

# Performance Analysis of Doubly Excited Brushless Generator with Outer Rotor for Wind Power Application

Yingchao Zhang\*, Huijuan Liu, Haijiao Zhang, Xiang Zhao

School of Electrical Engineering, Beijing Jiaotong University, Beijing, China, 010-51687101  
e-mail: 10121800@bjtu.edu.cn\*

## Abstrak

Pada tulisan ini, sebuah generator tanpa sikat berpenguat ganda yang baru (DEBG) dengan rotor berlaminasi penghalang magnetik radial (RLMB-rotor) untuk aplikasi pembangkit tenaga angin telah dirancang dan dianalisis. DEBG ini memiliki 10 nomor kutub rotor dengan rotor luar. Kinerjanya telah diselidiki dengan metode elemen hingga peralihan 2D. Medan magnet, kemampuan torsi, karakteristik tegangan belitan akhir, gaya magnet radial dan efisiensi energi telah dianalisis. Semua studi ini menunjukkan kesederhanaan, kehandalan, efisiensi tinggi dan rendahnya getaran serta kebisingan dari DEBG dengan rotor luar. Hal ini menarik untuk diterapkan pada variasi kecepatan dengan frekuensi konstan (VSCF) sistem pembangkit tenaga angin.

**Kata kunci:** generator pembangkit tenaga angin, generator tanpa sikat berpenguat ganda (DEBG), rotor berlaminasi penghalang magnetik radial (RLMB-rotor), rotor luar

## Abstract

In this paper, a novel doubly excited brushless generator (DEBG) with outer radial laminated magnetic barrier rotor (RLMB-rotor) for wind power application was designed and analyzed. The DEBG has 10 rotor pole numbers with outer rotor. Its performance was investigated using the 2D transient finite element method. The magnetic fields, torque capability, end winding voltage characteristics, radial magnetic force and energy efficiency were analyzed. All studies in this paper show that the simplicity, reliability, high efficiency and low vibration and noise of the DEBG with outer rotor were attractive for variable speed constant frequency (VSCF) wind power generation system.

**Keywords:** doubly-excited brushless generator (DEBG), outer rotor, radial laminated magnetic barrier rotor (RLMB-rotor), wind power generator

## 1. Introduction

Since a few years ago, the wind power generation has been commercialized because of high fuel efficiency and low air pollution. The generator technology used for variable-speed constant-frequency (VSCF) generating has gone a long way. Nowadays, the most popular motors used for wind power system are permanent magnet synchronous generators (PMSG) and doubly-fed induction generators (DFIG)[1-6].

PMSG does not have gear transmission mechanism, which reduces mechanical noise, eliminates the excitation losses, improves reliability and reduces maintenance costs [7-12]. But there are two disadvantages of PMSG: on the one hand, rare-earth permanent magnets are very expensive and temperature sensitive; on the other hand, it is large volume of motor and requires full-power rectifier inverter controller lead the costs of construction and operation increase. The advantages of DFIG are small volume of motor and without full-power rectifier inverter controller [13]. The obvious disadvantage is the motor rotor has brushes and slip rings which greatly increases the system's failure rate and the costs, and reduces the reliability of the system.

With the development of the power electronics converter in recent years, doubly excited brushless generators (DEBGs) have deserved attention in the applications of variable speed constant frequency generating and wind power systems. A DEBG appears very attractive attribute to its rugged structure (complete absence of slip rings and brushes), reliability, good compatibility with power converter, and flexible operational modes for various application needs.

A schematic diagram of a DEBG variable speed drive (generating) system is shown in Figure 1, the DEBG has two sets of separate windings with different pole numbers located on

the stator, and the rotor is composed of several reluctance segments with pole number different from either of stator windings. A bi-directional converter consists of two inverters in back to back connection which used to supply power to the stator windings with flexible control models. The designed laminations in the radial direction serves dual purposes: a) to force the magnetic flux lines passing along the magnetic layer imposed by the lamination though the designed magnetic paths do not coincide with the pole-pitch of either stator MMFs; b) to minimize the eddy-current losses by orienting lamination along the magnetic flux lines.

