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# A Novel Dual-Structure Double-Stator Bidirectional Modulation Vernier Permanent Magnet Direct-Drive Machine

**Kangshuo Zhao*, Zhenghao Li**, Mingyuan Jiang**, Shuangxia Niu**†, Wei Liu**, C.C. Chan**, K.T. Chau****

**Abstract** - Low-speed direct-drive motors have been widely used in wind power generation systems, robotics and electric vehicles due to their reliability and simplified structure. Traditional permanent magnet synchronous motors usually require a large number of stator slots to achieve high pole pair number for higher torque output, which often leads to problems such as increased flux leakage and elevated copper loss. To address these issues, this paper proposes a novel permanent magnet synchronous motor, which innovatively combines the excellent flux modulation effect of the dual-stator bidirectional modulation structure with the merits of a compact Vernier motor structure, thus significantly reducing the number of stator slots and effectively improving flux utilization and output torque. To verify the effectiveness of the proposed motor's flux regulation mechanism and the rationality of its structural design, the time-stepping finite element method is adopted to systematically analyze the motor performance under typical operating conditions, including rated speed and rated load. The results demonstrate that the proposed motor exhibits superior performance in magnetic field modulation, torque output increased by 45.8% and overall efficiency increased from 82% to 86% at speed of 150rpm. Meanwhile, it features stable torque output, low torque ripple, high flux utilization and low losses, confirming its promising application prospects in electric vehicle drives, wind power generation systems and other related direct-drive application fields.

**Keywords**: Bidirectional flux modulation, Double-stator structure, Low-speed drive, Permanent magnet direct-drive machine, Vernier machine

## 1. Introduction

Low-speed direct-drive motors, featuring the absence of intermediate transmission components such as gearboxes, the capability to deliver large torque at low speeds, as well as high efficiency, high reliability, high precision, and low noise and vibration, are widely used in wind power generation systems, the robotics field, and the automotive industry [1][2]. In such applications, the motor is required to simultaneously achieve high torque output and a compact structure, while also meeting the requirements of low power loss and a high magnetic flux utilization rate, so as to align with the development demands for more high-efficiency equipment.

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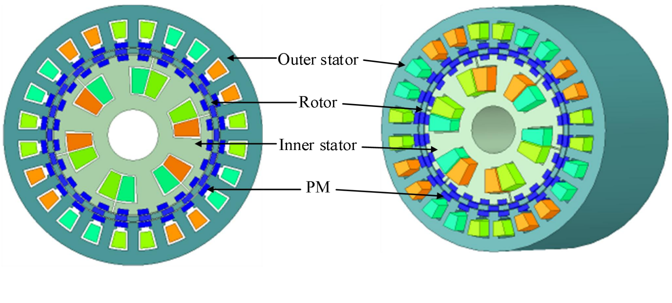
In the structural design of conventional permanent magnet synchronous motors (PMSMs), a large number of stator slots and an increased number of permanent magnets are often required to deliver high torque output.[3-5] However, an excessively high number of slots gives rise to a series of issues: On one hand, it exacerbates the stator slot effect, resulting in increased magnetic leakage flux and a reduced magnetic flux utilization rate; on the other hand, the dense winding arrangement leads to an increase in winding resistance, which causes elevated copper losses and compromises the operational efficiency and service life of the motor.

To further improve the performance of such motors and address the structural drawbacks of conventional PMSMs, scholars have conducted extensive research on structural improvements, proposing topologies such as the Vernier motor[6-13] and the dual-stator motor[14-20]. Nevertheless, such single-structure improved motors still have limitations including insufficient magnetic flux modulation capability and a less compact structure. Based on this, this paper proposes a novel type of permanent magnet synchronous motor, which innovatively integrates the strong magnetic flux modulation capability of the dual-stator bidirectional modulation structure with the compact structural advantage of the Vernier motor. This design significantly reduces the number of stator slots, achieving an improved magnetic flux utilization rate and enhanced torque output [21][22][32-34], thus offering a more optimal driving solution for low-speed direct-drive applications.




(a) (b)

**Fig. 1.** Proposed dual-structure double-stator bidirectional mo dulation vernier permanent magnet direct-drive machine. (a) Cross section. (b) 3D model.

