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A New Self-decoupling Magnetic Levitation Generator for Wind Turbines

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Abstract—In order to decouple traditional levitation windings and armature windings, a new self-decoupling magnetic levitation generator (SDMLG) is proposed for wind turbines. This new generator adopts double-stator structure. The armature windings are in the outer stator, and the levitation windings are in the inner stator. The rotor is made of a distributed hollow structure, so that it can effectively decouple the levitation subsystem and armature subsystem. The new structure and operating principle of the generator are presented in this paper. Then the expressions of levitation forces are deduced by analyzing magnetic flux distributions and winding flux linkages. Finite-element analysis method (FEA) is used as the tool for analyzing the performance of the new generator. And the results verify that the levitation windings and armature windings are effectively decoupled.

1. INTRODUCTION

With the development of magnetic levitation technology, magnetic levitation machines have received more and more attention. Since no lubricants are needed and no wear caused by friction is occurring, they need only very little maintenance, which makes them extremely suitable for applications for wind turbines [1, 2]. At the present stage, many researches were focused on the magnetic bearings and control systems [3–5]. In [6–9], the mechanical bearings were replaced by the magnetic bearings, so that the magnetic bearings can levitate the shafts of the permanent magnet generators in wind turbines. Now, most of the magnetic levitation generators in wind turbines adopt this structure. Refs. [10, 11] proposed bearingless permanent magnet machines, in which two sets of windings were in the stator slots, namely armature windings and levitation windings. Refs. [12, 13] proposed bearingless switched reluctance generators, which also had two sets of windings in the stator slots. However, these above machines suffered from complex magnetic structures and strong magnetic coupling between two sets of windings, which are embedded in the stator slots [14, 15]. Some of the known techniques for decoupling and simplifying are applied in Refs. [16–18].

This paper presents a novel self-decoupling magnetic levitation generator (SDMLG) used in wind turbines, in which the armature windings and levitation windings are decoupled magnetically. The novelty of this topology is that the rotor adopts a distributed hollow structure as a "flux barrier". This paper will first look into the new structure. The new structure is especially suitable for the generators with short shafts. The operation principle of the new generator will be analyzed. And then the electromagnetic performance will be predicted by using finite-element analysis method (FEA). Finally, the expression of the levitation forces will be derived and FEA method will be employed to verify the validity of the levitation forces.

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2. STRUCTURE AND OPERATING PRINCIPLE

Figure 1 shows the structure of the 5-degree-of-freedom magnetic levitation wind power generation system, which consists of a 3-degree-of-freedom magnetic bearing and a 2-degree-of-freedom self-decoupling magnetic levitation generator. Both of them are connected along the axial direction. The layout of the magnetic bearing is shown in Figure 2. The magnetic bearing adopts AC-DC hybrid magnetic bearing, which will provide stiffness against the displacement of shaft in 3-degree-of -freedom. The magnetic bearing is composed of an axial stator, a permanent magnetic ring, two radial stators, a rotor, the radial control windings and the axial control windings. The permanent magnetic ring provides the bias flux in radical and axial direction. The radial control windings can control the 2-degree-of-freedom in radial direction, and the axial control windings can control the 1-degree-of-freedom in axial direction.

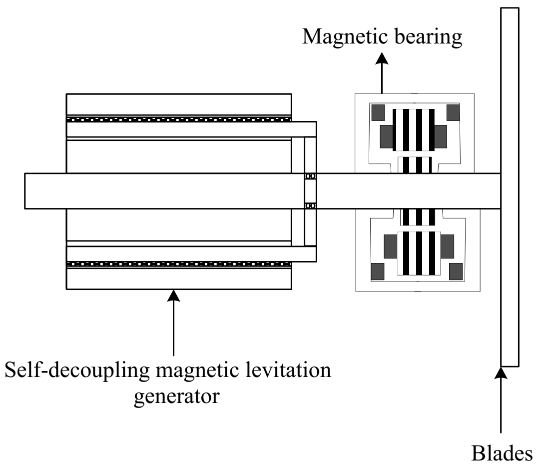

Figure 1. Structure of proposed wind turbine.

