Design and analysis of a novel claw-shaped modular stator relieving-DC-saturation doubly salient machine with 3D complementary magnetic circuit

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1 INTRODUCTION

Due to overexploitation and consumption of energy, environmental pollution has been increasingly serious, and fossil fuels are running out. Therefore, it is urgent to find new renewable energy power generations to replace conventional fossil fuels, and wind power generation is the most popular and attractive technology [1, 2]. According to the operation speed and output voltage frequency, the wind-generation system can be categorized into two different types, namely, constant-speed constant-frequency (CSCF) and variable-speed constant-frequency (VSCF) wind harvesting system [3]. As the CSCF type wastes abundant mechanical power to keep speed constant, the system efficiency is rather low. In recent years, thanks to the development of power electronics, VSCF system with improved wind energy conversion capability has attracted more attention in the wind harvesting field.

As shown in Figure 1, VSCF wind harvesting basically consists of the following parts, which include blades, gear box, wind turbine, converters, and load. As one of the most critical parts in the wind power generation system, wind turbine should satisfy lots of criteria to achieve the energy conversion mission efficiently. The current development trend for wind turbine is to develop a generator with low cost, high reliability, high-power conversion efficiency, low torque ripple, good voltage-regulation ability, and high fault-tolerant capability etc. Especially, with the fluctuating supply of rare earth materials and drastic increase in price of PM material, to improve product competitiveness, less permanent magnet or magnet-free machine becomes a new trend of wind generator design [4, 5]. Considering the drawbacks of PM-excited machines, researchers are shifting their attention back to DC-excited (DCE) machines. Among all kinds of DCE machines, DC-excited doubly salient machines (DCE-DSM), which have merits of good flux-regulation capability, high robustness, and low cost, are suitable for wind power generation application. In [6], a
To improve the robustness and reliability of DSMs and to facilitate the manufacturing process, modular stator doubly salient machines (MS-DSM), which separate the stator into several modules, are proposed [7–11]. In [7], a hybrid-excited modular stator DSM is proposed to extend the speed range. Benefiting from the modular stator design, the proposed machine is easy to manufacture, assemble, and maintain. Moreover, the hybrid excitation topology increased the power capability of this machine. However, this DSM suffers from higher-order harmonics of back EMF, which causes torque ripple and extra power loss in wind-power application, and the problem of unbalanced magnetic force (UMF), which may further cause vibration and noise. In [8], a modular stator switched reluctance machine (MS-SRM) which could accomplish fault-tolerance, high efficiency and high power density is designed. The torque ripple, however, has reached almost 40%, which greatly hindered the application of this machine. Therefore, due to the inherent weaknesses of structure, both modular stator machine and non-modular stator machine still suffer from problems such as high torque ripple and low torque density, which hinder the development of this kind of machine.

To address the torque ripple issue, complementary structures have been applied in different types of DSM [11–13]. In [11], a radial-flux machine with complementary structure is proposed, which is composed of an inner rotor and outer rotor. A disk doubly salient machine is proposed in [12], which adopts axial complementary structure. In the existing literatures, however, most of them focused on the 2D complementary structure, which involves two air gaps, and the complicated mechanical structure results in higher requirement for bearings and manufacturing accuracy.

To improve the torque density of machines with less permanent magnet or magnet-free DSM machines, researchers have investigated variable methods [3, 14, 15]. In [3], a dual-mode motor, which is excited by only DC winding, has been proposed to improve the output torque by adopting both doubly salient design and flux switching design in one machine. Apart from power electronics device to switch mode, this machine employed two sets of winding to realize the dual-mode operation, which makes the whole system quite complicated and redundant. In [15], high temperature superconductor (HTS) is employed to provide field excitation for DSM. However, for HTS excitation machine, a complicated cooling system is required, which increases its manufacturing cost and difficulties of the machine. Another method to improve the machine’s torque density and increase the energy conversion capability is to solve the DC-component saturation issue in the machine. From this perspective, auxiliary PMs located at slot opening, which are named as slot opening, have been employed by researchers to relieve DC-saturation in the core [16].

