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Inner Evaporative Cooling Wind Power Generator with Non-overlapping Concentrated Windings

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Abstract – As the space of the wind power generator stator end is limited, it is difficult for us to place the inner evaporative cooling system in it. We use the non-overlapping concentrated windings scheme to solve the placing and cooling problem. The characteristic of a 5MW direct-driven permanent magnet generator with non-overlapping concentrated windings were analyzed under no-load, rating-load and short-circuit by (Finite Element Method) FEM for verification of design. We studied the connection methods of the stator windings and designed the end connection member. The heat dissipation of the stator end was simulated by FEM, the result showed that the end cooling could satisfy the wind generator operation needs. These results show that the direct-driven permanent magnet wind power generators with non-overlapping concentrated windings and inner evaporative cooling system can solve the cooling problem of wind power generator, and obtain good performance at the same time.

Keywords: Permanent magnet generator, Concentrated winding, Inner evaporative cooling, Wind power

1. Introduction

Inner evaporative cooling system has been widely used in electrical equipment like hydro-generator, turbo-generator, high-voltage circuit breaker etc. Evaporative cooling system has the advantage of high cooling performance, good insulation properties, less electrical fault, easy to maintain and high reliability [1], can meet the requirements of the cooling system in wind power generators.

Distributed winding is generally used in traditional wind power generator, causing the winding connection overlaps lead to the stator end crowded and hard to cool. Because of the limited space, it is hard for us to place the cooling medium joints of the inner evaporative cooling system and the electrical joints. This has hindered the application of inner evaporative cooling system in wind power generator. We use the non-overlapping concentrated windings generator to solve this problem. Conductors between two slots are connected to form coil, so the connection has no overlap. The fractional-slot makes enough space for the arrangement and heat dissipation of stator end, making the inner evaporative cooling system can be applied in wind turbines.

In this paper, we taking a 5MW non-overlapping concentrated windings directed driven permanent magnet wind power generator as an example, using FEM to analysis its operating performance in no power, rated power and short circuit conditions [2], [3]. Connect method of the stator coil endings also studied in this paper and we analyzed the temperature field of the coil endings.

2. Permanent Magnet Synchronous Generator Design and Performance Analysis

Based on the design method of traditional permanent magnet generator and combine the characteristics of the non-overlapping concentrated generator together, we use Ansoft RMxprt to design the generator. Table 1 shows the result of optimal design and Table 2 shows the performance index of the generator.

2.1 No Load Characteristic

We should calculate the electromotive force (EMF) at no load condition to make sure whether the windings are well designed according to the generating voltage range. Moreover we analyzed the harmonics from the voltage wave form by FEM. The no load voltage with rated speed

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10 rpm is showed in Fig. 1 and the line voltage RMS is about 770V. Fig. 2 is the harmonics of no load voltage as shown in Fig. 1. The THD is about 4.83%. The cogging torque is about 2.08% of the rated torque in Fig. 3. Fig. 4 shows the magnetic line of force at no load condition.

Table 1. Design Result of the Permanent Magnet Synchronous Generator

Item	Value
Phase	3
Rated Power	5 MW
Poles	90
Stator Slots	108
Rated Speed	10 rpm
Pitch	1
Magnet thickness	50 mm
Stator Outer Diameter	6893 mm
Rotor Outer Diameter	6560 mm
Core Length	1340 mm

Table 2. Performance Index of the Generator

	Item	Value
No load	EMF	828 V
	Gap flux density	0.9 T
Rated load	Rated voltage	750 V
	Rated current	3950 A
	Stator current density	4.52 A/m2
	Copper loss	263 kW
	efficiency	94.63 %
Short circuit	Short current	7094 A