In past research activities, conducted detailed investigation and presented throughout analysis on the magnetic coupling between the two stator windings with inner rotor structures. The research work shows that a DEBM with 10 poles rotor has much better magnetic coupling and torque performance than those with 6 poles and 8 poles [4, 5, 6]. In addition to the rotor style and laminations design, we also found that the magnetic coupling of the DEBG with outer rotor is similar to the DEBG with inner rotor. However, multipole can be achieved by the DEBG with outer rotor.

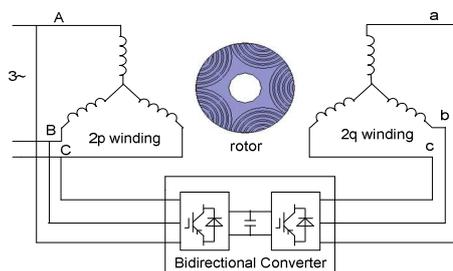


Figure 1. Schematic diagram of the DEBG system

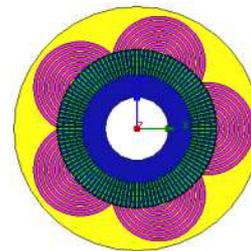


Figure 2. The cross section of the DEBG

The paper starts with a brief review of main configuration and basic principles of DEBG and system. Then, using finite element analysis, the magnetic fields distribution, the torque capability, the terminal characteristics, the rotor's radial forces and the core losses of the DEBG with outer rotor of 1.5MW/600rpm are presented.

After calculation by finite element analysis, all the results show that the torque production for the DEBG with outer rotor is large. The results of torque capability are consistent with those the induced speed voltages of the DEBG. Therefore, the speed performance of DEBG with outer rotor is better than DEBG with inner rotor. In addition, though the iron loss of DEBG with outer rotor is large, the rotor remains cool and natural ventilation cooling is sufficient for its heat dissipation.

All the results indicate that the DEBG with outer rotor can substantially enhance the motor's torque and speed capability, and improve reliability. DEBG with outer rotor as a new type of motor is potential to apply in variable speed constant frequency operation system.

## 2. Structure and Design of DEBG

### 2.1. Structure of DEBG

The DEBG with outer RLMB-rotor is structured as a doubly fed induction motor without brushes and slip rings. The cross section of the DEBG is shown in Figure 2. There are two sets of windings placed in the stator core of different pole numbers. The two sets of windings differ in pole numbers, one of  $2p$  and another  $2q$ . The two sets of windings share the same unique rotor.

The rotor of the DEBG with outer rotor is a special design, with a group of magnetically isolated segments of number  $p_r$  where [6-10]

$$p_r = p + q \quad (1)$$

When one set of symmetrical sine-wave currents of frequency  $\omega_1$  are flowing in the primary windings, a set of three-phase back EMFs will be induced with a frequency of  $\omega_2$  in the secondary windings. The two electrical frequencies  $\omega_1$  and  $\omega_2$  are related to the rotor mechanical speed  $\omega_m$  by the following equation:

$$\omega_{rm} = (\omega_1 - \omega_2) / p \quad (2)$$

Electromechanical energy conversion will take place in DEBGs if Eq. 2 is satisfied. Depending on the sequence and value of the controlled frequency  $\omega_2$ , a DEBG can operate in different modes. In particular, in the doubly-excited mode with  $\omega_2=0$ , the DEBG is operated as a synchronous machine at natural synchronous speed. On the other hand, with  $\omega_2 > 0$  or  $\omega_2 < 0$  (negative sequence), a DEBG can operate as an induction machine below or above natural synchronous speed. In terms of power flow, regardless at the sub-, super-, or synchronous rotor speed, DEBG always can be operated as a motor or generator.

A special case for  $\omega_1 = -\omega_2$  will allow the rotational speed to reach two times rated speed without the need to run into flux weakening region.