In this paper, a novel claw-shaped modular stator doubly salient motor (CM-DSM) with complementary structure is proposed. The stator adopts modular stator design, which improves the fault-tolerant capabilities of machine. The combinations of claw-shaped stator and dual rotors construct a complementary structure artificially, which reduce the torque ripple of machine, and boost the output torque meanwhile. In addition, thanks to the 3D complementary structure, the two parts of the machine share one common air gap, which simplifies the mechanical structure. To further improve overload capability, the auxiliary PMs located at slot-opening is also employed in this machine to relieve the DC-saturation in the stator core. To simplify the calculation, 2D equivalent finite element (FE) model is developed to replace the 3D finite element model. Multi-objective optimization algorithm is also developed to further improve the performance of this new machine.

This paper is organized as follows: In Section 2, the topology and operation principle of this new design is demonstrated; methods and proof of simplified 2D equivalent FE model replacing 3D model are illustrated in Section 3. The configuration parameters of the model are optimized by the multi-objective optimization algorithm to improve the performance of this new machine in Section 4. Section 5 analyses the specific characteristics and performances of this novel machine. In Section 6, the electrical performance of the optimized model is compared with the conventional modular stator DSM using the finite element method (FEM), and the simulation results are verified by 3D model. Some conclusions are drawn in Section 7.

## 2 | MACHINE STRUCTURE AND OPERATION PRINCIPLE

### 2.1 | Machine structure

Due to the serious open-circuit flux leakage in conventional DSMs, the energy conversion capabilities of it are limited and the output torque of the machine is also affected, which may influence the quality of the power generation. In this paper, CM-DSM develops a 3D complementary structure to address the flux leakage issue of DSM.

Figure 2a shows the structure of the proposed machine and Figure 2b demonstrates the cross section of the machine. The proposed CM-DSM consists of 6 modular stator segments, which cut off the magnetic path connection between two different modules, and the rotor adopts 10 salient-tooth rotor poles.
namely, a classic 12/10 slot/pole combination adopted in this machine. The rotor has two segments along the axis, between which the screw electrical angle shift is set as $\pi$. Each modular stator adopts claw-shaped design, which has 4 stator teeth with both DC windings and AC windings wound around. DC field coils are wound around the yoke of each module identically to provide a balanced DC excitation field for each module. The stack length of yoke is decreased artificially to reduce the copper loss of DC windings. Since the flux going through the armature windings is unipolar, tangential magnetized auxiliary PMs are installed at slot opening to relieve the DC-component flux in the core.

The design features of the proposed DSM can be summarized as follows:

1. The stator adopts claw-shaped modular design with 4 coils of AC concentrated winding wound around, which could improve the fault-tolerant capabilities of the machine and simplify the manufacture and the installation of the machine.
2. The rotor has two segments in the axial direction between which an electrical angle of $\pi$ is switched. This artfully 3D axially complementary structure could realize the torque ripple suppression.
3. The PMs are installed at slot opening of each module to provide a constant reversal flux to relieve DC-saturation issue, which could improve the torque production.

2.2 | Operation principle

As presented in Figure 2, the proposed generator accomplished a complementary structure along the axis. The 3D model is quite complicated. Therefore, in this section, the 3D complementary structure magnetic circuit of one module is simplified to a 2D model, which is shown in Figure 3.

As denoted in Figure 3, when the rotor moves to position (a), where the lower rotor salient poles, which is denoted as Rotor 1, are aligned with the lower part of the modular stator, flux generated by DC windings would go through Coil 1, Rotor 1, and Coil 2 to form the loop, and the reluctance of the lower loop for DC excitation is minimized. Therefore, the flux in coil 1 and coil 2 reaches the top. The windings of this module are aligned with d axis at this position. On the other side, due to the large reluctance between the upper part of the modular stator and rotor 2, the flux going through Coil 3 and Coil 4 at this position reaches the minimum value. Vice versa, when the rotor moves to position (b), as shown in Figure 3b, the rotor rotates to the position where Rotor 2 aligned with the upper part of the modular stator, the flux in coil 3 and coil 4 reaches the top in opposite direction.

