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A feasibility study on a new brushless and gearless contra-rotating permanent magnet wind power generator

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In this paper, a novel fully integrated contra-rotating permanent magnet (PM) generator is proposed. In order to efficiently capture wind energy, two contra-rotating rotors are integrated, based on magnetic field modulating principle, into a single PM machine. A relatively high angular velocity is created and the torque density is improved. The steady-state and transient performance of the machine is simulated using time-stepping finite-element method. The computation results are used to showcase the validity of the proposed machine design. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4862513]

I. INTRODUCTION

Wind turbines are the fastest growing renewable energy harvesters for electricity generation in the world.[1] Conventional single rotor wind turbines have low efficiency and limited optimization scope. According to the aerodynamic characteristics of wind turbines, there are, however, lots of untapped wind energy behind the single rotor. It is feasible to install an additional rotor in the wake area to further extract the otherwise wasted wind energy.

In existing practices, researchers use two separated electric generators to realize the additional wind energy harvesting. However, such structure is bulky. To reduce the weight and volume, and improve the torque density and efficiency, a contra-rotating generator with one permanent magnet (PM) rotor and one wound rotor rotating in opposite directions is designed and a relative high angular velocity is produced.[2] To remove the slip ring, one possibility is to use a counter-rotating bevel-planetary gear system, in which the outside is the ring gear, the middle gear is a planet gear, and the spur gear is the sun gear.[3] Obviously, mechanical gear box systems are troubled by acoustic noise, mechanical losses, lubrication, and overloading problems.

Magnetic harmonic gear can utilize the magnetic flux modulation principle to transmit torque and power without mechanical contact.[4] One promising application of magnetic gear (MG) is to integrate it with an electric machine to realize a high torque density output. In this paper, a novel MG based contra-rotating wind turbine is presented. Modulating poles are installed as a contra-rotating rotor so as to capture the additional wind energy in the wake area behind the outer rotor.

II. DESIGN RULE

This proposed contra-rotating machine exploits the magnetic flux modulating principle to modulate the rotating magnetic field in order to realize the contra rotating operation. The purpose is to increase the wind speed range in which the wind energy is captured efficiently and hence improving the torque density of the machine.

In the MG, the ferromagnetic pole pieces function to modulate the high-order harmonic components of the airgap magnetic field. A specific low-order harmonic component is generated to synchronize the high-speed mover to produce a continuous positive thrust force. In the MG, the number of pole pairs of the space harmonics of the flux density distribution and the speed of the space harmonics produced by either the high or low speed rotor PMs are

$$p_{m,k} = |mp + kn_s| \tag{1}$$

$$\Omega_{m,k} = mp\Omega_i/|mp + kn_s|, \tag{2}$$

where m = 1,3,4,…, ∞, k = 0, ±1, ±2,…, ±∞; p is the number of pole pairs of the inner PMs; n_s is the number of the ferromagnetic pole pieces, and Ω_i is the inner rotating speed of the magnetic field. To transmit torque at different speeds, the pole pairs of the outer PMs must be equal to $p_{m,k}$ and if the ferromagnetic pole pairs are stationary, the speed of the space harmonics of the outer rotor must be equal to $\Omega_{m,k}$. When $m = 1, k = -1$, the largest space harmonic component is obtained. Thus if the ferromagnetic pole pieces are stationary, the speed of the outer rotor of the gear is

$$\Omega_{1,-1} = p\Omega_i/|p - n_s|, \tag{3}$$

and the gear ratio is given by

$$G_r = |p - n_s|/p. \tag{4}$$

If all of the three parts of MG rotate simultaneously, the rotational velocities of different rotors satisfy the following relationship:

$$p_o\Omega_o - n_m\Omega_m + p_i\Omega_i = 0, \tag{5}$$

where Ω_m is the rotational velocity of the modulating poles, Ω_o and Ω_i are the rotational velocities of outer rotor and inner rotor, respectively. p_o and p_i are the PM pole-pair

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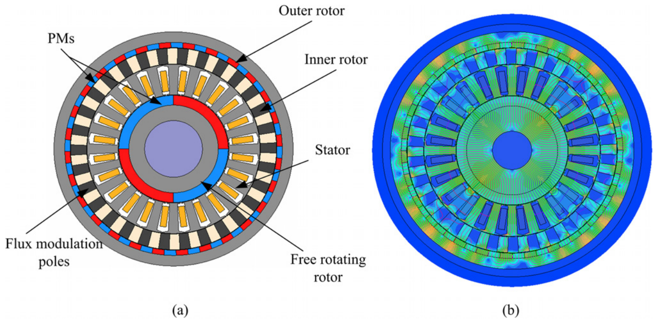