In DEBG, when one set of stator winding is excited by DC or AC, Back EMF voltages will be induced in another set of stator windings, due to mechanical rotation of the rotor; and electromechanical energy conversion will take place in DEBG. The torque is

$$\begin{aligned} T_e &= \frac{3E_p I_p \cos \varphi + 3E_q I_q \cos \varphi}{\omega_{rm}} = \frac{3\omega_1 \lambda_{mq} I_p \sin \varphi + 3\omega_2 \lambda_{mp} I_q \sin \varphi}{\omega_{rm}} \\ &= \frac{3}{2} (p+q) \lambda_{mq} I_p \sin \varphi \end{aligned} \quad (3)$$

where the  $E_p$  and  $E_q$  are the induced back EMF, the speed voltages associated with the variations of the mutual flux linkages;  $I_p$  and  $I_q$  are the phase currents;  $\varphi$  is the angle between the induced speed voltages and the current;  $\lambda_{mp}$  and  $\lambda_{mq}$  are the mutual flux linkages under the given currents.

## 2.2. DEBG Design

The sizing of the 1.5MW/600rpm DEBG starts with a comparable and conventional doubly fed wound rotor induction machine. By trial and error, the main dimensions of DEBG with outer rotor are determined with the design specifications listed in Table 1.

Since the DEBG to be designed relies on the rotor modulation to create mutual coupling between the two sets of stator windings, the DEBG is designed with two sets of stator windings, one for 6-pole and another 4-pole. In [9-10], three cases of pole number combinations are investigated using the same stator frame and lamination structures, with finite element analysis for the same currents, the torque production for  $p_r=5$  is more than that achieved in the other two cases. The results of torque capability are consistent with those of the induced speed voltages of the DEBG with different rotor pole numbers. So, we select  $p_r=5$  for the DEBG with outer rotor.

The synchronous speed of the designed DEBG is 600 rpm. In operation, the primary winding of 4-pole will be connected to the power grid of 50Hz while the secondary winding of 6-pole will be controlled by a bi-directional converter.

Table 1. Main Dimensions

Variabel	Value	Variabel	Value
Rated Power (kW)	1500	Stator Slots	108
Stator OD (mm)	750	Stack Length (mm)	900
Stator ID (mm)	300	Primary winding	4-pole
Rotor OD (mm)	1100	Secondary winding	6-pole
Rotor ID (mm)	754	Rotor Segments	10-pole
Rated Speed (rpm)	600	Ampere-turns	45*24

## 3. Results and Discussion

### 3.1. Magnetic Field Distribution

Using ANSOFT software, the electromagnetic fields distribution of the above generator model under load operation have been calculated. For the objectives verification, the DEBG is operating at natural-synchronous speed, when the primary winding of 4-pole is excited with a three-phase symmetrical AC at a frequency of 50Hz while the secondary winding of 6-pole is excited with three-phase symmetrical DC, the sample machine will operate in load operation. The amplitude of current is 45\*24 ampere-turns.

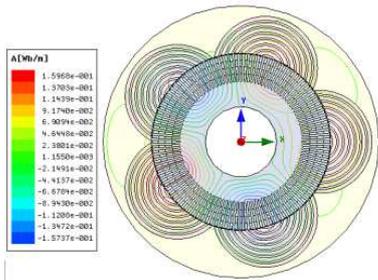


Figure 3. Flux distribution of the DEBG

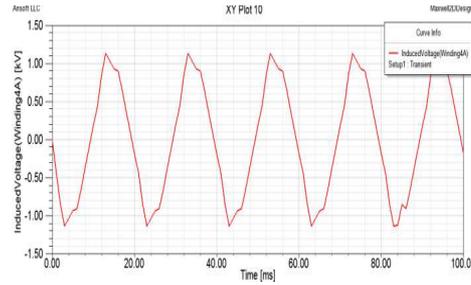


Figure 4. Induced voltage of A-phase of 4-pole winding

As shown in Figure 3, the magnetic field of the DEBG with outer rotor is not symmetric and calculation of the entire magnetic field for the DEBG is needed.