As shown in Figure 3, since the stator yoke provides a shortcut path, the flux linkages excited by the auxiliary PMs, namely, $\phi_{pm1}$ and $\phi_{pm2}$, flow through the modular stator constantly and are always opposite to flux linkages generated by DC field winding. With slot PM desaturation effect, the DC-component of flux linkages, which makes no contribution to output torque, is relieved. In this way, the energy conversion capabilities of the machine, especially at heavy electrical load, could also be improved as well. With a continuous anti-clockwise rotation, the alignment between the modular stator teeth and rotor salient poles changes periodically, which makes it possible for the electro-mechanical energy conversion. Thanks to the complementary design, the flux leakages at the open-circuit position are effectively reduced, and the induced voltage generated by the effective flux linkages linking could be prompted as well. The validation of this will be presented in Section 5.
2.3 Complementary magnetic circuit

Equivalent magnetic circuit (EMC) analysis is one of the most useful methods to simplify and analyse the static magnetic field in electrical machines. In this section, with the help of EMC analysis, the merits of the complementary structure of the proposed machine are demonstrated. The EMC model of one complementary-structure modular stator under no-load condition is shown in Figure 4. As shown in Figure 4, there are two symmetric magnetic return paths for the field DC winding excitation $F_{DC}$, and fluxes excited by both DC winding and PMs can also be solved using the loop current method, where $F_{DC}$ and $F_{w}$ are the magneto-motive force (MMF) of DC field winding and PMs, $R_{sy}$ is the internal reluctance of PM, $R_{sy}$ and $R_{sy}$ are the reluctance of stator yoke and stator teeth, respectively, $R_{sy}$ is the reluctance of rotor yoke, and $R_{sy}$ and $R_{sy}$ are the reluctance of air gap at both sides of the complementary stator, and the value of them is varied periodically according to the relative position between the rotor and stator.

$$\begin{bmatrix} R_{m} + 2R_{sy} + R_{sy} & -R_{m} & -R_{sy} & 0 \\ -R_{m} & 2R_{g1} + R_{sy} + R_{m} & 0 & 0 \\ -R_{sy} & 0 & R_{m} + 2R_{sy} + R_{sy} & -R_{m} \\ 0 & 0 & -R_{m} & 2R_{g2} + R_{sy} + R_{m} \end{bmatrix} \begin{bmatrix} \phi_{11} \\ \phi_{12} \\ \phi_{21} \\ \phi_{22} \end{bmatrix} = \begin{bmatrix} \frac{F_{DC} - F_{m}}{R_{m}} \\ \frac{F_{m}}{R_{m}} \\ \frac{-F_{DC} + F_{m}}{R_{m}} \\ \frac{-F_{m}}{R_{m}} \end{bmatrix}$$  \hspace{1cm} (1)

According to the loop current method, the main flux in the proposed generator $\phi_{11}$, $\phi_{21}$ under no-load situation can be solved with Equation (1), which is further expressed as Equations (2) and (3).

$$\phi_{11} \approx -\frac{1}{R_{m}} F_{m} + \frac{R_{sy} - R_{2}}{R_{sy}^2 - R_{1}R_{2}} F_{DC}$$  \hspace{1cm} (2)

$$\phi_{21} \approx -\frac{1}{R_{m}} F_{m} - \frac{R_{sy} - R_{1}}{R_{sy}^2 - R_{1}R_{2}} F_{DC}$$  \hspace{1cm} (3)

where $R_{1} = 2R_{sy} + R_{g1} + R_{g2} + R_{sy}$; $R_{2} = 2R_{sy} + 2R_{g2} + R_{g1} + R_{sy}$. When the complementary structure is adopted, $R_{1}$ and $R_{2}$ could be divided into constant part and variable part and be rewritten as, $R_{1} = R_{01} + \Delta R$ and $R_{2} = R_{02} - \Delta R$, where $R_{01}$ represents the constant part of reluctance and $\Delta R$ represents the variable part ($\Delta R > 0$).

In this way, the difference between the maximum value of flux and the minimum value of flux $|\phi_{max} - \phi_{min}|$, which represents the amplitude of the fundamental components of flux linkage could be expressed as Equation (4).