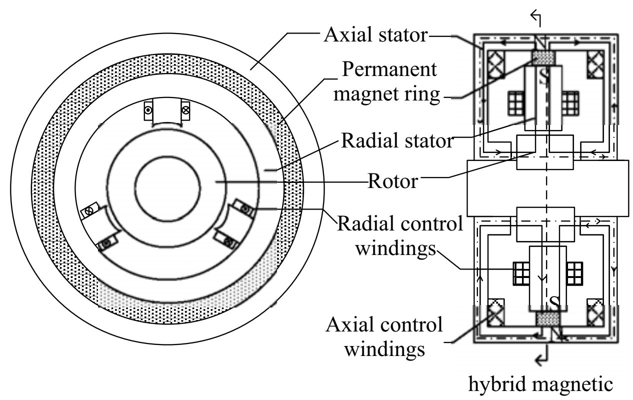

Figure 2. AC-DC 3-degree-of-freedom hybrid magnetic bearing.

The magnetic levitation generator will provide the forces against the displacements of the rotor ring in radial with 2-degree-of-freedom. The radical cross-section of the proposed generator is shown in Figure 3(a). This paper is only focus on the new 2-degree-of-freedom magnetic levitation generator.

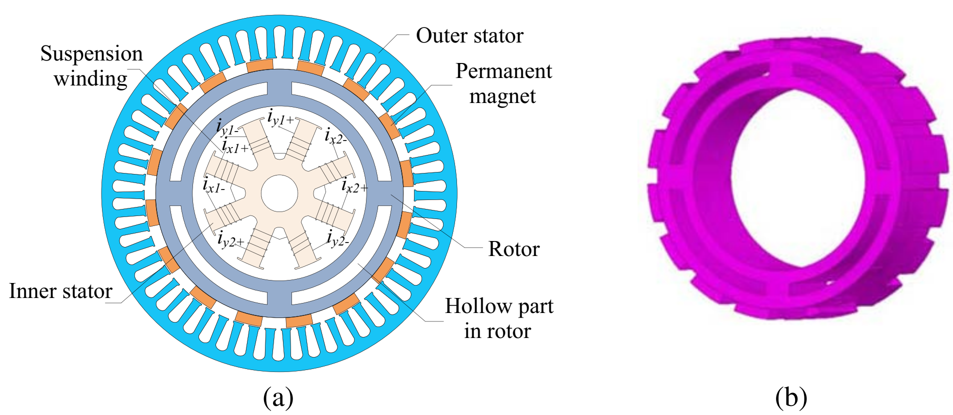

Figure 3. Proposed self-decoupling magnetic levitation generator. (a) Structure. (b) The three-dimensional structure of hollow rotor.

Different from the conventional structure, the generator is composed of the inner stator, outer stator, armature windings, levitation windings, distributed hollow rotor and the permanent magnets. The armature windings are in outer stator, and the levitation windings are in inner stator. In addition, the surface-mounted permanent magnets adopt radial magnetization. The three-dimensional structure of the distributed hollow rotor is shown in Figure 3(b).

As shown in Figure 4, in order to reduce the cogging torque of the proposed generator, the armature windings adopt double-layer fractional windings in combination with short pitching. Meanwhile, there will be some coupling between the adjacent poles. In order to reduce these coupling, the inner stator adopts the salient-pole structure with eight-pole [19].

The rotor ring is made stiff in the radial direction, so that it counteracts the negative stiffness of the permanent magnets and the deflection due to the gravitational force. The cross section of the rotor in axial direction is rectangular. The rotor ring has a rectangular cross-section, so that it can resist both torsion and bending efficiently. The dimensions of the rotor ring can be calculated using analytical methods [20]. According to the analytical methods, the maximum deflection will be in the middle of the cylinder. In order to improve the stiffness of the rotor, four ring stiffeners are added to rotor as shown in Figure 3(b).

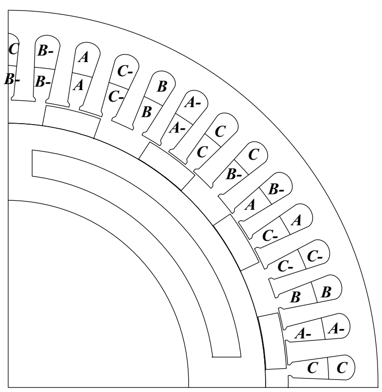

Figure 4. The armature windings in outer stator.