FIG. 1. Configuration of Proposed machine. (a) Front view. (b) Magnetic field distribution.

number of the outer and inner rotor, respectively. The gear ratio is defined as

$$G_r = -p_i/p_o. \tag{6}$$

Hence, the rotational velocity relationship can be further expressed as

$$\Omega_o - (1 - G_r)\Omega_m - G_r\Omega_i = 0. \tag{7}$$

Based on the law of energy conservation, one has

$$T_o\Omega_o - T_m\Omega_m + T_i\Omega_i = 0, \tag{8}$$

where T_o,T_m, and T_i are the torque on the outer rotor, modulating poles, and inner rotor, respectively.

If the inner rotating magnetic field is produced by the stator windings, the pole-pair numbers of the stator windings and rotor PMs need to satisfy the following relationship in order to achieve stable torque and speed transmission

$$p_o = n_s - p_i. \tag{9}$$

The outer rotor PM pole-pair number p_o and the ferromagnetic pole piece number n_s are designed to be very large and close to each other. The reason is that the rotor speed is governed by the rotor pole-pair number, and this design aims to reduce the rated speed. With close numbers of p_o and n_s, the pole-pair number of the windings can be small, and hence they can be housed with less slots and with this design the flux leakage is reduced and the copper fill factor is increased.

III. MACHINE DESIGN AND ANALYSIS

Taking into account the limitation of current density in the conductors of the stator slots, the magnitude of the ampere conductor $IN_{slot}N_c$ is 9000 A, where I is the phase current, N_{slot} is the stator slot number, and N_c is the conductor number in each slot. The phase resistance is

$$\begin{aligned} R &= \frac{1}{k}N_c \times \rho \times \frac{l_p}{(S_{slot}/N_c)} \times N_{slot} \\ &= \frac{1}{k}(N_c)^2 \times \rho \times \frac{l_p}{S_{slot}} \times N_{slot}, \end{aligned} \tag{10}$$

where S_{slot} is the slot area, ρ is the resistivity of conductor, k is the phase number, and l_p is the phase coil length. The phase resistance of the machine is 0.2 ohm.

The structure and magnetic field distribution of the proposed machine is shown in Fig. 1. There are totally three rotating parts, namely the outer rotor, modulating poles, and inner rotor. The number of pole-pairs of PMs mounted on the outer rotor surface and inner rotor surface are 28 and 2, respectively. There are 30 pieces of modulating poles which are assembled between the outer rotor and stator. Epoxy is filled into the air slots between modulating poles to enforce the structure strength. There are 24 stator slots, which houses one layer of three-phase windings. The stator teeth can be connected with a thin iron yoke which is in the middle of the stator, and the coils are housed in the inner and outer slots of the stator with the same winding connections.[5]

The performance of the machine is analyzed using finite-element method (FEM). When the outer rotor rotates at 53.6 rpm in anticlockwise direction and the modulating pole rotates at 50 rpm in clockwise direction, the inner rotor would rotate at 1500 rpm in clockwise direction by virtue of the rotating magnetic field. Fig. 2 shows the torque on the inner and outer rotor. The average torque on outer rotor is around 150 Nm and that on the inner rotor is about 11 Nm. It illustrates that even winds at low speed can directly drive the outer rotor and, with the modulating poles, the magnetic field can rotate at an amplified speed to produce electric power at 50 Hz. The back electromotive force (emf) waveforms of the stator windings are shown in Fig. 3. The flux density and its harmonic spectrums in the airgaps are shown in Figs. 4–6, respectively. It can be further verified that the high order harmonic component (28th order) of the magnetic field can be successfully modulated to produce the specific fundamental order of harmonic component (2nd order).

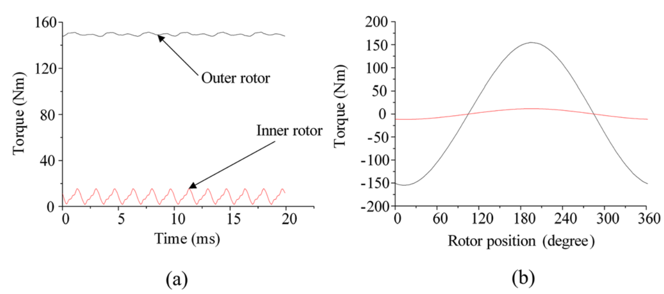

FIG. 2. Torque waveforms at the rated speed. (a) Transient torque. (b) Static torque.

