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Design of dual-rotor PMSG for wave energy conversion

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Abstract

In the paper, a novel dual-rotor permanent magnet synchronous generator (DRPMSG) for wave power generation is designed. The no-load reaction characteristics and load reaction characteristics of the DRPMSG are analyzed with back-EMF, air gap magnetic density harmonic, torque and current results presented. A significant advantage of this machine is that it can achieve variable stiffness adjustment for wave energy conversion. The output power of DRPMSG is a summation of the inner and outer rotor's power. Therefore, it can transform wave power into electric power more steadily since it can operate in a wider wave speed. The simulation results verify the feasibility of the optimized DRPMSG and the effectiveness of the proposed design scheme.

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Keywords: Dual-rotor permanent magnet synchronous generator; Variable stiffness adjustment; Finite-element method; Wave energy conversion

1. Introduction

With the increasing concerns on energy and environment problems, wave power generation is attracting more and more attentions [1]. As wave energy converter (WEC) has the drawbacks of low speed and poor stability, generators with features of low-speed, high torque density and high efficiency are urgently required in wave power generation.

In this case, dual-rotor machines, as new types of high efficiency electric machines, have been paid more and more concentration in recent years [2,3]. Researchers search different ways to analyze its magnetic field and improve the efficiency. For example, a new type of double-rotor induction machine with inner and outer rotors was put forward by Nikolaus Neuberger [4]. Its efficiency and power factor could be increased by more than 3% and 0.08, respectively. However, although a few radial-flux dual-rotor or dual-stator induction machines [5] and dual-rotor PM machines

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have been reported, many design and control issues are still to be studied for the dual-rotor permanent-magnet synchronous generator (DRPMSG).

In the paper, the principles of operation, configurations, and features of the DRPMSG machines are introduced. Then the parameters, such as rated capacity, voltage and current, PM material, the size of inner and outer generator, the length of iron core, etc., are determined so that the DRPMSG was designed and verified by finite-element analysis (FEA). The variable stiffness adjustment function of the wave energy conversion is achieved by a coordinated control of the two mechanical imports of the DRPMSG in a parallel operation mode. The simulation results verify the effectiveness of the proposed design scheme and the feasibility of the optimized DRPMSG, thus providing a fundamental basis for further study on DRPMSGs in wave energy conversion system.

2. Structure and principle of operation

In the paper, a novel dual-rotor permanent-magnet synchronous generator (DRPMSG) for wave power generation is designed. The diagram of the DRPMSG structure and the wave energy conversion system is shown in Fig. 1. The DRPMSG mainly includes outer rotor iron core, outer-rotor PM, inner rotor core, inner-rotor PM and stator windings. It can be considered as an external rotor permanent magnet generator combined with an internal rotor permanent magnet generator. These two parts share a common stator winding. The common stator winding is composed by the inner stator and outer stator winding. The two windings are connected in parallel as shown in Fig. 1, so the two rotors can be controlled independently. The wave energy conversion system includes DRPMSG, rectifiers, inverter, AC load, and two float-type WECs.

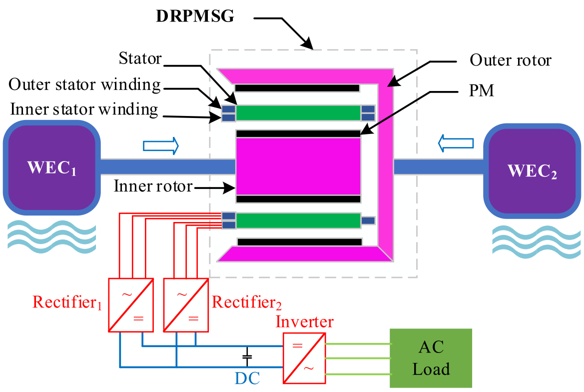

Fig. 1. Diagram of DRPMSG and wave energy conversion system.