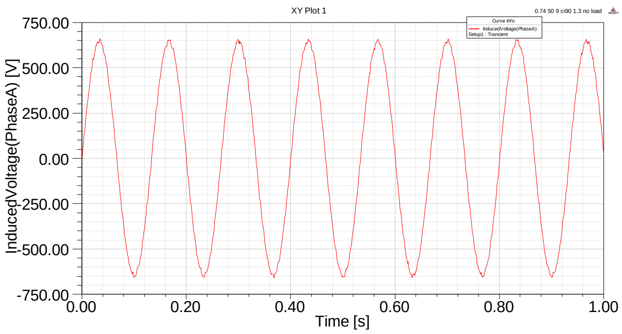

Fig. 1. No-load voltage waveform

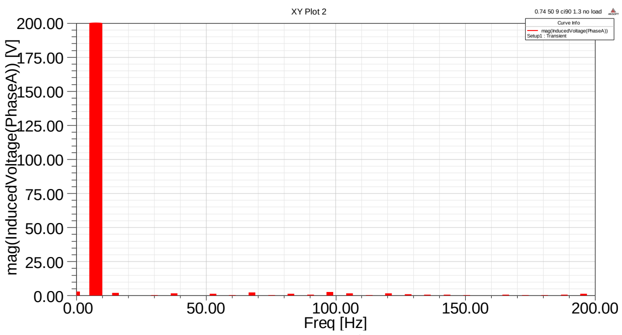

Fig. 2. Harmonics of no load voltage

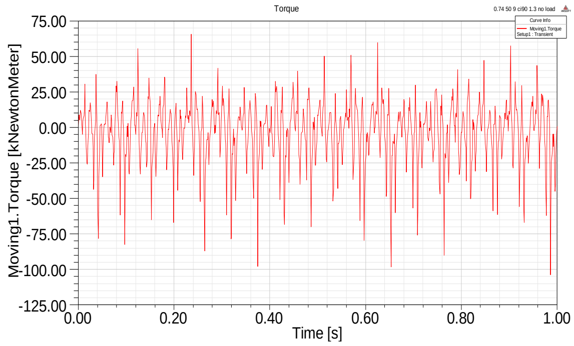

Fig. 3. Cogging torque

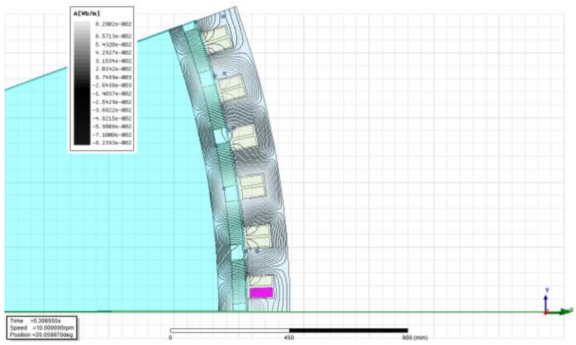

Fig. 4. Magnetic line of force at no load condition

2.2 Rated Load Characteristic

In this paper, we will not consider the effect of the converter when analyze the characteristic of wind power generator at rated power condition, only resistive rated load is considered. Voltage equation of the generator is expressed as follows.

$$E_a = R_a I_a + L_l \frac{dI_a}{dt} + R_{load} I_a \qquad (1)$$

Where, E_a is the phase EMF, Ra is the phase resistance, L_l is leakage inductance of the coil ends, I_a is the phase current and R_{load} is the load resistance, the loads are Y connected. Fig.5 shows the phase voltage, phase current and output power waveform at the rated load operation. From Fig.5 we can see that the phase voltage, phase current and output power of the generator basically meet the design requirements. Fig.6 shows the harmonics of rated load voltage, comparing with no load operation the harmonics are weaken. Rated load torque is shown in Fig.7, the curve is smooth and the torque ripple is small. Fig.8 shows the magnetic line of force at rated load operation.

2.3 Short Circuit Characteristic

The three-phase short circuit is the most serious fault situation. The impact current produced by it has great harm to the generator and magnetic field produced by armature current when the fault happen will have a strong demagnetization effect on the permanent magnet. Fig.9 shows the phase current waveform at short circuit operation, it's about 2.19 times of the rated phase current. Moreover the magnetic line of force at short circuit operation is shown in Fig.10.