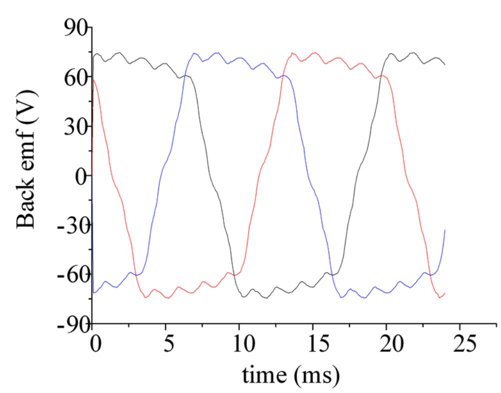

FIG. 3. Back emf waveform at rated speed.

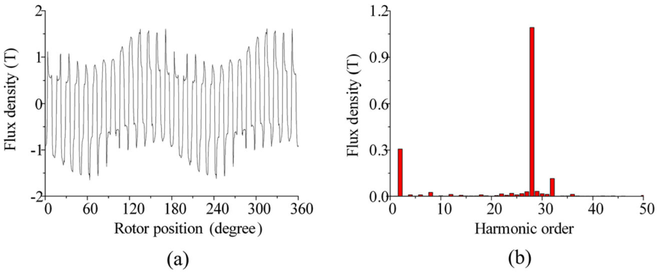

FIG. 4. Flux density in outer airgap. (a) Flux density. (b) Harmonic spectrum.

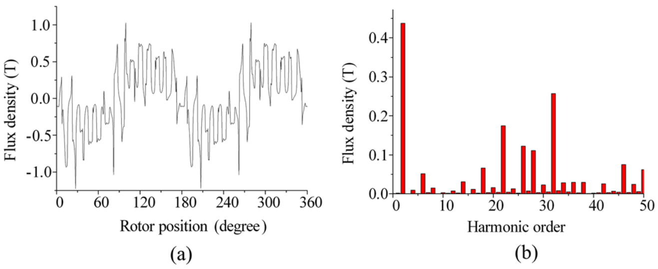

FIG. 5. Flux density in middle airgap. (a) Flux density. (b) Harmonic spectrum.

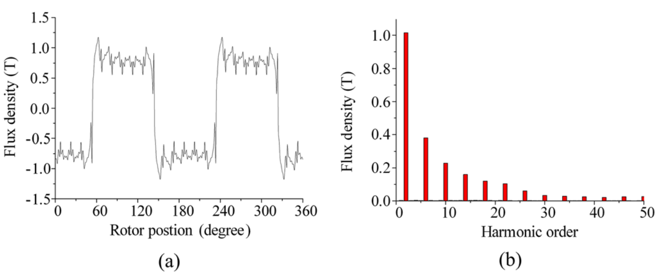

FIG. 6. Flux density in inner airgap. (a) Flux density. (b) Harmonic spectrum.

The wind power generation system has two contra-rotating wind turbines, and due to the contra rotation of PMs and modulating poles, the magnetic field rotating speed can be doubled when compared with those with only one rotor rotating at the same wind speed, and the low speed operation allows the machine to directly drive the wind generator to convert mechanical energy into electrical energy. The full load torque waveform during wind generation is shown in Fig. 7. The input torque in the outer rotor is 150 Nm. The copper loss is 135 W and core-loss is about 23 W. The efficiency of this machine is around 88%. Compared with the 1500 W 24-stator-slot/22-rotor-pole modular PM brushless generator reported in prior art,[6] the volume is reduced by nearly 50%, but the utilization of PM material is improved by 39.4%.

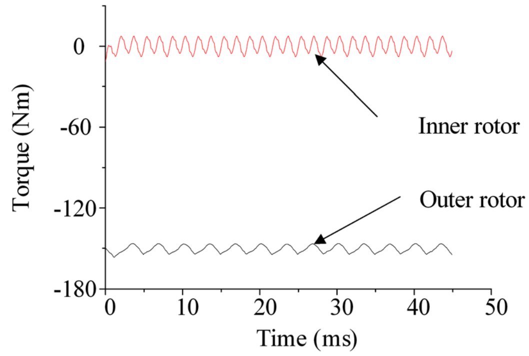

FIG. 7. Full load torque waveforms at the rated speed.

IV. CONCLUSION

In this paper, a novel contra-rotating machine is proposed for wind power direct drive applications. This machine adopts gear integrated effects and flux modulating principle and with this design, the machine produces a very high torque at relatively low rated speed. The transient and static performances simulated using 2-D time-stepping finite-element method (TS-FEM) are reported in this paper to showcase the effectiveness of the proposed machine design.

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