In wave generation system, the WEC receives volatile wave energy, so the output mechanical energy of WEC is low and it has a large fluctuation. A significant advantage of the designed machine is that it can achieve variable stiffness adjustment automatically for wave energy conversion. The DRPMSG has two mechanical input ports as shown in Fig. 1. The inner rotor is connected to the WEC1. The outer rotor is connected to the WEC2. The two WECs are installed with $\lambda/4$ space between each other. λ indicated the wave length. In this condition, when the input mechanical power of single WEC unit is low, the proposed two-WECs array working mode can increase the torque and reduce the torque oscillation so that the stability and reliability for wave energy conversion are improved. With the help of two mechanical input ports, the output power of DRPMSG is a summation of the inner and outer rotor's power. Therefore, it can transform wave power into electric power more steadily in a wider wave condition.

3. Design of DRPMSG

In order to investigate the operation performance and magnetic field, a design has been carried out based on the traditional three-phase PMSG. Compared with the traditional three-phase PMSG, the design of DRPMSG is divided into 2 parts: the inner generator and outer generator. During the design process, the inductance of the DRPMSG is calculated. It can be seen as inner-rotor permanent magnet generator and outer-rotor permanent magnet generator connected in series. Therefore, the inductance of the machine should be calculated separately in two parts, and finally be added together. Take part of the winding of phase A on the outer rotor as an example, inductance of armature reaction per phase winding is

$$L_{mo} = \frac{\psi_{m1}}{\sqrt{2}I} = 2\mu_0 \frac{m}{\pi} \frac{(NK_{dp1})^2}{p^2} l_{ef} \frac{R_{g0}}{l_{mgo}}, \quad (1)$$

where ψ_{m1} is the magnetic flux generated by fundamental magnetic field, I is the winding current per phase, μ_0 is the air permeability, m is the number of phase, K_{dp1} is the coefficient of fundamental winding, N is the number of turns, p is the number of pole pairs, l_{ef} is the effective length of armature core, R_{g0} is air gap radius of outer rotor, l_{mgo} is the equivalent air gap length of outer rotor. Inductance of armature reaction per phase winding for the inner generator is

$$L_{mi} = 2\mu_0 \frac{m}{\pi} \frac{(NK_{dp1})^2}{p^2} l_{ef} \frac{R_{gi}}{l_{mgi}}, \quad (2)$$

where R_{gi} is the length of magnetization direction of inner rotor, l_{mgi} is the equivalent air gap length of inner rotor.

Therefore, inductance of armature reaction of DRPMSG can be expressed as

$$L_m = 2\mu_0 \frac{m}{\pi} \frac{(NK_{dp1})^2}{p^2} l_{ef} \left(\frac{R_{gi}}{l_{mgi}} + \frac{R_{go}}{l_{mgo}} \right), \quad (3)$$

Table 1 gives the main parameters of the designed DRPMSG.

Table 1. Main parameters of DRPMSG.

Parameters	Value
Rated capacity (kVA)	100
Number of pole pairs	4
Outer diameter of outer rotor (mm)	163.8
Inner diameter of outer rotor (mm)	143.8
Permanent magnet thickness of outer rotor (mm)	14
Outer diameter of stator (mm)	142.4
Inner diameter of stator (mm)	61.3
Outer diameter of inner rotor (mm)	59.5
Inner diameter of inner rotor (mm)	43.2
Permanent magnet thickness of outer rotor (mm)	15

4. Magnetic field analysis of DRPMSG

4.1. No-load characteristic analysis

No-load back-EMF refers to the induced electromotive force in the stator winding generated by permanent magnet magnetic field. The no-load back-EMF directly affects the generator's dynamic and steady-state performances. Assuming the speed of double-rotor generator is 1200r/min, the back-EMF of the inner DRPMSG and the outer DRPMSG, and the synthetic back-EMF are obtained and shown as Fig. 2(a), (b) (c) respectively. It can be seen that the back-EMF waveform is three-phase symmetry, and the fluctuation is relatively small, so the design is reasonable.

