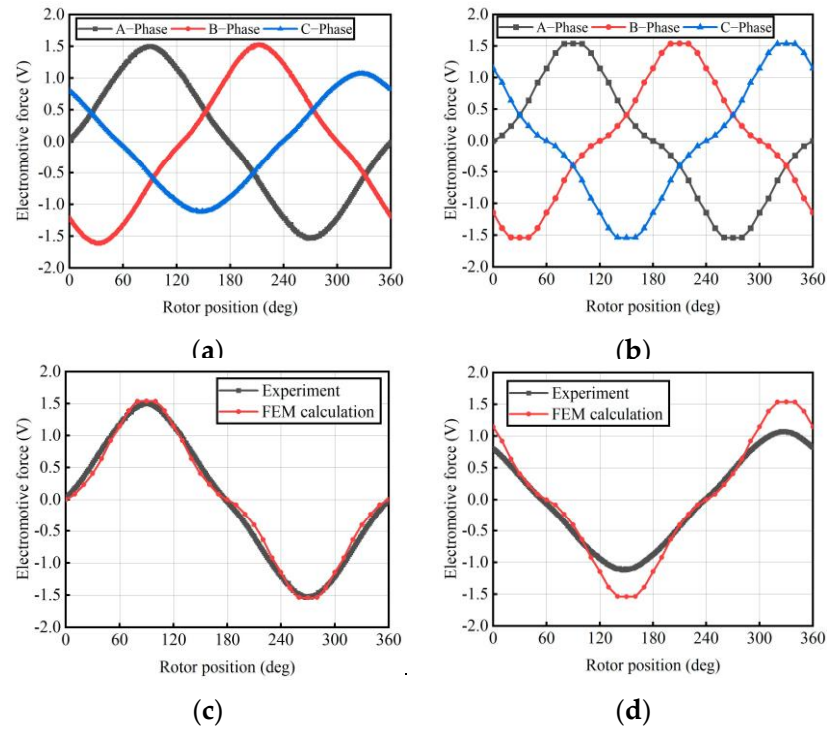


Figure 27. Comparison of experimental and test results. (a) Measured three-phase EMF; (b) calculated three-phase EMF; (c) comparison of calculated and tested of A-phase EMF; (d) comparison of calculated and tested of C-phase EMF.

The misalignment of the permanent magnet production in this experimental type is undergoing readjustment and will take some time. The controller of the claw pole motor is currently under production, and the controller can be subjected to load experiments to further verify the correctness of the mixed-material magnetic core design.

6. Conclusions

Two types of concentric double-stator PMCPMs with different rotor structures were designed using a double-stator structure. The high torque performance of PMCPM1 and PMCPM2 was verified using three-dimensional finite element analysis. Through analysis, it was found that the double-stator structure can significantly improve the torque performance of PMCPMs. The efficiency of the double-stator PMCPM structure is slightly lower than that of TPMCPM. In the interference assembly between the stator core and the casing, the stator core may be damaged if the stator core is made of SMC material completely. Therefore, it is proposed that the stator yoke core is rolled with silicon steel sheet and the stator claw pole is made of SMC material. Through multiphysics simulation analysis, it was verified that the interference assembly and electromagnetic performance meet the requirements.

Author Contributions: H.Z. and S.W. performed Material preparation, data collection, and analysis; H.Z. and C.L. wrote the main manuscript text; S.Z. prepared Figures 4–15 and Tables 1–3. Y.W. and S.W. helped to proofread and suggest changes to the manuscript. All authors reviewed the manuscript. All authors

commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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