On the contrary, when there is no complementary structure, it could be expressed as Equation (5). In this condition, $R_{1}$ equals to $R_{2}$, which could be expressed as $R_{1,2} = R_{0} \pm \Delta R$.

$$|\phi_{max} - \phi_{min}| = \frac{4\Delta R}{R_{sy}^2 - R_{1}^2 + \Delta R^2} F_{DC}$$  \hspace{1cm} (4)

$$|\phi'_{max} - \phi'_{min}| = \frac{4\Delta R}{R_{sy}^2 - R_{01}^2 + 2R_{sy}R_{01} + \Delta R^2} F_{DC}$$  \hspace{1cm} (5)

Comparing Equations (4) and (5), it could be found that, due to the complementary structure, the amplitude of the fundamental components of flux linkage is boosted, namely, the reluctance torque of the proposed machine could be improved under the same magnetic load.

Besides, when the complementary structure is adopted, flux going through the stator yoke at short-circuit position could be
calculated as

\[ |\phi_{\text{max}}| = \frac{2R_0 - 2R_{sy}}{R_0^2 - R_{sy}^2 + \Delta R^2} F_{\text{DC}} \]  \hspace{1cm} (6)

However, it could be calculated as follows, when the complementary structure is not adopted,

\[ |\phi'_{\text{max}}| = \frac{2R_0 - 2R_{sy}}{R_0^2 - R_{sy}^2 - \Delta R(R_0 - R_{sy})} F_{\text{DC}} \]  \hspace{1cm} (7)

Comparing Equations (6) and (7), it could be found that, due to the 3D complementary structure, the maximum of flux linkages flowing through the stator yoke in the machine with complementary structure is reduced, namely, the saturation in the stator of the proposed machine could be relieved as well.

3  |  2D SIMPLIFIED EQUIVALENT MODEL

The 3D model is complicated and time consuming, an equivalent 2D finite element model is proposed in this section to accelerate calculation efficiency, the parameter relationship between the 2D FE model and 3D FE model is revealed in this section.

3.1  |  Parameters relationship

According to EMC analysis, the 2D equivalent linear model which has the same magnetic circuit as that of the 3D model is proposed, which is shown in Figure 5b. Figure 5a demonstrates the parameters of the original 3D model.

However, to ensure the 2D model replaces the 3D model properly, some principles of equivalence between two models should be obeyed, which are listed as follows:

1. The reluctance of each part of the 2D model should be equal to those of the 3D model.
2. MMF of each excitation sources in 2D model should be equal to that of 3D model.
3. The stator and rotor poles width and stack length of 2D model are equal to those of 3D model.

The variation of reluctance of air gap has a great effect on the behaviour of back-EMF and torque of machines. Therefore, the equivalence of air gap plays a critical role in this equivalent methodology. According to Figure 5a, when the stator is aligned with the rotor poles, the reluctance of the proposed machine in the air gap \( R_g \) of the original 3D model can be calculated as Equation (8).

\[ R_g = \Lambda_{\text{air}}^{-1} \int_{\alpha_1 - g}^{\alpha_0} (\alpha_\text{rt} r_L)^{-1} dr \]  \hspace{1cm} (8)

where \( r_0 \) is the inner radius of the stator, \( \Lambda_{\text{air}} \) is the permanence of air, and \( l_z \) is the stack length of the machine.

The reluctance in the air gap of 2D linear model \( R'_g \) is expressed in Equation (9). According to principles 1 and 3, it should be equal to \( R_g \).

\[ R'_g = (\Lambda_{\text{air}} g' l_z)^{-1} w_{\text{rt}}' \]  \hspace{1cm} (9)

where \( g' \) is the equivalent length of air gap in the 2D model.

Apart from reluctance of air gap, reluctance of other counterparts of 2D and 3D model should be equal. The relationships of the parameters in 2D and 3D models are presented in Table 1.

According to principle 2, apart from the magnetic path, the MMFs of DC windings and PMs, \( F'_{\text{DC}} \) and \( F'_{\text{m}} \) are supposed to be equal to those of 3D model as well. The equivalence of \( F_{\text{DC}} \) can be guaranteed when both DC current and the number of DC-winding turns of the two models are equal. In terms of MMF of PMs, \( F_{\text{m}} \) could be expressed as shown by Equation (10).

\[ F'_{\text{m}} = F_{\text{c}}' + \Lambda_{\text{m}}^{-1} \phi'_{\text{m}} \]  \hspace{1cm} (10)
where \( \phi_{em} \) is flux linkage provided by PM, \( \Lambda_m \) is inner permanence of PMs, and variables with/without prime represent the parameters of the 2D/3D model.