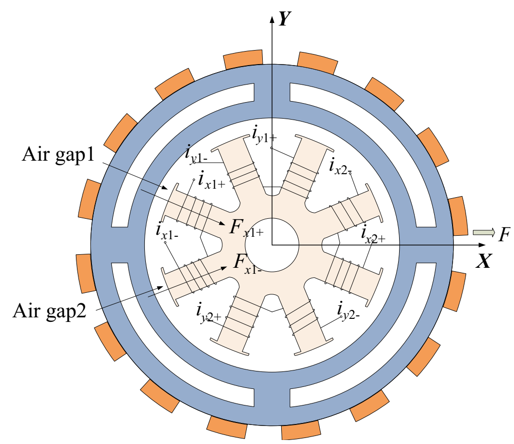

Figure 5. The electromagnetic forces on the rotor when the levitation windings are energized.

As shown in Figure 5, the magnetic levitation windings are in the inner stator, and the turns of each levitation windings are N_f. Each of the two windings in inner stator is connected in series, and these windings are independent to construct eight radial forces in radial directions. Figure 5 shows the principle of levitation forces generation, the flux density in air gap 1 and 2 is changed when changing the current i_{x1+}. According to the principle of Maxwell force generation, there will be the levitation forces F_{x1+}, F_{x1-} in radial directions. Because the two forces are equal, the composition of force F is acting along the x-axis.

Similarly, there will be same situation when the remaining three pairs of levitation windings are changed currents separately. Levitation windings in four directions are individually controlled by four sets of power conversion circuits. Meanwhile, a levitation force can be generated in any desired direction by a vector sum of these forces.

In an example of the y-axis, if the rotor is detected deviation from the equilibrium position, and shifted downwards. At this time, the flux density of the lower air gap is less than the upper. In order to make the rotor back to its equilibrium position, the currents in the levitation winding i_{y2+} should be increased, and the currents of i_{y1+} should be decreased simultaneously. The control principle of the levitation forces in x-axis direction are the same.

3. MAGNETIC FIELD CHARACTERISTICS

A prototype of new self-decoupling magnetic levitation generator is designed based on Ansoft/Maxwell2D. The main parameters are shown in Table 1. The stator and rotor laminations are made of DW360-50 steel silicon, and the permanent magnets are NdFeBN42SH.

Table 1. Main parameters.

Parameter	**Value**
Diameter of the outer stator/mm	290
Internal diameter of the outer stator/mm	220
Outer diameter of the rotor/mm	202
Internal diameter of the rotor/mm	142
height of the hollow portion inside the rotor/mm	10
Outer diameter of inner stator/mm	140
Internal diameter of inner stator/mm	30
The thickness of the permanent magnet/mm	8
The width of the permanent magnet/mm	22
Length of air gap/mm	1
Height of outer stator slot/mm	25
Numbers of outer stator slots	54
Numbers of poles	16
Turns of armature windings	16
Turns of levitation windings	30
Length of axial/mm	80

(a) (b)

Figure 6. Magnetic field distribution diagram. (a) Solid rotor. (b) The distributed hollow rotor.

In order to study the flux distribution and effect of each flux linkage, the FEA in static magnetic field has been exploited. Figure 6 shows the open-circuit field distributions with different rotors. It will be seen that there are some couplings between permanent magnets and levitation windings when using the solid rotor. And the distributed hollow rotor can decouple permanent magnets and levitation windings. As can be seen from the Figure 6(b), there are little couplings among the eight-pole levitation windings.

In order to study the electromagnetic properties of the levitation windings in the new self-decoupling magnetic levitation generator, the transient analysis in FEA is performed. Figure 7 gives the radial magnetic forces on the distributed hollow rotor when the speed is set 375 r/min, and the current of i_{x2+} is $5A$. As can be seen from Figure 7, the radial forces on the rotor in x and y axis have only very slight fluctuations during rotation of the rotor. The force in the x-axis direction remains substantially constant at a fixed value, and the force in y-axis fluctuates substantially around $0N$. This shows that there are only least couplings among the radial levitation windings. And it shows that the new eight-pole levitation structure of SDMLG may reduce the complexity of control algorithm.

The waveforms of the three-phase flux linkage in the case of no-load and $5A$ in levitation windings

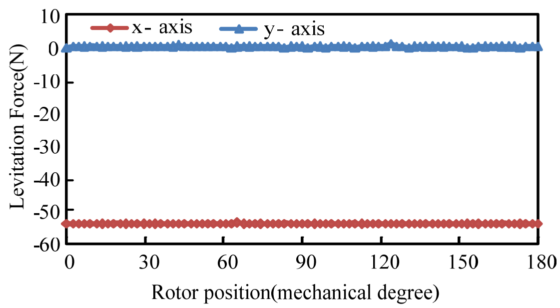

Figure 7. The radial magnetic forces on the rotor when a pair of levitation windings apply currents.

