

Comparison Study of Superconducting Generators with Multiphase Armature Windings for Large-scale Direct-drive Wind Turbines

Jin Wang, *Member, IEEE*, Ronghai Qu, *Senior Member, IEEE*, and Yingzhen Liu

Abstract—To reduce the cost of energy and increase the reliability, large-scale direct-drive wind turbines are preferred, especially for the rising offshore wind generation. Compared to the traditional generators, superconducting generators offer many advantages, such as higher power density, higher efficiency at all load, less maintenance and so on. Therefore they are regarded as the most promising candidates for large-scale direct drive wind generators with power of 10 MW and larger. For such generators, a great challenge is the full-power converters which are required as the interface with the grid. Multiphase armature windings are usually utilized to reduce the current stress of the power electronic devices. Two 12 MW nine-phase superconducting generators are designed. Both armature windings consist of three sets of 3-phase lap windings, and the primary difference is the phase difference between the adjacent phase sets. Using finite element method, the characteristics of the two generators are analyzed and compared, from the view point of torque performance, eddy-current losses on the damping shell, and power conversion system.

Index Terms—Multiphase armature winding, Superconducting field winding, Superconducting generator, Wind generation.

I. INTRODUCTION

WIND power generation is regarded as an alternative energy sources to be beneficial to solve the growing problems of energy crisis and environmental pollution in the world. To improve the efficiency and reduce the cost per unit power, the capacity of wind turbines and wind generators has been increasing in recent years, especially for the rising offshore wind generation [1]. To reduce the maintaining and operating cost, the demand for wind turbines with higher reliability impels great development on the direct-drive wind generation [2]. In such driving trains, the generators are driven by the turbines directly without any gearbox which is considered as one of the most frequent fault sources [2].

For large-scale direct-drive wind turbines with power of 10 MW or above, superconducting generator offer a more feasible alternative, compared to the traditional double-fed induction generators or permanent magnet synchronous

generators [3],[4],[5],[6]. High power density is one of the greatest advantages of superconducting generators, which results in remarkable decrease of nacelle weight [3]. This is very important for the offshore wind generation and can significantly reduce the cost of foundation and installation.

Full-power converters are required to transmit the energy from the direct-drive wind generators to the power grid. And fully-controlled power electronic converters are preferred for better system characteristics [2]. To reduce the current and voltage stress of the switching devices, generators with multiphase armature windings are usually adopted [7]. The multiphase windings can be arranged in different ways [8]. The influences of various multiphase winding arrangements on the superconducting generator performance are necessary to be investigated during the design period.

Two 12 MW nine-phase superconducting synchronous generators with different armature winding arrangements are designed and compared in this paper. Design considerations and parameters are proposed in Section II. Two kinds of multiphase windings are compared in Section III. And the magnetic motive force (MMF) of the windings is analyzed by analytical method. Section IV presents the finite element (FE) simulation results of the two generators. And comparison analysis is performed, from the view point of torque performance, eddy-current losses on damping shell, and power conversion system. A final conclusion is drawn in Section V.

II. DESIGN CONSIDERATION OF 12 MW MULTIPHASE SUPERCONDUCTING WIND GENERATORS

A. Main Features

Two nine-phase superconducting synchronous generators with rated power of 12 MW were designed. The traditional radial flux topology with inner rotor was chosen, as shown in Fig. 1. Both generator designs have the same main dimensions, and the design parameters are summarized in Table I.

The copper field windings in the traditional synchronous generators are replaced with superconducting coils, accompanying a unique cryostat to maintain the required constant low temperature environment for superconductivity. Additionally, a torque tube has to be utilized to transfer the torque from the rotor poles to the main shaft. Since the torque tube also acts as a bridge between the low temperature part and the room temperature, the materials which have low thermal conductivity and high stress, just like glass-fiber

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reinforced composite or titanium alloy, should be considered.

The rated rotating speed of the generators is 9 r/min, which is identical to that of the turbine. Therefore, a torque of about 13 MNm should be transferred to the generator, which deems to be a great challenge to the mechanical structure design. The rated line voltage is 3.3 kV, and the corresponding dc link voltage of the voltage source converters is 5.5 kV.

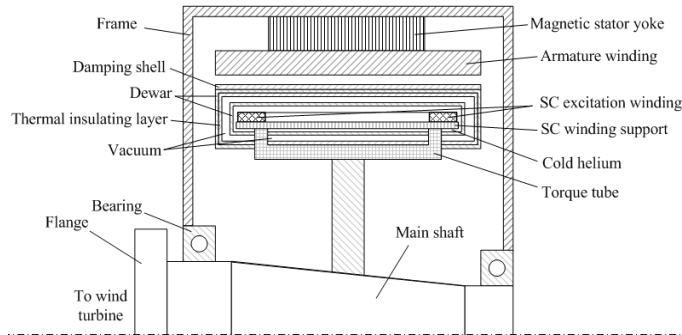


Fig. 1. Sketch of the superconducting wind generator.