According to Equation (10), when the constant MMF \( F_c \) and inner reluctance of PMs remain unchanged, the equivalence of PMs is guaranteed. To satisfy the principles above, the parameters of 2D and 3D model should obey the relationships which are listed in Table 1.

### 3.2 Comparison of 2D and 3D FE Model

To verify the validation of the equivalent method proposed above, the static performances of 3D and 2D equivalent model, including main flux linkages and static angle-torque characteristics, are compared with Ansys Maxwell software, which is presented in Figures 6 and 7. Figure 6 presents the flux linkages of one module at aligned position and unaligned position under no-load condition. The DC field excitation current varies from 1 A to 12 A, which simulates the equivalent effect under different saturation condition. Figure 7 presents the static torque of two models, when the excitation current is fixed as 4A. It could be found that the two models agree well with each other in the static performance indicating that the 2D equivalent model replaced the 3D model properly.

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put torque could be achieved. Figure 8d describes the effect of the height of stator yoke on the performance of the machine.

4.2 Optimization results

According to the parameter analysis above, it could be found that the targets of torque maximization and torque ripple minimization could not be reached simultaneously. Therefore, the optimization front of the CM-DSM, which integrates two objectives, is derived after 40 generations of iteration of MOGA, as presented in Figure 9. The number of individuals in each iteration generation is set as 40. The parameters of the initial design are presented in Table 3.

It could be found that the torque of the proposed machine could achieve approximately 6.2 Nm, and torque ripple could be reduced to as low as 6%. An optimal case which achieves both high torque and low torque ripple, as shown in Figure 9, is picked up for further analysis. The specific parameters of the optimal design are summarized and listed in Table 4. The major materials of the proposed machine are listed in Table 5.

5 PERFORMANCE EVALUATION AND COMPARATIVE STUDY

In this section, the electromagnetic performance of the proposed CM-DSM, including its flux distribution, voltage characteristics, torque characteristics, and fault-tolerance capability, is evaluated. The performance of the machine with 3D complementary structure is compared with a conventional MS-DSM machine without 3D complementary structure to illustrate the effectiveness of the proposed complementary structure.

5.1 Open-circuit performance

Figure 10 demonstrates the flux distribution of both conventional MS-DSM and the CM-DSM proposed in this paper.
TABLE 5  Materials of proposed machine

| Material | Specification | Value       |
|----------|---------------|-------------|
| PMs      | Type          | NdFeB30     |
|          | Br            | 1.1T        |
|          | Coercive force| 838 kA/m    |
| Steel    | Type          | JFE_Steel_35|
|          | Saturated point| 1.7T       |
| Winding  | Conductivity  | 5.8 × 10^7 S/m |

FIGURE 10  Flux distribution in 3D model at aligned position. With 12/10 slot/pole combination, the machine is symmetric. Thus, only half of the model is built.

Different from MS-DSM shown in Figure 10a, with claw-shaped complementary magnetic path design, the flux linkages generated by DC winding passing air gap are always linking with the two rotors regardless of the position of the rotor. Therefore, the air gap flux leakages are reduced, and the main flux is strengthened as well. On the other hand, the flux linkages in the yoke remain constant.

Figure 11 presents the flux linkage distribution in both armature winding (Figure 11a) and yoke (Figure 11b) when DC-excitation current is set as 4A and 10A, respectively. It is found in Figure 11a that different from the conventional MS-DSM, flux linkages in CM-DSM are bipolar. As the current increases from 4A to 10A, the amplitude of the flux linkages increases as well in CM-DSM, whereas the increasing current only brings more DC-saturation in the conventional MS-DSM machine. Figure 11b illustrates that the flux linkages in the yoke of conventional MS-DSM vary a lot, while those of CM-DSM machines remain relatively constant.