### 3.2. EMF of the Winding

The voltage characteristic of end winding is a primary performance of a generator. Load operation simulation of the DEBG has been carried out by ANSOFT software, winding induced EMF is the primary index. Induced voltage diagram of A-phase of 4-pole winding under negative maximum torque are shown in Figure 4.

In order to clearly demonstrate the voltage harmonics contents, the calculated voltage distribution is decomposed into Fourier components. The harmonic contents of voltage of 4-pole winding are shown in Figure 5.

### 3.3. Torque Capability

The finite element analysis is used to calculate torque production of the designed DEBG. In the calculation, both sets of the stator windings are excited with frequencies conforming to Eq. 2. At the same time the relative phase angles are changed as a parameter of the torque production. The torque production by finite element analysis is directly based on the magnetic field density and intensity on each element. The results are considered accurate because the complicated geometry of the DEBG and nonlinearity of the materials are full considered. The torque production of the DEBG operated at the rated current levels (45\*24 ampere-turns) and 600rpm as a function of the phase angle between the two sets of stator windings are shown in Figure 6.

As the results clearly show that the rated torque is fully achievable and the designed DEBG with outer rotor power capability is verified. The power at 360° achieves 1.7MW, it is the maximum operating point.

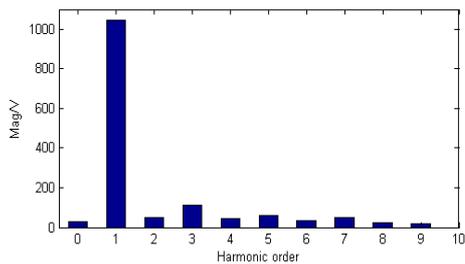


Figure 5. Harmonic contents of induced voltage for 4-pole winding

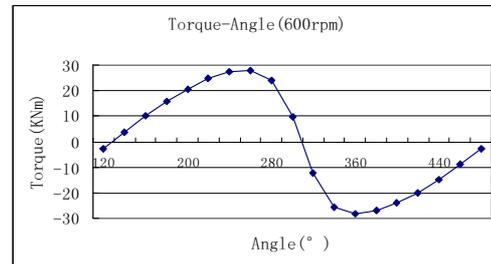


Figure 6. Torque characteristic of the sample DEBG

### 3.4. The Radial Electromagnetic Force of Rotor

The radial magnetic force is closely related to motor's mechanical strength requirements. The most important observation is the unsymmetrical distribution of air-gap flux density as shown in Figure 7 which implies a possible unsymmetrical pulling force in radial direction and non-uniformed magnetic force in tangential direction. RLBM-rotor is composed of five magnetic modules, so the whole radial force of rotor can be obtained by the superposition of five magnetic modules' force in the X-direction and the Y-direction respectively.

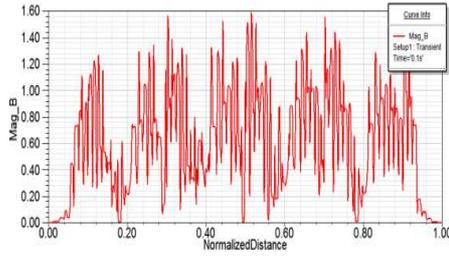


Figure 7. Air-gap flux density distribution

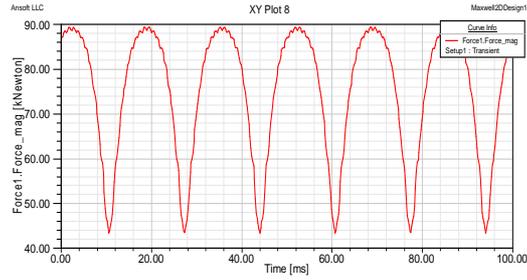


Figure 8. Radial electromagnetic force of the rotor

The changes of radial electromagnetic force under synchronous operation are related to the generator’s stability, vibration and noise. The radial electromagnetic force of the whole rotors is shown in Figure 8. FFT of the whole rotor’s radial electromagnetic force is analyzed under synchronous operation. The harmonic contents of radial electromagnetic force are obtained as shown in Figure 9. The high order harmonic contents of radial electromagnetic force are low, so the vibration and noise caused by rotor will be small.