TABLE I
 DESIGN SPECIFICATIONS OF THE SUPERCONDUCTING GENERATORS

Parameters	Nine-phase w/o phase shift (Design-1)	Nine-phase with phase shift (Design-2)
Rated power	12 MW	
Rated rotating speed	9 r/min	
Rated voltage	3.3 kV	
Frequency	0.9 Hz	
Winding sets number	3	
Phase shift	0 deg. ele.	20 deg. ele.
Number of poles	12	
Number of stator slots	108	
Coil pitch	9 slots	
Stator outer diameter	6000 mm	
Stator inner diameter	5124 mm	
Physical air-gap length	20 mm	
Effective air-gap length	65 mm	
Rotor outer diameter	5104 mm	
Rotor inner diameter	4714 mm	
Stack length	1500 mm	
Electrical loading	1126 A/cm	
Magnetic loading	2.75 T	
Stator current density	3.1 A/mm ²	
Supercon. material	YBCO	
Supercon. wire length	1357 km	
Excitation current	110 A	
Working temperature	20 K	

B. Stator

The stator is designed to locate at room temperature. To reduce the iron losses caused by high flux density and improve the waveform quality of the inducted back electromotive force (back-EMF), air-gap copper windings are used, fixed by non-magnetic supporting materials. On the other hand, magnetic stator yoke made of silicon steel laminations is retained to support the stator windings and confine the magnetic flux. The stator outer and inner diameters are 6000 mm and 5124 mm, respectively. And the stator stack length is equal to 1500 mm.

The armature windings of both generators are composed of three sets of three-phase star-connected windings. And the primary difference between them is the phase shift between the adjacent phase sets. Detailed description about the

multiphase armature windings is given in Section III.

The compact and lightweight design is certainly limited by the choice of stator cooling method. Higher electrical loading or armature current density can be adopted if the stator is effectively cooled. Since the copper losses will be the dominant losses in the low speed and low frequency superconducting generators, water cooling method is chosen. The end windings are cooled using totally-enclosed forced air ventilation.

C. Rotor with Superconducting Field Windings

As shown in Fig. 1, the rotor mainly consists of damping shell, cryostat, superconducting excitation windings and their support, torque tube, structural components and main shaft. To avoid the saturation problem and minimize the weight of active materials, ironless rotor structure is adopted. Unfortunately, more ampere-turns are needed to produce the expected air-gap flux density. In the proposed 12-pole superconducting generators, the superconducting tape length is more than 1300 km for a peak air-gap flux density of 2.75 T.

The superconducting field coils are designed as racetrack structure, which are enclosed by a cryostat. And the operating temperature is controlled to be 20 K via forced convection of helium gas. The 2G superconducting tapes YBCO are used due to the potential benefits of lower prices and better performance, compared to the 1G superconducting materials Bi2223 [3],[6],[9],[10]. The field current is set to be 110 A, and the resulting field current density is about 9.2×10^7 A/mm². Considering the cooling and supporting structures, the filling factor of field coils is about 0.5.

D. Power Conversion System

The schematic of the power conversion system is shown in Fig. 2. The three sets of three-phase armature windings of the superconducting generators are separated electrically. And each set winding is connected to a full-power AC/DC/AC converter. The fundamental frequency is just about 1 Hz due to the very low rotating speed and low pole number. The design of such converters deems to be very challenging and costly. While in the proposed topology, the power of the generator is shared by three convertors. Such topology potentially offers the advantages of reduced current stress, fault tolerance, and lower system cost.

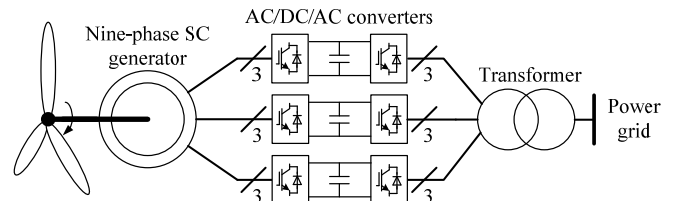


Fig. 2. Sketch of direct-drive superconducting wind generation system.