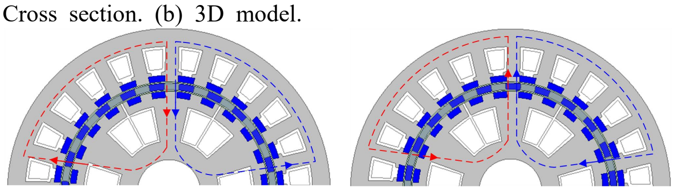


**Fig. 2.** Flux linkage distribution of the dual-structure double -stator bidirectional modulation vernier permanent magnet dire ct-drive machine.

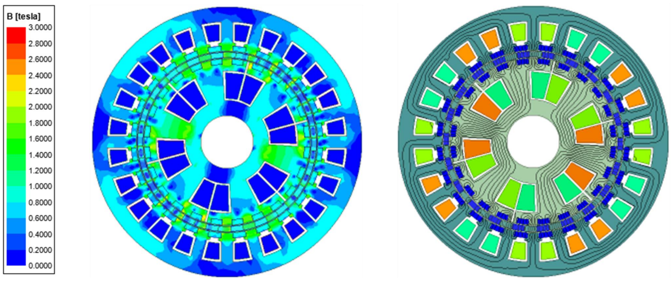


**Fig. 3.** Magnetic field distribution and flux linkages.

TABLE I
MOTOR DESIGN PARAMETERS

| Parameters | Unit | Values |
|---|---|---|
| Rated speed | rpm | 150 |
| Rotor tooth number | - | 22 |
| Inner stator slot number | - | 6 |
| Outer stator slot number | - | 24 |
| Outer stator outer diameter | mm | 104 |
| Rotor inner diameter | mm | 64 |
| Inner stator outer diameter | mm | 63 |
| Inner stator inner diameter | mm | 20 |
| Current density | A/mm2 | 6 |

## 2. Structure of the Proposed Motor

The novel permanent magnet synchronous motor proposed in this paper adopts a dual-stator structure and is integrated with a salient-pole rotor structure[23][24]. Its overall layout is a coaxial nested configuration of inner stator - rotor - outer stator, as shown in Fig. 1. This dual-stator structure incorporates a bidirectional magnetic field modulation mechanism. The stator teeth and the rotor core work together to precisely regulate three magnetic potential sources, namely the rotating permanent magnets on the rotor, the stationary permanent magnets on the dual stators, and the windings of the dual stators. Efficient energy conversion and torque output are achieved through the coupling of these three elements. Specifically, the total number of permanent magnet poles on the dual stators is 24, and that on the rotor is 22. The optimized slot-pole configuration further enhances the efficiency of flux modulation.

The outer stator has 24 slots and adopts a semi-closed slot design, with permanent magnets embedded in the slot openings. The slot-opening permanent magnet structure of the outer stator is collaboratively designed with the salient poles of the rotor. This design can effectively reduce the magnetic reluctance of the magnetic circuit, decrease the magnetic leakage loss, and at the same time enhance the magnetic flux modulation capability and boost the torque output capability of the motor.

The inner stator core has 6 slots. This design, which combines the Vernier structure with a concentrated winding configuration, is the core design for reducing the number of stator slots. The Vernier structure can fully exploit the advantages of flux modulation. When combined with the concentrated winding, it not only ensures the integrity of the magnetic circuit but also significantly increases the slot area. A larger slot area allows for the embedding of more winding conductors, reducing the winding resistance and thereby effectively lowering copper loss. At the same time, the low-slot design frees up the internal space of the motor, simplifies the winding layout, and improves the operational reliability and manufacturing processability of the motor.

The rotor adopts a consequent-pole structure and is combined with a 22-pole permanent magnet system, achieving an optimal slot-pole matching with the dual-stator to ensure the smooth implementation of bidirectional magnetic flux modulation. This structural design is intended to enhance the magnetic coupling effect with the dual-stator and improve the magnetic flux transmission efficiency. Meanwhile, in coordination with the permanent magnets and windings of the dual-stator, it jointly generates a high torque output, thus meeting the operational requirements of low-speed direct-drive scenarios.

As shown in Fig. 2, the flux linkage distribution of the motor is derived from the closed magnetic circuits formed by the magnetic circuit coupling between the inner stator, outer stator and the rotor respectively. As shown in Fig. 3, the magnetic flux distribution indicates that the effective magnetic flux has increased as expected, and no magnetic saturation phenomenon has occurred during loaded operation. This result is consistent with the design expectations. The motor design parameters are listed in Table 1.