**3.5. Efficiency of the DEBG**

The losses of a generator are consists of iron loss, copper loss, mechanical loss, stray loss and so on. Copper loss is concerned with stator windings, while iron loss is concerned with both stator and rotor core.

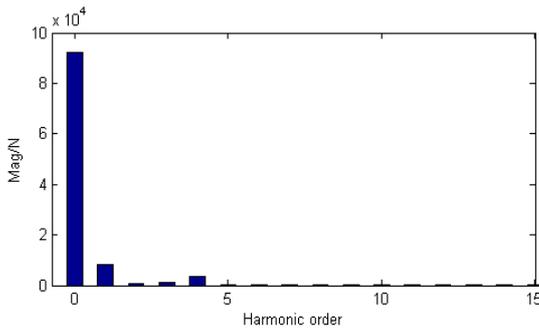


Figure 9. Harmonic contents of radial electromagnetic force

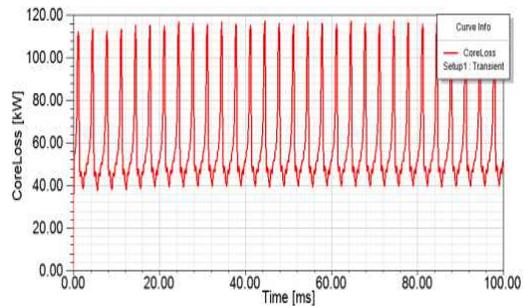


Figure 10. Core loss of the sample DEBG

As shown in Figure 10, the iron loss of the sample machine is about 80kW when the amplitude of current is 45\*24 ampere-turns, which is 4.5% of the rated power. The iron loss of DEBG with outer rotor is large, which is a disadvantage of DEBG with outer rotor.

However, the copper loss of DEBG with outer rotor is much smaller than those of DEBG with inner rotor. This is owing to DEBG with outer rotor can achieve the same rate power only with a smaller current than DEBG with inner rotor.

Copper loss can be calculated using Joule Lenz. Because the heat efficiency of the two sets of stator windings are same, we can calculate the copper loss [11] of each phase windings in equation 4.

$$P_1 = \sum (I_p^2 R_p) \tag{4}$$

where  $I_p$  is RMS of the phase current of each windings;  $R_p$  is the resistance of each windings under reference temperature.

After calculating in Eq. 4, the copper loss of DEBG with outer rotor is about 20.91kW, which is 1.18% of the rated power. Then the efficiency of DEBG with outer rotor can be calculated as shown in Table 2.

As indicated in Table 2, the efficiencies of DEBG only conclude copper loss and iron loss, for mechanical loss and others are not considered. The efficiency of DEBG can achieve

94%. The designed DEBG with outer rotor is a high efficiency machine. As shown in Figure 6, the torque can achieve 28.2 kNm at maximum operating point, so the maximum power can achieve 1.77MW. It can be predicted that the iron losses of the designed DEBG with outer rotor at rate level will less than 4% (1.5MW) of the rate output power, so the efficiency of the designed RLMB-rotor DEBG at rate level (1.5MW/600rpm) can achieve as high as 95%.

Table 2. Efficiency of The DEBG

DEBG	Copper loss(kW)	Core loss(kW)	Efficiency (%)
2 $p_r=10$	20.91	80	94.3

#### 4. Conclusion

This paper embarks from basic theory of variable speed constant frequency (VSCF) wind power generation, combined with the characteristic of radial laminated barrier DEBG, focuses on the design and performance verification of a DEBG with outer rotor(1.5MW/600rpm) for wind power generator application. The dynamic model of the DEBG with outer rotor is presented and analyzed. Using finite element analysis, the magnetic fields distribution, the torque capability, EMF of winding, radial magnetic force and efficiency are investigated. All the studies show that the DEBG with outer rotor is potential to achieve high efficiency, low cost, low vibration and noise, enhanced reliability and flexible control for VSCF generation system applications. Furthermore, all these results provide theoretical foundation for the practical application.

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