III. MULTIPHASE WINDING ARRANGEMENTS AND MMF HARMONIC ANALYSIS

Both generators have three sets of three-phase star-connected windings with isolated neutral points. Each set of winding is fed by a three-phase convertor, as shown in Fig. 2.

Therefore, the power of each convertor is only about one third of the generator power. Additionally, the three phase convertors are usually off-the-shelf, which can shorten the manufacturing cycle time and the cost.

A. Multiphase Windings of Design-1

In Design-1, the three sets of windings are in phase, as shown in Fig. 3 (a). The number of series coils per pole per phase of each set winding is 3. And the coil pitch is 9 slots. Accordingly, the full-pitch distributed windings are similar with that of the traditional three phase generators. The distribution coefficient of fundamental harmonic is 0.96. And the per unit values of the MMF harmonic amplitudes are expressed by three-dimensional square columns in Fig. 3 (b). The MMF harmonics were calculated analytically, supposing that the current waveforms are of 180 degree square waveforms to take consideration of all time harmonics. The letters v and k in the figure represent the space harmonic order and the time harmonic order, respectively. It should be illustrated that the fundamental harmonic amplitude value is divided by 4, to show the high order harmonics clearly.

B. Multiphase Windings of Design-2

The arrangement of the three sets of windings in Design-2 is depicted in Fig. 4 (a). It can be noted that the winding distribution distinct from that of Design-1. The adjacent set of winding is spatially shifted by 20 electric degrees. The windings are full-pitch concentrated windings since the number of coils per pole per phase is 1 and the coil pitch is 9 slots. The winding coefficients are all equal to 1. The MMF harmonic amplitudes are given in Fig. 4 (b), and similarly the fundamental one is purposely four times shorter. Compared with the MMF harmonics of Design-1, there are remarkably less harmonics in the nine-phase windings with phase shift.

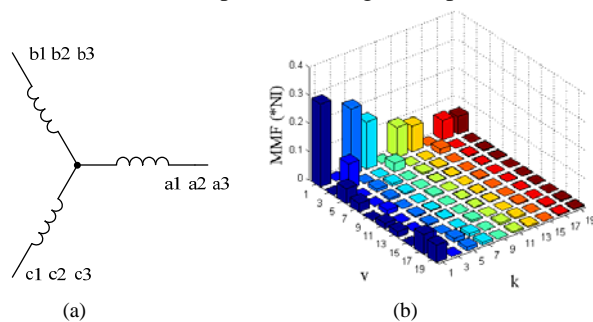


Fig. 3. Nine-phase windings without phase shift. (a) Winding arrangement. (b) MMF harmonic spectrum.

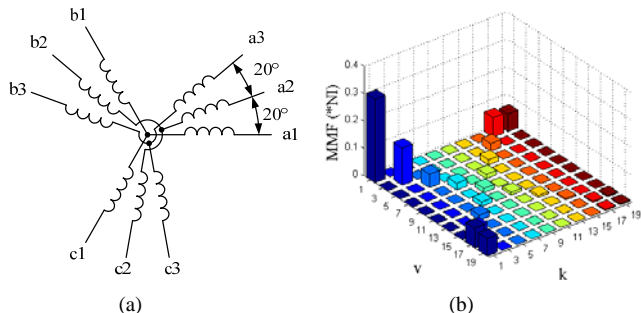


Fig. 4. Nine-phase windings with phase shift of 20 electric degrees. (a) Winding arrangement. (b) MMF harmonic spectrum.

IV. FE SIMULATION RESULTS AND COMPARISON

The two multiphase superconducting generators were designed using analytical design software, and then modeled and verified by transient FE simulation.

Firstly, the no-load simulation tests are performed. The only difference between the two designs is the armature windings. Therefore, they have the same no-load magnetic field. The excitation current is set to be 110 A, and the FE model with flux density distribution is shown in Fig. 5. It can be seen that the stator yoke is highly saturated since the materials is normal silicon steel. The thickness of stator iron yoke has a great impact on the generator's weight. Because the frequency is very low, a relatively high yoke flux density is preferred to reduce the weight, which has no significant influence on the iron losses. However, the leaking flux outside the stator yoke should be limited. The maximum value of flux density in the superconducting coil areas is about 5.6 T, and it can be noted that the maximum flux density appears around the inside corners of the cross profile of racetrack coils.

Fig. 6 shows the no-load back-EMF waveforms. The three phase back-EMF waveforms of the three sets of winding of Design-1 are overlapped with each other. While for Design-2, a phase shift of 20 electric degrees exists between the back-EMF waveforms of the adjacent winding sets. There are large amount of harmonics in the back-EMF waveforms, since the full-pitch windings are used.