## 3. Motor Optimization

After conducting finite element simulation analysis on the initial topology of the dual-structure dual-stator bidirectional flux-modulation permanent magnet direct-drive motor (DS-BFM-PMDDM)[25][26], it is found that although the motor exhibits a significant advantage of high torque density under low-speed operating conditions, it still suffers from problems such as excessive cogging torque ripple and potential room for improvement in torque density[27-31]. As a result, it is difficult to fully meet the stringent requirements for the comprehensive performance of low-speed direct-drive motors.

To further improve the overall operational performance of the motor and achieve the coordinated optimization of torque ripple, average torque and average power factor under given dimensional constraints, this paper carries out targeted research on the optimal design of the motor's structural parameters.

Based on the topological features and magnetic circuit characteristics of the dual-structure dual-stator bidirectional flux-modulation permanent magnet direct-drive motor[27][28], key structural parameters that significantly affect the motor's electromagnetic performance and possess engineering adjustability are selected as optimization design variables. The value ranges of all variables are determined comprehensively by considering machining process constraints and the rationality requirements of magnetic circuit design. The symbols and corresponding positions of each key structural parameter are shown in Fig. 4.

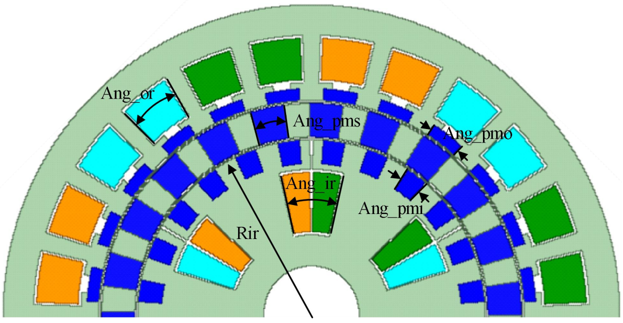



**Fig. 4.** Geometric dimensions of dual-structure double-stator bidirectional modulation ernier permanent magnet direct-drive machine.

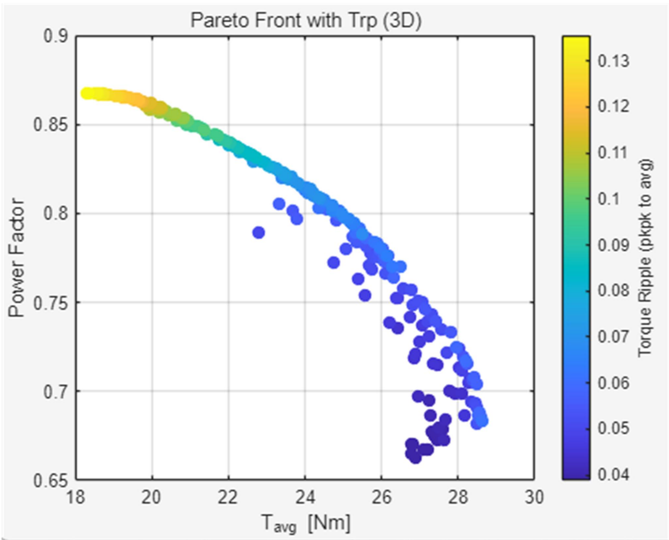
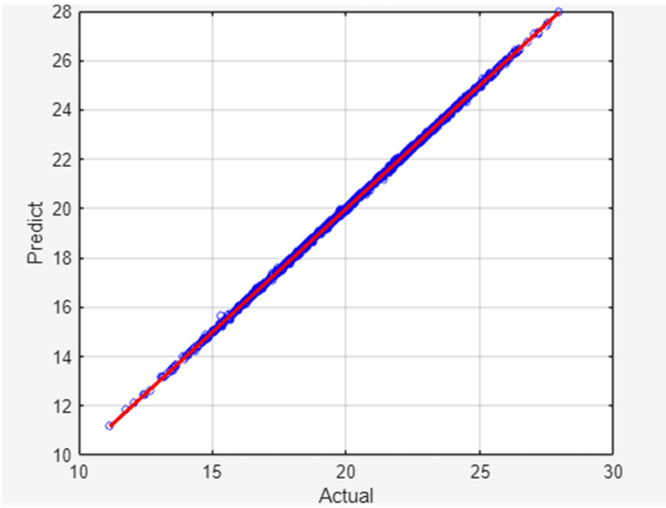



**Fig. 5.** 3D scatter Pareto front plot of multi-objective optimization results for a dual-structure double-stator bidirectional modulation vernier permanent magnet direct-drive machine.

