# A Segmented Brushless Doubly-Fed Generator for Wind Power Application

Yongjiang Jiang, Jianzhong Zhang*, and Tianyi Li
School of Electrical Engineering, Southeast University, Nanjing, China
*Corresponding author: jiz@seu.edu.cn

**In this paper, a new brushless doubly-fed generator (BDFG) with segmented stator and rotor is proposed. Compared with the traditional BDFG, the winding configurations of the segmented BDFG are in great flexibility as the power winding and control winding are separately put on the two stators. It also has the advantages of increased slot filling factor and improved power density. The design of the segmented BDFG is carried out and the asymmetry of the three-phase electromotive force in the power winding could be solved effectively. The model of finite element analysis is built in this paper and simulations are carried out to verify the effectiveness of the generator design.**

***Index Terms*—brushless doubly-fed generator, field modulation, segmented stator, wind power generation.**

## I. Introduction

THE DOUBLY fed induction generator (DFIG) based wind power generation system is the most widely used today due to the advantages of part-size converter with dramatically reduced cost and high wind power utilization[1]. However, traditional DFIGs have slip rings and brushes which need frequently maintenances and decrease the reliability. In recent years a kind of brushless doubly fed generator (BDFG) has been proposed which has no slip ring and brush and then greatly improves the reliability[2]. Nevertheless, BDFG still has some disadvantages, such as two independent windings in the stator, complex rotor structure, high harmonic distortions and low efficiency. In [3], a new BDFG with two stators is proposed. In this generator topology, there are power winding and control winding in each stator separately and then there has great flexibility for winding configurations. However, there are still some problems to solve, such as the asymmetrical three-phase electromotive force (EMF) in the power winding and the large harmonics.

In this paper, a segmented BDFG is proposed to solve the problem of asymmetrical three-phase EMF. And it could also effectively reduce the harmonics and torque ripples.

## II. Topology and Operation Principle

### A. Topology of the BDFG

In the magnetic gear, field modulation ring is used to realize the conversion of the magnetic field pole-pair number. In [3], a field modulation ring is used for BDFG which is similar to that of magnetic gears, as shown in Fig. 1. In the field modulation BDFG, the rotating PM rotor in the magnetic gear is replaced by two stationary windings which are excited by alternate current source, and the field modulation ring, which is stationary in coaxial magnetic gear, can be freely rotated.

### B. Operation Principle

Supposing the pole-pair number of the control winding, field modulation ring and power winding are po, Ns and pi, respectively. The magnetic field generated by control winding could be converted into a series of space harmonics by through the field modulation ring. According to the principle of coaxial magnetic gear and po=Ns-pi, the effective harmonics magnetic field in the outer airgap can be approximately expressed as [4]

$$B_o = \frac{a_1 c_1}{2} \times \cos((N_s - p_i)\theta - (N_s\theta_r - p_i\theta_i) + (N_s\theta_{r0} - p_i\theta_{i0})) \quad (1)$$

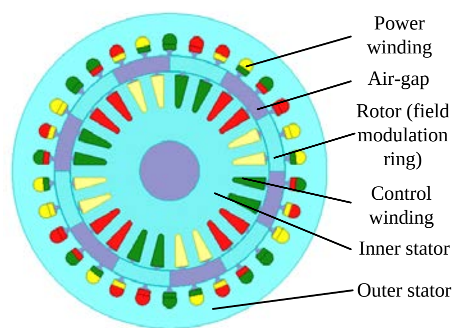


Fig. 1 The structure of BDFG

where a1, and c1 are constants. θi0and θr0 are the initial mechanical angular positions of the magnetic field generated by the control wingding and rotor, respectively. θi and θr are the mechanical angular positions of the magnetic field generated by the control winding and rotor, respectively.

According to equation (1), po=Ns-pi, and poωo=Nsωr-piωi, it has

$$\omega_r = \frac{2\pi(f_o - f_i)}{N_s} \quad (2)$$

### C. Introduction of the Asymmetry Problem

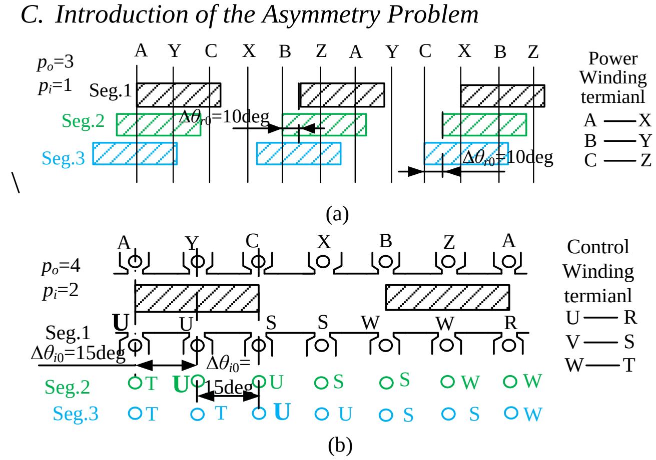


Fig. 2 Analysis of three-phase asymmetry (a) asymmetry control winding (b) asymmetry rotor relative to three phase power winding

As the result of the existence of the field modulation ring in the segmented BFDG, the pole-pair numbers of the control winding and power winding are not equal, and the rotating speeds of their magnetic field are not equal either. Fig. 2 (a) and (b) show the spatial asymmetry control winding and rotor relative to three phase power winding, respectively, which causes the asymmetrical no-load EMF in the three phase power winding in one electric cycle, as shown in Fig. 3.