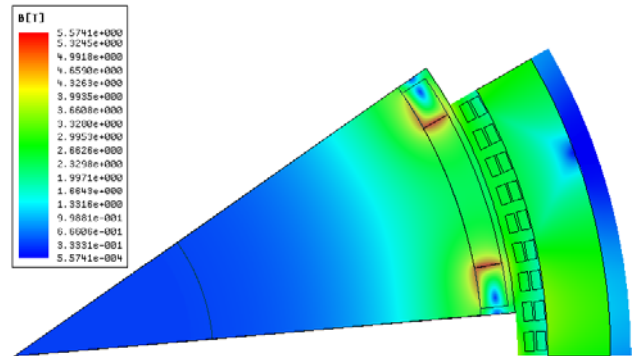
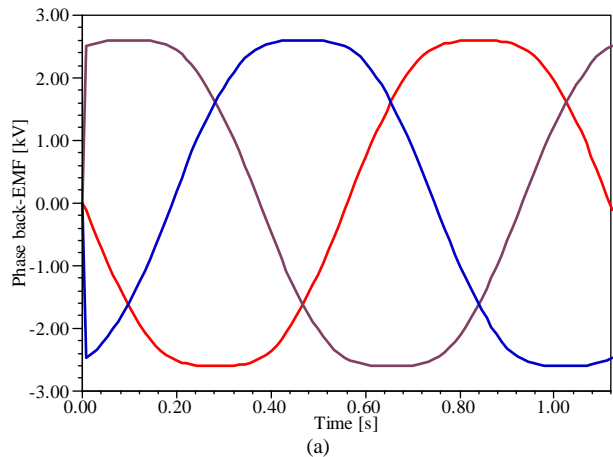


Fig. 5. FE simulated flux density distribution.



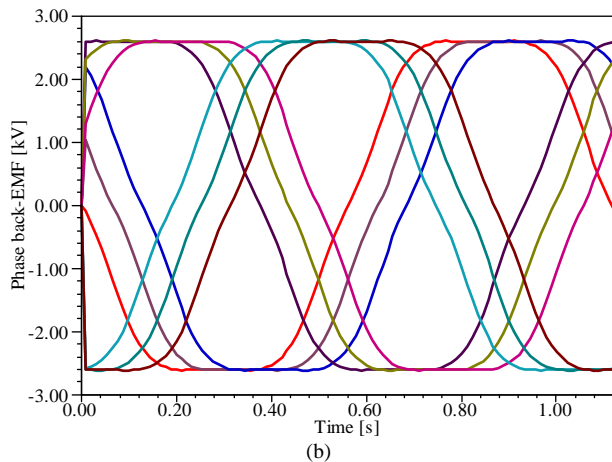


Fig. 6. No-load back-EMF waveforms. (a) Design-1. (b) Design-2.

During the rated load simulation, the phase currents are ideal sinusoidal and in opposite phase with the corresponding back-EMFs. The electrical loads and current densities of the two generators are kept constant. The electromagnetic torque waveforms under rated load conditions are present in Fig. 7. It can be seen that about 4% greater torque output is obtained by Design-2, compared to Design-1, which is caused by the larger winding coefficient with concentrated full-pitch windings. Assuming to produce the same torque, the lower heat load of Design-2 would result in lower cooling power, increasing the generator efficiency.

Additionally, 78% lower torque ripple is with Design-2, since the torque ripples produced by the three sets of windings are compensated with each other, which is helpful for vibrations and noise reduction.

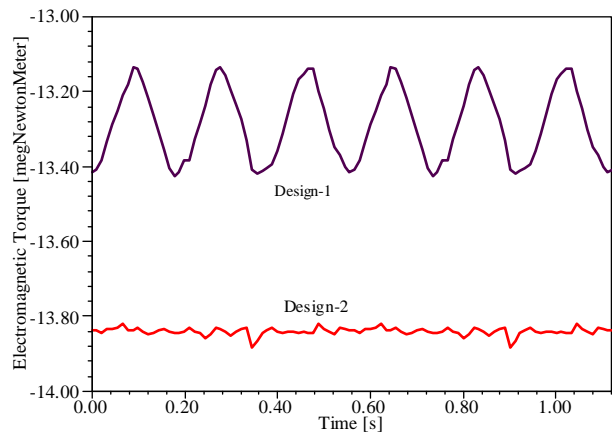


Fig. 7. Electromagnetic torque waveforms by simulation.