Using the method of fast Fourier transformation (FFT) analysis, the flux linkages spectra of both conventional MS-DSM machine and the proposed CM-DSM machine are illustrated in Figure 12. In accordance with the analysis above, Figure 12 shows that the fundamental component of flux linkage of machine with 3D complementary structure are higher than those of machine without 3D complementary structure, when the current is set as 10 A. In addition, though it has been proved in [7] that flux linkages of machines with 10 rotor poles have higher even-order harmonics, thanks to the 3D complementary structure, CM-DSM machine with 12/10 stator/rotor poles combination eliminated the even-order harmonics in flux linkages completely.

FIGURE 11  Flux linkages comparison: (a) armature-winding flux linkages, (b) yoke flux linkages

FIGURE 12  Flux linkages harmonics in CM-DSM and MS-DSM

Figure 13a presents induced voltage in one phase generated by CM-DSM and MS-DSM at a speed of 1200 rpm. Figure 13b presents the rectified voltage of the proposed machine after full-bridge rectification. It could be found that the proposed machine has better voltage-regulation capability: due to better desaturation capabilities of CM-DSM, its output voltage has wider range at the same excitation and speed comparing with conventional MS-DSM. Moreover, comparing with the conventional MS-DSM, the machine with the proposed structure has more stable output voltage after full-bridge rectification.

5.2  Torque characteristics comparison

Torque characteristics represent energy conversion capability of the proposed generator, which is critical in power generation
applications. For instance, cogging torque of the machine describes the initial start torque of wind turbines, and rated output torque of the machine represents its power conversion capability.

The output torque waveforms of the machine under 4 and 10 A current are shown in Figure 14. It can be found that the machine with claw-shaped structure could achieve lower torque ripple under any current condition. It indicates that comparing with the machine without 3D complementary structure, the average torque of CM-DSM is not improved evidently when the DC excitation current is set as 4A, and the average torque only increases when the excitation current comes to 10A. This indicates that the proposed machine has better electrical-mechanical conversion capability than the conventional one at heavy load situation.

Furthermore, the torque capability of the machine under different current density is also tested and compared, which is shown in Figure 15. Both the calculation results in Figures 14 and 15 indicate that the average torque of machines with 3D complementary structure could be improved at relatively heavy load situation.

Figure 16 compares the average torque of the proposed machine with or without slot-opening auxiliary PMs, indicating that the machine without auxiliary PM tends to be saturated easily and the output torque is limited as well.

Figure 17 presents the simulation results of the inductance of phase A, including the self-inductance and mutual inductance.
The result shows that thanks to the modular stator design, the mutual inductances between different phases are so small that could be neglected, which means that each phases of the machine could be functioned separately.

Table 6 compares the electromagnetic performance of the proposed CM-DSM machine and the conventional MS-DSM machine proposed in [7]. According to Table 6, it could be found that compared with conventional MS-DSM, the proposed CM-DSM generator could achieve higher power capability and lower torque ripple.

The dynamic cogging torque characteristics of CM-DSM and MS-DSM are shown in Figure 18. It shows that the CM-DSM achieves much lower cogging torque than MS-DSM, and the results of 3D and 2D model agree well with each other. Figure 18b presents the dynamic torque under rated current. It can be found that CM-DSM could achieve lower torque ripple and higher output torque. The results of the 3D and 2D models in this condition also agree well with each other.

6 CONCLUSION

This paper proposed a claw-shaped modular stator doubly salient machine (CM-DSM) with 3D complementary structure for wind power application. Considering the special structure of the machine, 2D equivalent model is proposed to replace 3D model, and the results verified the effectiveness of the equivalent model. The main contribution of this paper lies in the employment of the 3D complementary structure integrated with slot auxiliary PMs on the DCE modular stator machine. Some conclusions can be drawn as follows:

1. Comparing with MS-DSM, thanks to the 3D complementary structure, the voltage-regulation capability of the machine is improved, indicating that the proposed structure has better flux-regulation capability.
2. The output torque of the proposed CM-DSM is increased by 20% at rated current situation after design optimization, and the saturation current density can be improved from 800A/mm² to 1400A/mm². Torque ripple of the machine is also reduced from 15.49% to 7.05%.
3. Furthermore, the auxiliary PMs relieved the DC-saturation issue effectively, and the output torque can be increased by 41.6% at rated current excitation.

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