Optimization Study of Poles-slots Combination of Large Capacity Offshore HTS Wind Generator Based on Ansys Maxwell

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Abstract. The superconducting wind turbine has the advantages of large capacity, high power density, small size, low weight, high efficiency and low cost. In the case that the rotor has many poles, how to choose the number of slots of stator is very important to the performance of the motor. This paper took 10 MW Offshore HTS Wind Generator as an example, analyzed the influence of different poles-slots combination on the performance of the generator, and finally determined a set of relatively reasonable scheme. The simulation results showed that this scheme can effectively reduce the high harmonic of no-load counter electromotive force and improve the induced voltage distortion rate and torque vibration, significantly improve the motor performance. It is of guiding significance for the structural optimization of superconducting motors.

1. Introduction

Compared with onshore wind energy, offshore wind energy has the advantages of high reserves, good quality and no occupation of land resources, making offshore wind power generation gradually become the development trend of wind energy utilization [1,2]. In recent years, with the continuous development of superconducting technology especially high temperature superconducting (HTS) technology, the application of superconducting technology in motors has been increasingly mature. Compared with the conventional wind turbine, the superconducting wind turbine has the advantages such as large capacity, high power density, small size, low weight, high efficiency and low cost [3]. At present, most of the high-power wind turbines in the world adopt the operation mode of direct-drive synchronous generators. Since the direct-driven wind turbine does not have the function of gearbox increasing speed, the generator needs to adopt the operation mode of multi-poles and low speed. In the case that the rotor has many poles, how to rationally design the structure of the generator is the key problem to improve the operating performance of the HTS wind turbine.

The structural optimization of superconducting motors has been widely studied by scholars at home and abroad. Ref.[4] analysed the influence of the tooth width and the dimensions of tooth tips on
generator performance. Ref.[5] analysed the electromagnetic design and optimization of the rotor by using finite element method. The excitation coil of the rotor was designed considering variable working conditions. Ref.[6] proposed two structural optimization methods to reduce the alternating magnetic field and alternating current loss by using the homogenization model, that was, the stator teeth were made of non-magnetic materials and the air gap was added with magnetic shielding layer. In general, so far most of the structural optimization researches on superconducting motors were about the structure of excitation windings or stator teeth, and few involved poles-slots combination. Therefore, it is of great significance to study poles-slots combination for the performance of motors.

As for the poles-slots combination of motor, most of the current researches were about permanent magnet synchronous motor. Ref.[7] compared and analyzed different pole slots with PMSM, and found that pole slots with the number of slots per pole in each phase showed high winding factor, higher maximum value of counter electromotive force, and relatively low electromagnetic wave caused by slotting. Ref.[8] established a multi-physical field model, modal superposition method was adopted to compare the vibration and noise characteristics of PMSM with different pole slots. It was believed that the lowest space force wave order was the main cause of the electromagnetic vibration noise of the motor, and the single-layer winding of PMSM with concentrated winding in fractional slot was more noisy than the double-layer winding. According to Ref.[9], the number of slots for the motor should be an integer multiple of the rotor's magnetic pole harmonic, and in general, the vibration noise of the integer slot permanent magnet synchronous motor was lower than that of the fractional slot. All the above researches were aimed at permanent magnet synchronous motor, but there was few research on the optimization of poles-slots combination of superconducting synchronous motor.

This paper took 10 MW Offshore HTS Wind Generator as an example based on the finite element analysis method, used Ansys Maxwell simulation platform and analyzed the influence of different poles-slots combination on the performance of the superconducting wind turbine in detail, finally determined the solution of a set of relatively reasonable scheme from the aspects of harmonic, induction voltage and electromagnetic torque. The simulation results showed that the scheme under the condition of the basic operation of motor performance can effectively reduce the high harmonic of no-load counter electromotive force and improve the induced voltage distortion rate and torque vibration, significantly improve the motor performance, at the same time, the manufacturing cost of the motor was reduced.

2. Motor model and main parameters

2.1 Main parameters

As described in this paper the speed of 10 MW offshore HTS synchronous generator was very low, approximately 10 rpm, which adopted the mode of direct drive, and the gear box between wind turbine and alternator was canceled. In such a case, low-speed multipolar generator should be the most reasonable choice. Formula of frequency and pole number of synchronous generator was shown in (1),

\[ f = \frac{pn}{60} \]

2.2 Materials and Structure

Considering that the excitation coil of the superconducting motor can provide a strong magnetic field, which was different from the common synchronous generator, it did not need the ferromagnetic material to provide magnetic circuit, so the hollow structure was adopted and the rotor supporting structure was used instead of the iron tooth structure of the common synchronous generator. The stator winding adopted double-layer short distance winding to reduce the size and volume of the motor and reduce the harmonic component of the magnetic field induced EMF and the tooth harmonic EMF to a certain extent.
The superconducting excitation winding adopted racetrack structure. The stator was composed of stator back iron and stator tooth slot. The insulation layer, the damping layer and the vacuum layer were between stator and rotor. The overall mechanical 2D structure of the motor was shown in Figure.1.