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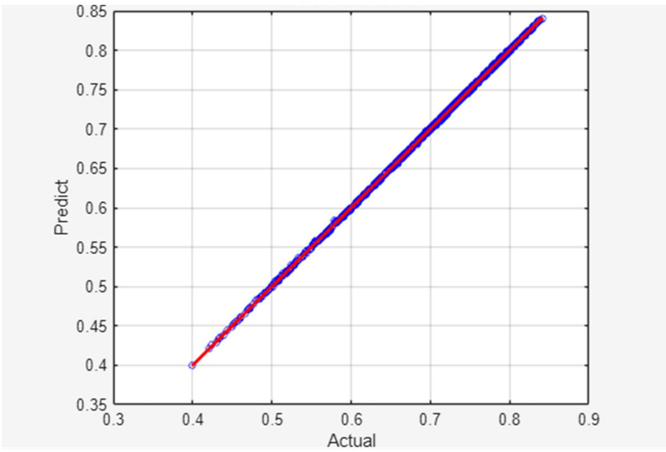
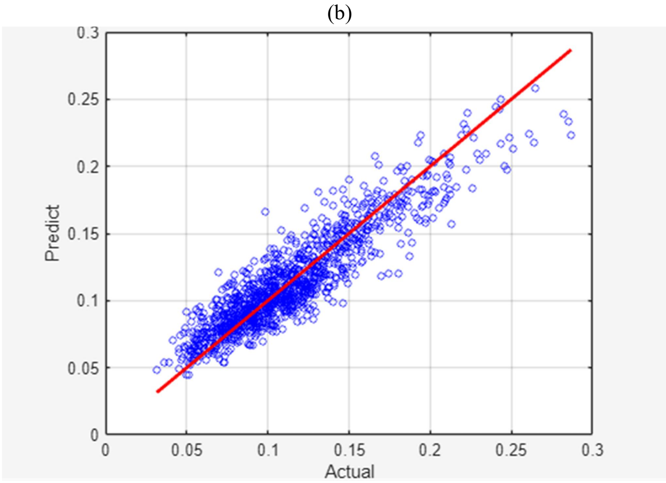



(b)




(c)

**Fig. 6.** Illustration surrogate model fitting accuracy. (a) Average torque. (b) Avg power factor. (c) Ripple.

TABLE II

MOTOR OPTIMIZATION PARAMETERS

| Symbol | Parameters | Unit | Pre-optimization Values | Post-optimization Values |
|---|---|---|---|---|
| Ang-or | Outer stator slot width angle | deg | 9.7 | 11.3 |
| Ang-ir | Inner stator slot width angle | deg | 37.03 | 25.93 |
| Ang-pms | Rotor PM pole arc angle | deg | 8.36 | 9.42 |
| Ang-pmo | Outer stator PM pole arc angle | deg | 8.38 | 8.74 |
| Ang-pmi | Inner stator PM pole arc angle | deg | 7.96 | 7.14 |
| Rir | Inner stator radius | mm | 31.5 | 29 |

The optimization is implemented via a multi-objective design method, yielding several sets of optimized variable combinations. Each combination corresponds to a different performance optimization focus. The detailed optimization results are presented in Fig. 5. Considering the actual operating conditions of low-speed direct-drive motors, the core selection criterion is defined as prioritizing both high torque density and high efficiency while ensuring low torque ripple. From the multiple optimization schemes, the parameter combination with the best overall performance is determined. Fig. 6. shows the fitting accuracy of the surrogate model. It can be seen from the figure that the surrogate model has a good predictive ability for the calculation results of the three optimization objectives, among which the fitting accuracy for the results of the two primary optimization objectives is higher with a more robust prediction performance.

The specific values and variation rates of each key structural parameter before and after optimization are listed in Table II. Through parameter adjustment, the motor's structural layout is effectively optimized, the magnetic flux leakage is reduced, the air-gap magnetic field density is enhanced, and the motor's operating efficiency is further improved.

To verify the effectiveness of the structural parameter optimization, 2D finite element electromagnetic performance analysis is carried out on the optimized motor topology using Ansys Maxwell software, and a comparative study is performed with the initial motor model. The flux linkage and magnetic field distribution of the optimized motor are shown in Fig. 7. The results demonstrate that the effective magnetic flux of the motor achieves the expected optimization effect, and no obvious magnetic saturation occurs under load operation, which is consistent with the design expectations.

Based on the multi-objective genetic algorithm, this work successfully completes the multi-objective optimization design of the dual-structure dual-stator bidirectional flux-modulation permanent magnet direct-drive motor. Fig. 8 shows the comparison of the motor's load torque output performance before and after optimization. Table III lists the specific values of the average torque, torque ripple coefficient and average power factor of the motor before and after optimization.