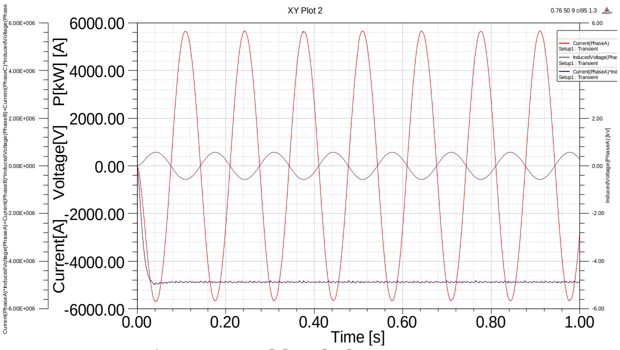

Fig. 5. Rated load characteristic

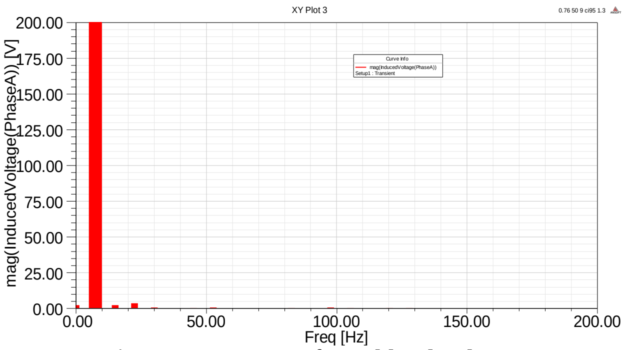

Fig. 6. Harmonics of rated load voltage

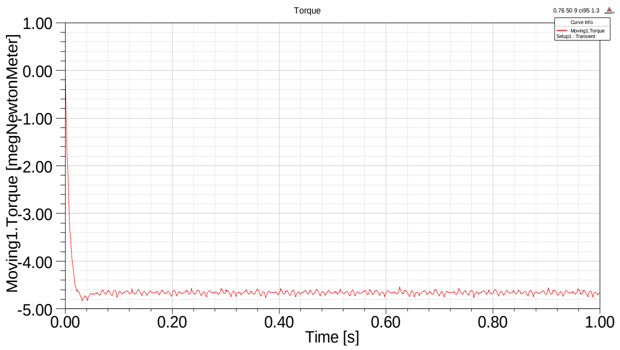

Fig. 7. Rated load torque

3. Stator Winding Connection Method and the Steady Thermal Simulation of the Winding Ends

Windings in the inner evaporative cooling generator are composed of hollow conductors and solid conductors. In order to achieve self-loop function of the inner evaporative cooling system, we should use the linear type coil and separate the coil ends. Using copper platoon for electrical connection and the cooling medium flows out directly through the joints, as shown in Fig. 11.

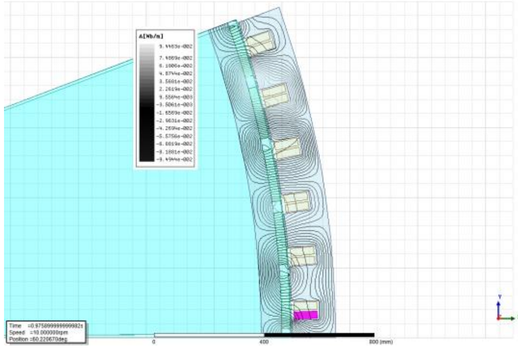

Fig. 8. Magnetic line of force at rated load operation

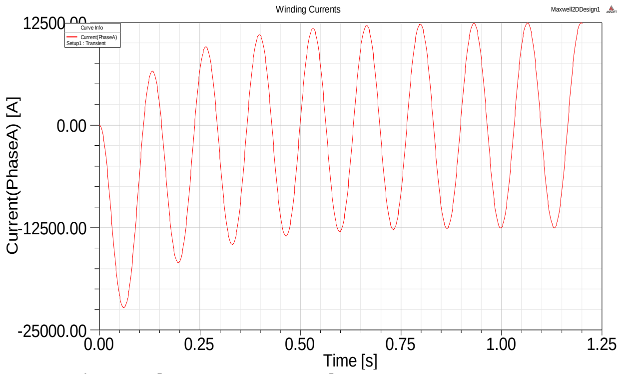

Fig. 9. Phase current at short circuit operation

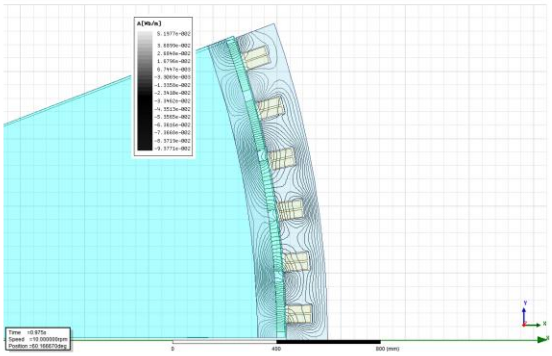

Fig. 10. Magnetic line of force at short circuit operation

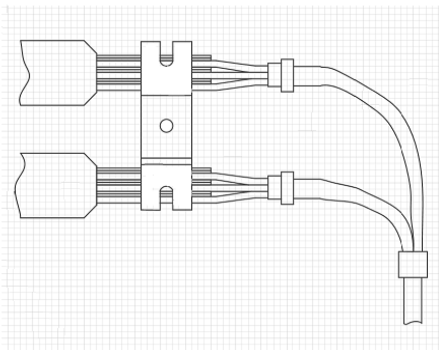

Fig. 11. End connection of windings for inner cooling system

3.1 Connection Method of the Windings

Conductors between two slots are connected by method shows in Fig.12 to make up a coil and coils are connected by method shows in Fig.13 to make up phase windings [5].