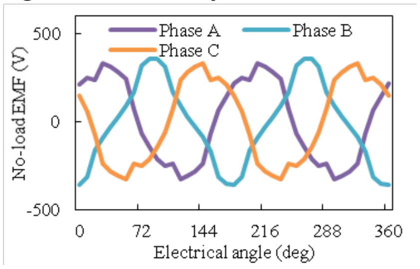


Fig. 3 No-load EMF of the three phases power winding

### *D. Structure of Segmented Stator and Rotor*

There are two cases for the segmented BFDM. The first case is according to the asymmetrical rotor relative to three phase power winding and has a pole pair relationship as

$$p_o = 3np_i,\ \ n = 1,2,3... \tag{3}$$

In this case, the control winding is symmetrical but power winding is asymmetrical due to the rotor speacial structure. In order to solve this problem, the rotor is segmented to make the magnetic circuits of the three phase power windings symmetry in space, as shown Fig. 2(a). The segment number should be equal to the phase number. An angle difference among three segments is defined as

$$\Delta\theta_{r0} = \min(\frac{360}{N_s} - n\frac{60}{p_o})\deg > 0,\ \ n = 1,2,3... \tag{4}$$

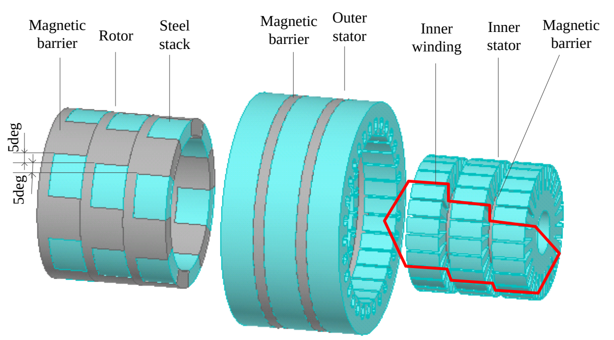


Fig. 4 The structure of segmented BDFG

The second case is according to the spatial asymmetrical control winding relative to three phase power winding, where segmented inner stator is used. The inner stator is divided into three segments, and the installation of windings in the three segments should turn several slots, and the angle difference of the slots is

$$\Delta\theta_{i0} = \min(\frac{60}{p_i} - m\frac{60}{p_o}, n\frac{60}{p_o} - \frac{60}{p_i})\deg > 0,\ \ m, n = 1,2,3... \tag{5}$$

There is an angle difference among the three segments for the same phase winding, and the angle difference is selected by (1). Only used the segmented rotor or inner stator, the effective harmonic magnetic fields of the three segments are not in the same phase, which will cause the EMF reduction similar to the skewed slot. In order to solve the problem, the inner stator and rotor should be both divided into three segments, and the angle difference satisfies the following equation

$$\Delta\theta_{r0} = p_i\Delta\theta_{i0} / N_s \tag{6}$$

## III. Finite Element Analysis

The electromagnetic field of the segmented BDFG is analyzed by the finite element method. According to the previous analysis, the simulation model is established as shown in Fig. 5. In order to use the two-dimensional finite element method to analyze the segmented BDFG, three independent BDFG models are established, corresponding to the three segments of the segmented BDFG. Then the simulation results of segmented BDFG can be obtained by summing up the results of the three models, as shown in Fig. 6.

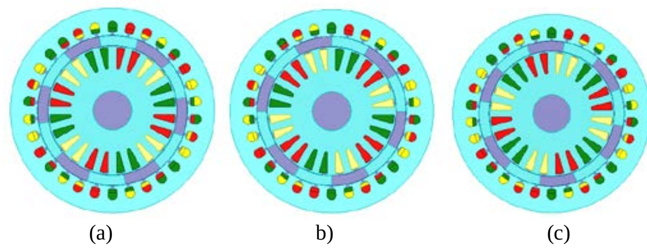


Fig. 5 The structure of segmented stator and rotor.
(a) segment 1 (b)segment 2 (c) segment 3

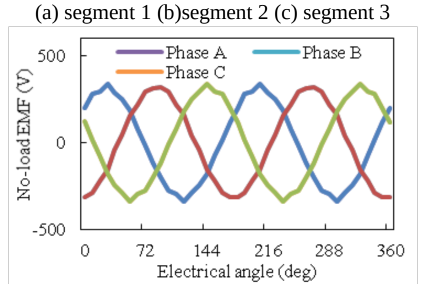


Fig. 6 No-load EMF of the three phase power winding

## IV. Conclusions

A BFDG with segmented stator and rotor for wind power application is proposed. In this paper, the reason of asymmetrical three-phase EMF of the BDFG is analyzed. Through the theoretical analyses, the solution to this problem is put forward. The simulations show that using the structure of segmented stator and segmented rotor, the asymmetrical problem of the three-phase winding EMF could be effectively solved, and the torque ripple could be reduced at the same time.

## References


[1] Datta, R., and V. T. Ranganathan. "Variable-Speed Wind Power Generation Using a Doubly Fed Wound Rotor Induction Machine: A Comparison with Alternative Schemes." IEEE Transactions on Energy Conversion, vol. 17, no. 3, pp.414-421, 2002.

[2] Min-Fu Hsieh, Yao-Hsin Chang, and David G. Dorrell. "Design and Analysis of Brushless Doubly-Fed Reluctance Machine for Renewable Energy Applications." *IEEE Transactions on Magnetics*, vol. 52, no. 7, 2016.

[3] Y.C. Wang, S. L.Ho, W.N. Fu, J. X. Shen. "A Novel Brushless Doubly Fed Generator for Wind Power Generation." *IEEE Transactions on Magnetics*, vol. 48, no. 11, pp.4172-4175, 2012.

[4] L. Sun, M. Cheng, and H. Jia. "Analysis of a Novel Magnetic-Geared Dual-Rotor Motor with Complementary Structure." IEEE Transactions on Industrial Electronics, vol. 62, no.11, pp. 6737-6747, 2015.