The comparison results indicate that the comprehensive electromagnetic performance of the optimized motor is significantly improved: the average torque increases from the initial value to the optimized value, with a notable growth rate; the torque ripple coefficient is reduced to a low level, which greatly improves the smoothness of the motor's torque output; the average power factor is also significantly increased. All performance indices better match the actual operating conditions of low-speed direct-drive motors, which fully verifies the rationality and effectiveness of the optimization model and method adopted in this paper.

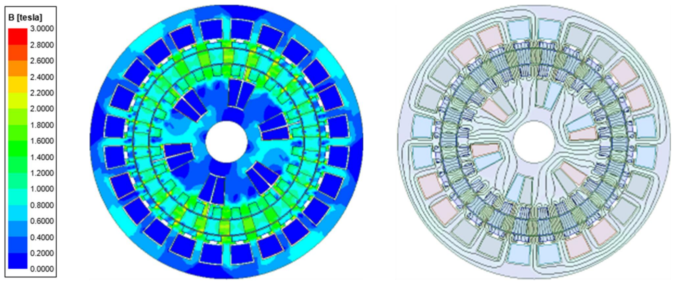



**Fig. 7.** Optimized flux linkages and magnetic field distributi on.

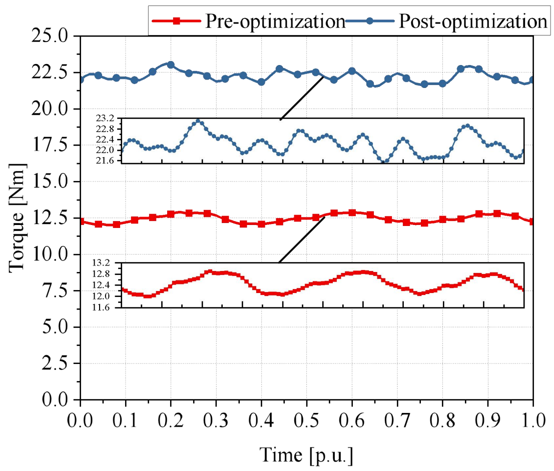
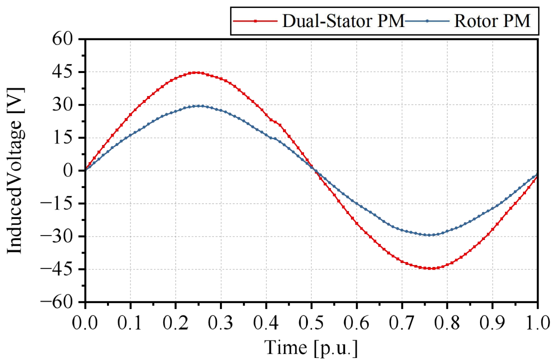



**Fig. 8.** Torque characteristics of dual-structure double-stator bidirectional modulation vernier permanent magnet direct-drive machine.

TABLE III

COMPARISON OF MOTOR OPTIMIZATION RESULTS

| Parameters | Unit | Pre-optimization Values | Post-optimization Values |
|---|---|---|---|
| Average torque | N·m | 12.46 | 22.23 |
| Ripple | % | 7.20 | 7.07 |
| Average power factor | - | 0.72 | 0.81 |

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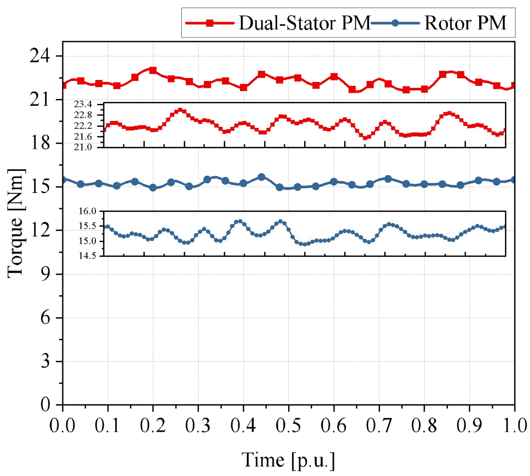
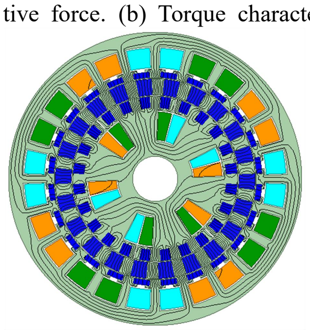
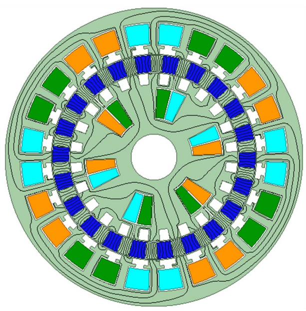



(b)

**Fig. 9.** No-load and load operating performances of dual -structure double-stator bidirectional modulation vernier perma nent magnet direct-drive machine. (a) No-load back electromo tive force. (b) Torque characteristics.