Fig. 2(d) shows the cogging torque. It can be concluded that cogging torque accounts for only 3.8% of the output torque, which is far below the usual requirement — 10%. This can greatly reduce the noise and vibration of the machine. When the stator windings are not energized, the distribution of the magnetic field generated by the permanent magnets in the air gap is referred to as the no-load air gap flux density. Fig. 2(e) and Fig. 2(f) give the flux density of the air-gap of the inner and outer parts of DRPMSG. As can be seen from the figure, the no-load air-gap flux density waveform shows a relatively good sinusoidal distribution. The small amount of harmonic component is mainly caused by the coupling of multiple magnetic fields. If Halbach magnetization is used, the harmonic component will be greatly reduced but the manufacturing cost will also be greatly increased.

The air gap magnetic density harmonic analysis curve is obtained from Fourier analysis of the no-load air gap magnetic density, as shown in Fig. 3(a) and Fig. 3(b). It can be seen from the Figures that the ratio of the 3rd and 5th harmonic components to the fundamental components in air-gap flux density harmonic analysis is slightly large, and the 7th, 9th and 11th harmonic content is close to zero. The total fundamental component value is 0.9124 T.

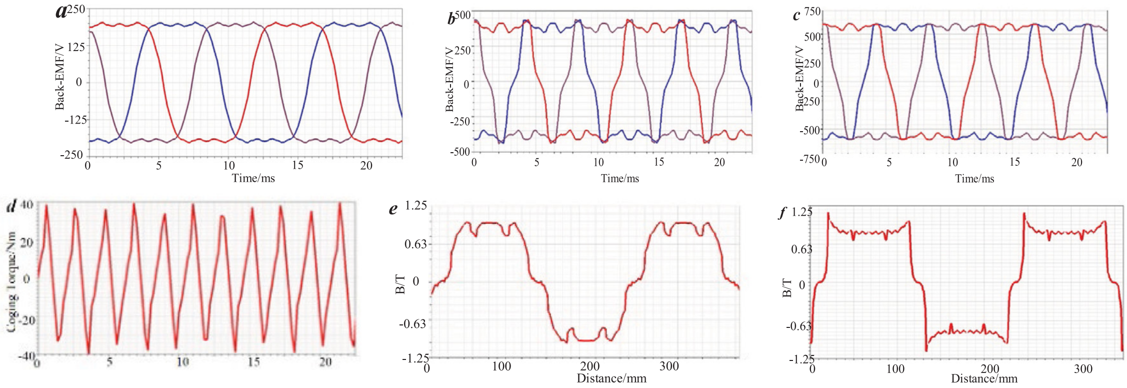

Fig. 2. (a) Inner Back-EMF of the DRPMSG; (b) outer Back-EMF of the DRPMSG. (c) synthetic back-EMF of the DRPMSG; (d) cogging torque of the DRPMSG; (e) flux density of the inner DRPMSG; (f) Flux density of the outer DRPMSG.