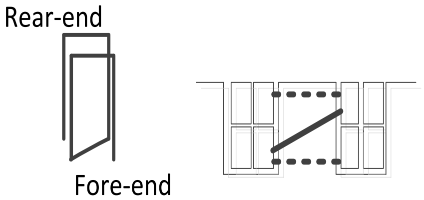

Fig. 12. connection method of conductors between two slots

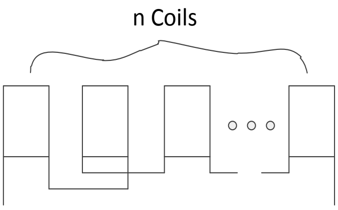

Fig. 13. connection method of coils for phase windings

Using non-overlapping concentrated windings makes enough space for the winding ends. We designed the winding end connect unit based on the size of the generator, as shown in Fig.14.

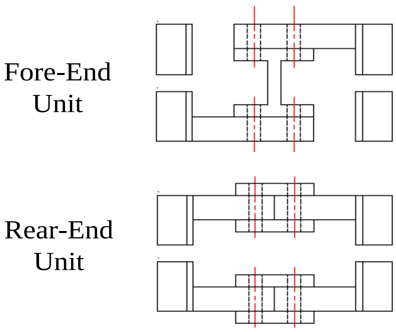

Fig. 14. Connect unit of the windings

3.2 Steady Thermal Simulation of the Stator Winding End Connection Components

The great thermal performance of windings with inner evaporative cooling system has been proved in many engineering practice, we only analyze the heat dissipation of the winding ends.

Heat of the connect units can't dissipate through the inner cooling system, so it dissipates by heat convection with the ambient air and radiation heat transfer with its surroundings [8]. Heat transferred by heat convention is expressed as follows

$$\Phi_1 = Ah(T_w - T_f) \tag{2}$$

Heat transferred by radiation is expressed as

$$\Phi_2 = \varepsilon A\sigma(T_w^4 - T_f^4) \tag{3}$$

The total transferred heat is

$$\Phi = \Phi_1 + \Phi_2 \tag{4}$$

where, A is the heat exchange area of the connect unit, h is the natural convention heat transfer coefficient between connection unit and ambient air (2.6W/(m^2·K)), Tf is the temperature of the ambient air and the surroundings (30℃), ε is the surface emissivity of the connect unit (0.95), σ is Boltzmann constant.

We use the thermal electric simulation model of ANSYS Workbench for FEM analysis, the result is as shown in Fig.15 and Fig.16.

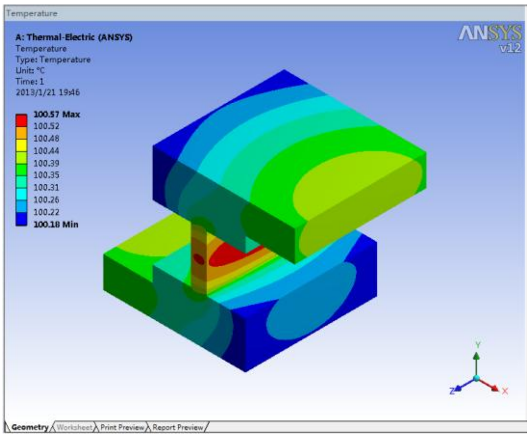

Fig. 15. Thermal-electric simulation result of fore end unit

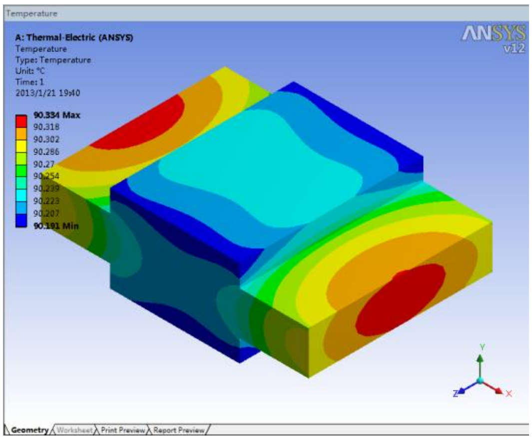

Fig. 16. Thermal-electric simulation result of rear-end unit.

We can see from Fig.15 and Fig.16 that the highest temperature of the fore-end unit is about 100°C, that of the rear-end unit is about 90^{o}C, and the temperature distribution is very uniform. So the connect unit can meet the heat dissipation requirement in actually operating.

4. Conclusion

In this paper, we use the no-overlapping concentrated windings solving the problem that the stator end is crowded and doesn't have enough space for the inner evaporative cooling system. A 5MW permanent magnet directly driven wind power generator is designed by conventional magnetic equivalent circuit method and corrected by FEM. We analyzed the characteristics of the generator at no load, rated load and short circuit condition. Moreover, we designed the connect method of the winding ends and the heat dissipation of the stator end was simulated by FEM, the result showed that the end cooling could satisfy the wind generator operation needs.

Inner evaporative cooling wind power generator with non-overlapping concentrated windings can solve the placing and cooling problem of stator winding in wind power generators.

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