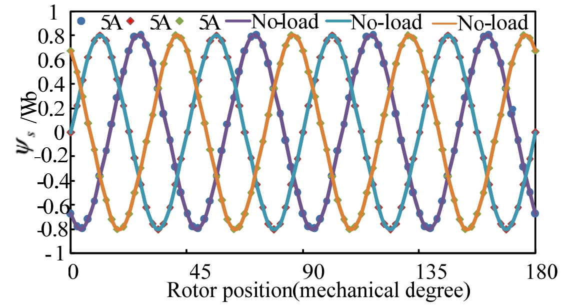

Figure 8. The waveforms of the three-phase flux linkage.

are shown in Figure 8. As can be seen from the Figure 8, the two situations of waveforms coincide basically. These further validate that the distributed hollow rotor can decouple magnetic fields.

4. DEDUCING THE EXPRESSION OF LEVITATION FORCE

According to the principle of virtual displacement, the electromagnetic force suffered by rotor is equal to the partial derivatives of magnetic energy storage W_a,

$$W_a = \frac{1}{2}BHV = \frac{1}{2}BHA(2l) = BHAl \tag{1}$$

where B is the flux density of air gap, H the magnetic field intensity, V the volume of air gap under the two levitation poles, l the length of air gap, and A the cross section of the levitation pole.

The electromagnetic force suffered by the rotor under the levitation pole is

$$f = \frac{\partial W_a}{\partial l} = BHA = \frac{B^2 A}{\mu_0} \tag{2}$$

Assuming the flux density remains constant. According to Ampere's law

$$B = \mu_0 \frac{2Ni}{2l} = \mu_0 \frac{Ni}{l} \tag{3}$$

Substituting (3) into (2), after some manipulation yields

$$f = k\frac{i^2}{l^2} \tag{4}$$

where, Ni is the magnetomotive force, $\mu_0 = 4\pi \times 10^{-7}$ H/m, $k = \mu_0 N^2 A$.

Since the inner stator is eight-pole, there will be eight levitation forces on the hollow rotor. And the angle between each adjacent forces is $\alpha = 22.5^\circ$. Considering the effect of α, the composition of each two radial levitation forces is

$$f = k\frac{i^2}{l^2}\cos 22.5^\circ \tag{5}$$

Because there are little couplings among the levitation windings, so this paper introduces the coupling factor η as the average values of couplings. According to the results of FEA, η can be set 0.02. Assuming that the displacement of rotor in x and y axis are respectively x_0 and y_0. The air gap width at equilibrium position of rotor is l_0. The currents in four pairs of levitation windings are respectively i_{x1}, i_{x2}, i_{y1} and i_{y2}.

As an example of the electromagnetic force for the rotor in the negative direction of x-axis, the force in the negative of x-axis contains two parts. One is the electromagnetic force of i_{x1}, the other is the coupling forces because of the currents in other three groups of levitation windings. The electromagnetic force of i_{x1} is:

$$F_{x1} = k\cos 22.5^\circ \left(\frac{i_{x1}}{l_0 - x_0}\right)^2 \tag{6}$$

Considering the coupling forces of the other three levitation windings, the total force in the negative direction of x-axis is:

$$F_{x-} = k \cdot \cos 22.5^\circ \left[\left(\frac{i_{x1}}{l_0 - x_0} \right)^2 + \left(\frac{\eta i_{y1}}{l_0 + y_0} \right)^2 - \left(\frac{\eta i_{x2}}{l_0 + x_0} \right)^2 + \left(\frac{\eta i_{y2}}{l_0 - y_0} \right)^2 \right] \tag{7}$$

The total radial forces in other three directions of axis are:

$$F_{x+} = k \cdot \cos 22.5^\circ \left[\left(\frac{i_{x2}}{l_0 + x_0} \right)^2 + \left(\frac{\eta i_{y1}}{l_0 + y_0} \right)^2 - \left(\frac{\eta i_{x1}}{l_0 - x_0} \right)^2 + \left(\frac{\eta i_{y2}}{l_0 - y_0} \right)^2 \right] \tag{8}$$

$$F_{y+} = k \cdot \cos 22.5^\circ \left[\left(\frac{i_{y1}}{l_0 + y_0} \right)^2 + \left(\frac{\eta i_{x1}}{l_0 - x_0} \right)^2 - \left(\frac{\eta i_{y2}}{l_0 - y_0} \right)^2 + \left(\frac{\eta i_{x2}}{l_0 + x_0} \right)^2 \right] \tag{9}$$

$$F_{y-} = k \cdot \cos 22.5^\circ \left[\left(\frac{i_{y2}}{l_0 - y_0} \right)^2 + \left(\frac{\eta i_{x1}}{l_0 - x_0} \right)^2 - \left(\frac{\eta i_{y1}}{l_0 + y_0} \right)^2 + \left(\frac{\eta i_{x2}}{l_0 + x_0} \right)^2 \right] \tag{10}$$