![Figure 1. The overall 2D mechanical structure of the superconducting motor](image)

3. Selection of poles-slots combination scheme
The original plan selected the stator slot number from the view point of the stator iron core loss, comparing and analysing from 120, 240, 360 three integer slot scheme, because the radial air gap magnetic field of 360 slots has a relatively larger amplitude component and minimum higher harmonic components, therefore the existing scheme was that the number of stator slot was 360, the number of rotor slot was 40. The 1/20 2D mechanical structure of the superconducting motor in the case of 360 slots was shown in Figure.2.
Result of fractional slot itself can significantly reduce the cogging torque and the vibration of the motor, so this paper proposed fractional slot instead of integer slot. The number of slots per pole per phase of the motor was shown in (2),

\[
q = \frac{Z}{2 \cdot pm}
\]  

Since the \( m \) of the three-phase motor was 3, the stator slots of 150, 180, 210, 270, 300 and 330 were analyzed respectively. Considering the rotor pole under the condition of same number, the greater the greatest common divisor \( D \) of stator slot number and rotor pole number is, the smaller the cogging torque.

The corresponding relationship between the number of stator slots and the greatest common divisor was shown in Table 1, it can be seen from the table that 180 and 300 are the minimum greatest common divisor. Considering the production cost, the smaller the number of slots in the stator, the less the manufacturing cost, so the stator slot number is 180.

| Slot number | 150 | 180 | 210 | 270 | 300 | 330 |
|-------------|-----|-----|-----|-----|-----|-----|
| \( D \)     | 10  | 20  | 10  | 10  | 20  | 10  |

![Table 1. The relationship between the number of stator slots and the greatest common divisor](image)

Figure 3. The air gap radial magnetic field harmonic components with the stator slots of 360
As shown in Figure 3 and Figure 4, the air gap radial magnetic field harmonic components with the stator slots of 360 and 180 were simulated by Ansys Maxwell platform, it can be seen from the figure, two cases of the amplitude component was slightly different, the latter reduced 0.01 T than the former, three times harmonic component did not change, five times harmonic component increased 0.008 T, the change of stator iron loss was not much in such a case, but the slot number reduced half, so stator winding copper losses can be significantly reduced.

To sum up, poles-slots combination scheme with the number of stator slots and the number of rotor poles being 180 and 40 is adopted in this paper. The 1/20 2D mechanical structure of the superconducting motor in the case of 180 slots was shown in Figure 5.

4. Results & Discussion
After replacing the original scheme with the optimized scheme, the electromagnetic characteristics simulation results of the generator before and after optimization were respectively run on Ansys Maxwell platform.
4.1 No-load induced voltage distortion

Figure 6. No-load induced voltage distortion before optimization

Figure 7. No-load induced voltage distortion after optimization

Figure 6 showed the waveform figure of no-load counter-EMF of the superconducting generator with 360 stator slots and 40 rotor poles. It can be seen from the figure that the sinusoidal three-phase voltage has a significant waveform distortion with a waveform distortion rate of 18.77%. Figure 7 showed the waveform figure of no-load counter-EMF of a superconducting generator with 180 stator slots and 40 rotor poles. It can be seen from the figure that the three-phase voltage waveform is smoother and closer to the sinusoidal wave at this time, with a waveform distortion rate of 8.71%, which is significantly reduced compared with the original scheme.
4.2 No-load induced voltage harmonic

Figure 8. No-load induced voltage harmonic before optimization

Figure 9. No-load induced voltage harmonic after optimization

Figure 8 was a schematic diagram of no-load induced voltage FFT of a superconducting generator with 360 stator slots and 40 rotor poles. It can be seen from the figure that the motor has obvious high-order harmonics under the condition of such pole slots. Figure 9 showed the schematic diagram of no-load induced voltage FFT of a superconducting generator with 180 stator slots and 40 rotor poles. It can be seen from the figure that compared with the original scheme, the high-order harmonic component is significantly reduced, and the fundamental component is increased from 2.69kV to 2.75kV.
### 4.3 Electromagnetic torque

Figure 10. Electromagnetic torque before optimization

![Figure 10. Electromagnetic torque before optimization](image)

Figure 11. Electromagnetic torque after optimization

![Figure 11. Electromagnetic torque after optimization](image)

Figure 10 showed the electromagnetic torque waveform of the generator with 360 stator slots and 40 rotor poles under rated load. It can be seen from the figure that the electromagnetic torque finally stabilizes around -9.4 megNM, and the fluctuation amplitude is about ±5.7%. As shown in Figure.11 was the case that stator slot number is 180, the number of rotor is 40, it can be seen from the diagram that the electromagnetic torque final stabilizes near 10.4 megNM, fluctuation amplitude is about plus or minus 3.6%, compared with the original plan, pulsation frequency significantly reduces than before, the electromagnetic torque increases by about 1.1 megNM.

### 5. Conclusion

This paper took 10 MW Offshore HTS Wind Generator as an example based on the finite element analysis method, used Ansys Maxwell simulation platform and analyzed the influence of different poles-slots combination on the performance of the superconducting wind turbine in detail, finally determined the solution of a set of relatively reasonable scheme from the aspects of harmonic, induction voltage and electromagnetic torque. The simulation results showed that:
The scheme under the condition of the basic operation of motor performance can effectively reduce the high harmonic of no-load counter electromotive force and improve the induced voltage distortion rate. The torque vibration of generator was significantly reduced and the motor performance was improved. At the same time, the manufacturing cost of the motor was reduced.

The scheme obtained in this paper has certain engineering application value for the field of wind power generation and important reference value for the structural optimization of superconducting motors.

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