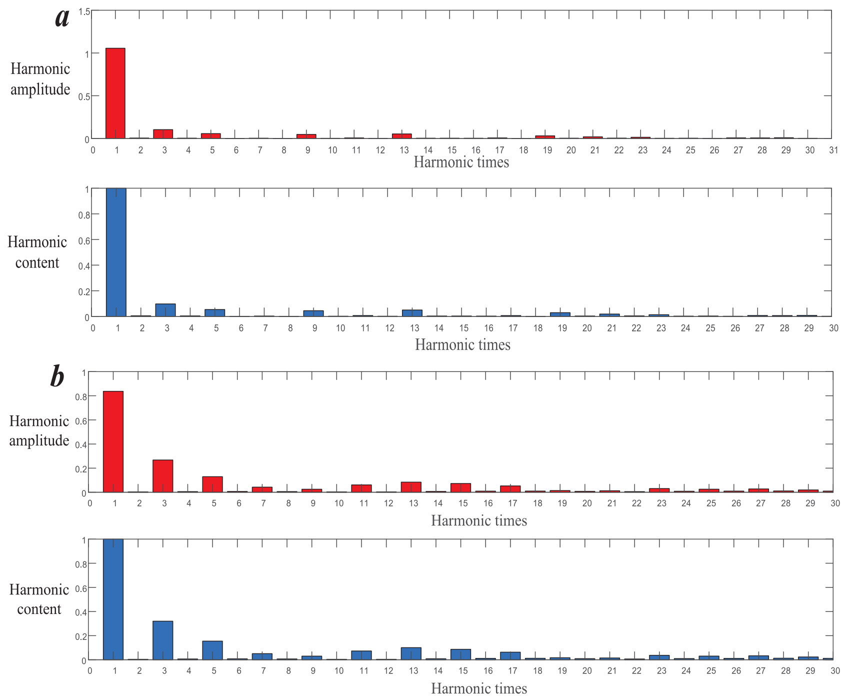

Fig. 3. (a) Outer air-gap magnetic density harmonic analysis; (b) inner air-gap magnetic density harmonic analysis.

Usually, the total fundamental component should be higher than 0.7 T. Within the allowable error range, the air-gap flux density waveform obtained in this paper is more reasonable.

4.2. On-load characteristic analysis

As The load analysis of low-speed permanent magnet synchronous generators mainly observes the rated voltage and output power of the generator, the value of the flux density and the torque value of the generator, and so on. Fig. 4(a), (b), (d), (e) show the corresponding voltage waveforms when the generator runs on load. Fig. 4(c) shows the electromagnetic torque waveform. From Fig. 4, it can also be seen that the variable stiffness adjustment for wave energy conversion is achieved. And it can improve the survivability of the wave energy conversion system in

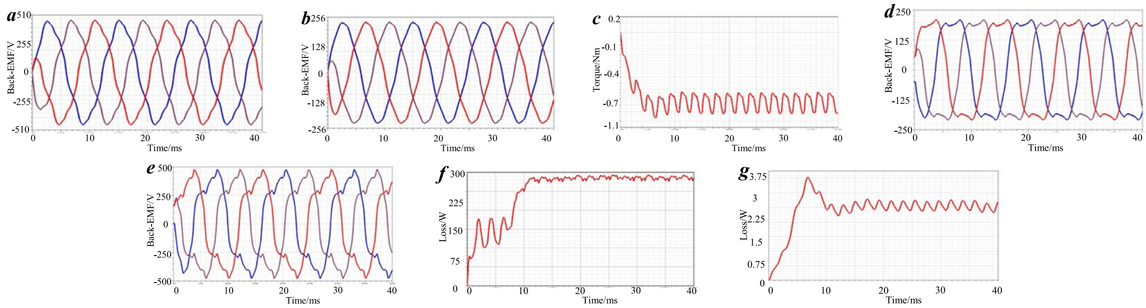

Fig. 4. (a) Voltages of the outer stator winding; (b) voltages of the inner stator winding; (c) electromagnetic torque waveform; (d) inner back-EMF diagram; (e) core loss of DRPMSG; (f) stranded loss of DRPMSG.

a wider wave spectrum range. Fig. 4(f) and Fig. 4(g) show the corresponding core loss and stranded loss curves, respectively.

The average value of core loss and stranded loss are shown in Table 2. It can be seen from Table 2 that the efficiency of the wave energy conversion of DRPMSG can reach 86% in the ideal wave condition.

Table 2. Loss and efficiency of DRPMSG.

Core loss (kW)	Stranded loss (kW)	Output power (kW)	Efficiency
0.285	2.5598	108	86%

5. Conclusions

In this paper, a novel dual-rotor permanent magnet synchronous generator (DRPMSG) for wave power generation is designed with a variable stiffness control function achieved. Its validity and superiority have been verified by analyzing no-load reaction characteristics and load reaction characteristics. Finally, it can achieve stiffness adjustment by the two mechanical input ports driven by the two WECs with reasonable installation in sea or by control the inner DRPMSG in motor running mode. Therefore, it can contribute to designing DRPMSGs with variable stiffness adjustment applied in most renewable generation systems such as wave generation and wind generation, where how to increase the output power and improving efficiency are both critical issues. Further, the control wave energy conversion scheme can be applied in multi-freedom WEC too.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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