As can be seen from Figure 8, because of the presence of distributed hollow rotor, there is almost no coupling between the inner and outer stator. So the mathematical mode of the armature windings in the new magnetic levitation generator is similar to an ordinary permanent magnet synchronous generator.

5. FEA VERIFICATION

In order to verify the correctness of the mathematical analysis formulas of the levitation force, the finite element analysis model of the new self-decoupling magnetic levitation generator is analyzed in static magnetic field. Figure 9 shows the contrast curves of the radial force F_{x-} obtained by FEA and (7) when the current $i_{x1} = 0.2 \sim 2A$, the rotor position angle $\theta = 0^\circ$. As shown in Figure 9, where F is the levitation force calculated based on the deduced mathematical formula (7), and F_{FEA} is the result obtained by FEA. The values calculated by the mathematical formula basically coincide with the FEA at a given angle of the rotor position.

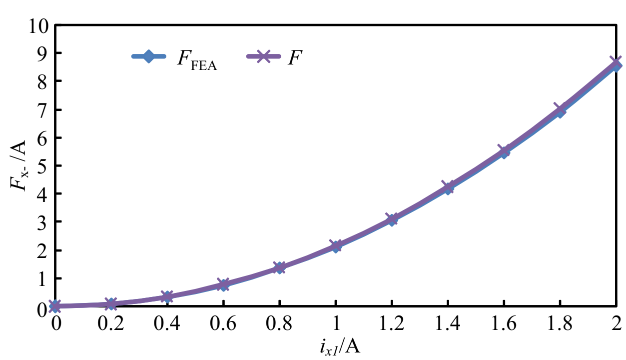

Figure 9. The contrast curves of the radial force F_{x-}.

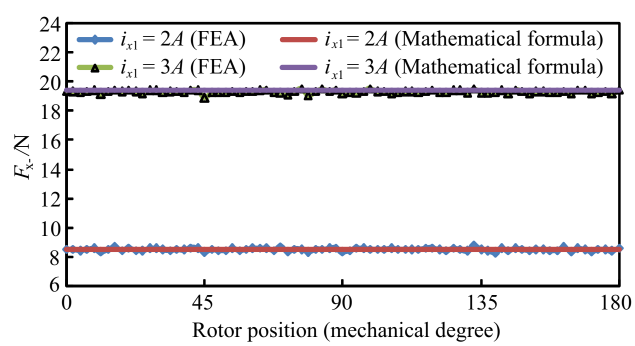

Figure 10. The contrast curves of the radial force in transient field.

Figure 10 gives the contrast curves of the radial force in transient field when $i_{x1} = 2A$, $3A$. As can be seen from Figure 10, in the course of rotation of the rotor, the values calculated by the mathematical formula remain constant, and the transient values of the FEA are only minor fluctuations. So the values calculated by the analytical calculation are anastomotic with the values from the software. These verify the validity and accuracy of the derived formulas.

6. CONCLUSION

This paper puts forward a new magnetic levitation generator, describes its operation mechanism, and derives the formula of levitation forces, then verifies its validity by FEA. Compared with the traditional magnetic levitation generator, the levitation windings are in inner stator, the armature windings are in outer stator, and the distributed hollow rotor is used to separate magnetic coupling between inner and outer windings. This new generator has clear structure and function, which is easy to maintain and control. And the new kind of setting is equivalent to a 2-degree-of-freedom radial magnetic bearing and a common generator. This generator is suitable for the case of short shaft. Meanwhile, this new setting enhances the radial load capacity of the generator, which greatly improves the performance of the levitation. Because there are the least couplings between the armature windings and levitation windings, the complexity of the circuit will be reduced. Generally, the new self-decoupling magnetic levitation generator is a new ideal and new attempt for structural optimization about the wind power generation, which has some certain references for other studies about bearingless motor.

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