Finally, transient analysis on eddy-current losses of the damping shell was carried out. The thickness of the damping shell enclosing the rotor is set to be 5 mm, and it is made of aluminum. The injected phase currents are of sinusoidal waveform without any time harmonics. Under rated rotating speed, the waveforms of eddy-current losses of the damping shell are calculated and shown in Fig. 8.

It can be seen from Fig.8 that greater eddy-current losses are with Design-1, which is mainly caused by the great amount of space harmonics, as shown in Fig. 3 (b). The eddy-current losses of the damping shell in Design-2 are only 10%

of its counterpart. Accordingly, there may be no need to separate the damping shell and the cryostat to prevent the heat from conducting to the cryostat, which will simplify the structure design of the damping shell and the cryostat.

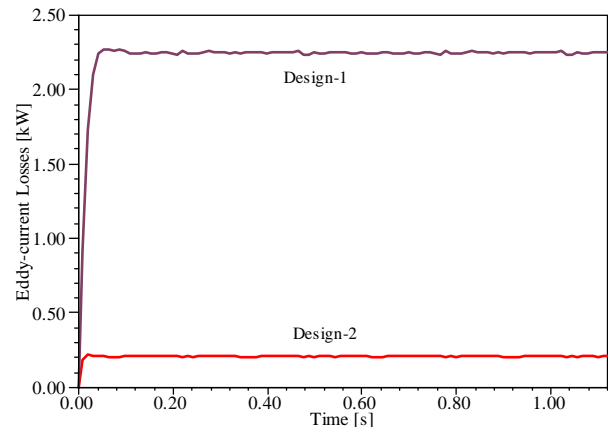


Fig. 8. Damping shell eddy-current losses by simulation.

V. CONCLUSION

Multiphase superconducting generators with phase shift between the winding sets are preferred, considering the torque performance, eddy-current losses in the damping shell and efficiency. Higher torque density can be obtained using multiphase armature windings with phase shift. And the torque ripple is significantly reduced, although the phase back-EMF contains high order harmonics. Eddy-current losses in the damping shell are reduced remarkably using multiphase windings with phase shift, which will simplify the structure design and be helpful to restrain the heat leakage.

Since the direct-drive superconducting generators are fed by full-power converters, higher amount of time harmonics may exist because of the low inductance of the generators and the limited switching frequency. Multiphase topologies with phase shift are still suitable since they are insensitive to the time harmonics. Multiphase topologies show positive impact on the power conversion system, despite of the increasing system complexity resulting from the large amount of devices.

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REFERENCES

- [1] Global Offshore Wind Energy Markets and Strategies: 2009–2020, Emerging Energy Research, Dec. 2009
- [2] D. Bang, H. Polinder, G. Shrestha, J. Ferreira, "Review of generator systems for direct-drive wind turbines," in proceedings of European Wind Energy Conference & Exhibition, Brussels, Belgium, March 31 - April 3, 2008.
- [3] B. Maples, M. Hand, and W. Musial, Comparative assessment of direct-drive high temperature superconductor generators in multi-megawatt class wind turbines, NREL report, Oct. 2010.
- [4] O. Keysan, M. A. Mueller, "Superconducting generators for renewable energy applications," IET Conference on Renewable Power Generation (RPG 2011), Edinburgh, UK, 5-8 Sept. 2011.
- [5] A. Abrahamsen, B. Jensen, E. Seiler, N. Mijatovic, V. Rodriguez-Zermeno, N. Andersen, O. J., "Feasibility study of 5mw superconducting

- wind turbine generator,” *Physica C: Superconductivity* Vol. 471, No. 21–22, pp. 1464–1469, Nov. 2011.
- [6] G. Snitchler, B. Gamble, C. King, and P. Winn, “10 MW class superconductor wind turbine generators,” *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1089-1092, Jun. 2011.
- [7] S. Brisset, D. Vizireanu, and P. Brochet, “Design and optimization of a nine-phase axial-flux PM synchronous generator with concentrated winding for direct-drive wind turbine,” *IEEE Trans. Ind. Appl.*, vol. 44, no. 3, pp.707-715, May-June 2008.
- [8] E. Levi. “Multiphase electric machines for variable-speed applications,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 5, pp.1893-1909, 2008.
- [9] S. Fukui, J. Ogawa, T. Sato, O. Tsukamoto, N. Kashima, and S. Nagaya, “Study of 10 MW-Class wind turbine synchronous generators with HTS field windings,” *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp.1151-1154, Jun. 2011 .
- [10] O. Keysan, A. M. Mueller, “A homopolar HTSG topology for large direct drive wind turbines,” *IEEE Trans. Appl. Supercond.*, vol. 21, no. 5, pp.3523-3531, Oct. 2011.