(a)



(b)

**Fig. 10.** Comparison of magnetic flux line distributions. (a) DS-BFM-PMDDM. (b) Rotor PM.

## 4. Performance Analysis and Comparison

To verify the effectiveness of the proposed motor's flux regulation mechanism and the rationality of its structural design, the time-stepping finite element method is adopted in this paper to systematically analyze the motor performance under typical operating conditions (rated speed and rated load). A professional electromagnetic simulation package is used to establish the motor simulation model, and reasonable boundary conditions and simulation settings are applied to guarantee the accuracy and reliability of the results.

Fig. 9. compares the key performance indicators of the two topological structures, including the no-load back electromotive force (waveform and amplitude) and the load torque output performance. Fig. 10. shows the magnetic flux line distributions of the two topologies, conventional double-stator vernier rotor permanent magnet direct-drive machine, short for Rotor PM. As shown in Fig.9, comparing to its counterpart, the no-load back electromotive force of proposed DS-BFM-PMDDM is increased by 51.7%, and the torque of it can be increased by 45.8%.

TABLE IV
COMPARISON OF MOTOR RESULTS

| Parameters | Unit | Rotor PM | DS-BFM-PMDDM |
|---|---|---|---|
| Average torque | N·m | 15.24 | 22.23 |
| Ripple | % | 8.11 | 7.07 |
| Average power factor | - | 0.54 | 0.81 |
| Induced Voltage | V | 29.4 | 44.6 |
| Efficiency(@150rpm) | - | 0.82 | 0.86 |

As shown in Table IV, the above analysis demonstrates that the proposed motor presents superior performance in magnetic field modulation, torque output and overall efficiency. It overcomes the problems of flux leakage and high copper loss caused by an excessive number of slots in conventional permanent magnet synchronous motors. Meanwhile, it features a compact structure and reliable operation, which confirms its promising application prospects in electric vehicle drives, wind power generation systems and other related fields.

## 5. Conclusion

This paper addresses the problems of excessive flux leakage, high copper loss and structural redundancy that occur in traditional permanent magnet synchronous motors for low-speed direct-drive applications, which are mainly caused by an excessive number of stator slots. To solve these problems, a novel dual-structure dual-stator bidirectional flux-modulation permanent magnet direct-drive motor is proposed.

Through structural design, parameter optimization and simulation verification, it is demonstrated that the proposed motor innovatively integrates the merits of the dual-stator bidirectional modulation structure and the Vernier flux-modulation motor. The motor adopts a coaxial nested configuration of inner stator-rotor-outer stator: the outer stator employs 24 slots with slot-embedded permanent magnets, the inner stator adopts 6 slots with a flux-modulation structure and concentrated winding, and the rotor is designed with 22 salient poles. Such a structure significantly reduces the number of stator slots, while achieving both structural compactness and magnetic circuit integrity. The dual-stator bidirectional flux-modulation mechanism, combined with the synergistic effect of three magnetic potential sources, effectively improves the flux utilization rate and overcomes the insufficient flux-modulation capability of conventional motors. The optimization based on key structural parameters further upgrades the comprehensive performance.

The results demonstrate that the proposed motor exhibits superior magnetic field modulation performance, with its no-load back electromotive force increased by 51.7%, torque output increased by 45.8%, and overall efficiency improved from 82% to 86% at a speed of 150 rpm. Time-stepping finite element simulation verification shows that the proposed motor is superior to traditional permanent magnet synchronous motors in terms of flux-modulation effect, torque output and operating efficiency. The results show that its structural design is reasonable and its electromagnetic performance is excellent, showing good application prospects and promotion value in low-speed direct-drive fields such as wind power generation, robotics and electric vehicles.

This research also provides new insights for the design and optimization of novel low-speed direct-drive permanent magnet motors. In future work, the actual performance of the motor can be further verified through prototype fabrication and experimental testing, and the performance characteristics under variable operating conditions can be investigated to provide more comprehensive support for engineering applications.

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