Research on the Optimization about Air-Gap Magnetic Field of AC-Excited Generator

LV Yanling [1,a], Chen Wenhai [2,b] and Teng Chong[3,c]

[1, 2, 3]*Harbin University of Science and Technology, Harbin,China*
[a]*Yanling@163.com,* [b]*chenwenhai_haha@163.com,*[c]*tc4956410@sina.com*

Abstract

Due that the air-gap harmonic wave magnetic field impacts the motor torque property, additional loss and vibration noise, it is critically important to accurately calculate the electromagnetic field, particularly the air-gap magnetic field distribution. On the basis of the research of structure of AC-excited generator, a field-circuit-motion coupled analysis model for AC-excited generator is established using field-circuit-motion coupling method. For investigating the relationship among the air-gap magnetic field, slot of rotor, air-gap and width of rotor slot, the distribution diagram of air-gap magnetic field is provided under different states. By harmonic analysis of the air-gap magnetic field of different model, the method to reduce the air-gap harmonic wave magnetic field is proposed. It provides the theoretical support for the optimization design of AC-excited generator.

Keywords: AC-excited generator; air-gap magnetic field; optimized analysis

1. Introduction

The three-phase field winding of rotor of AC excitation generator displays a symmetrical distribution, and with three-phase symmetric excitation current. The frequency, amplitude, phase and phase sequence can be controlled [1]. Due to the increase the degrees of freedom of excitation system of AC excitation generator, it can implement variable speed constant frequency. Since it can independently adjust active power and reactive power, the generator can operate under the optimal phase depth and has strong stability [2]. It is found that the plant efficiency of power station can be increased by 10% with AC excitation generator in investigation of J. Bendl, M. Chomat, L. Schreie. *etc.* [3].

The air gap harmonic magnetic field of motor is important to the design of motor, the manufacture of motor and the operation of motor. Not only influence the induction electromotive force, torque characteristics of the motor, additional loss and vibration noise, *etc.*, it is particularly sensitive to noise [4]. The motor running, the air gap harmonic magnetic field mainly includes two parts. The part is built by magnetic potential of rotor winding in air gap. The other part is tooth harmonic magnetic field built by the Magnetic reluctance of air gap changing [5]. The harmonic magnetic field of brushless doubly-fed motor is analyzed and researched and optimization scheme is put forward [6-7].

In traditional motor electromagnetic calculation, because the nonlinear saturation of motor, skin effect and complex boundary shape factors, magnetic circuit method cannot get accurate results[8-9]. On the other hand, because of the complexity of the wire way of the motor end, analysis method is very difficult to achieve [10]. So, using field-circuit coupling method analyzes motor electromagnetic fields, the calculation results can be obtained [11].

In this article, the field-circuit coupling method of AC exciting generator is established, and the air-gap magnetic field of AC exciting generator is analysis on no-load running by using finite element method. Under the influence of rotor trough, the air gap size, and the

width of the slot, the air gap magnetic field is studied. It puts forward a ways to reduce the air gap magnetic field harmonic content. It provides the reference for further research of structure optimization of AC excitation generator.

2. The Basic Principle and Structure of AC Excitation Generator

The stator of AC excitation generator stator is same with traditional synchronous motor, but rotor is different with traditional synchronous motor. The rotor, with three-phase controllable exciting winding, can connect with balanced three-phase alternating current. The stator winding of Ac excitation generator is connected to the electricity grid through transformer. The rotor winding of Ac excitation generator is connected to the grid through energy bi-directional flow excitation converter. It is shown in Figure 1.
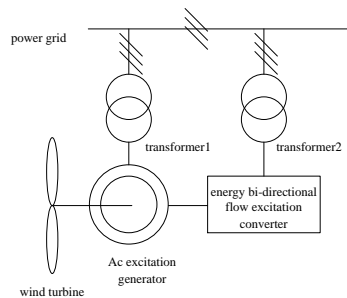

Figure1. Interconnected AC-Excited Doubly-Fed Wind Power Generator

Ac excitation generator normally working, the stator winding and rotor winding both produce rotating magnetic field. According to the induction rotating magnetic field of stator and rotor is relatively static, AC excitation generator working, the relations of speed of rotating magnetic field produced by rotor winding to speed of rotating magnetic field produced by stator winding as follows:

$$n_1 = n_r \pm n_2 \tag{1}$$

Use frequency is expressed as:

$$f_1 = \frac{p}{60} n_r \pm f_2 \tag{2}$$

Type: n_1 as rotating magnetic field rotation speed of the stator; n_2 as the rotating magnetic field rotation speed of the rotor; n_r as the rotor speed; f_1 as the frequency of the stator current; f_2 as the frequency of the rotor current; p as logarithmic of ac excitation generator.

The speed of the AC excitation generator rotor changes with fan. The speed of rotating magnetic field can be adjusted by adjusting the frequency of the exciting current, so that speed of rotating magnetic field is synchronous speed. The purpose of Variable-speed constant-frequency of ac excitation generator is achieved.

3. The Field-Circuit-Motion Coupling Mode of AC Exciting Generator

In order to simplify the analysis of this article, emphasize the research question and ensure reasonable computational mathematics model is set up, assumptions as follows:

1) The mode of AC excitation generator can be divided into linear part and the head part, as shown in Figure 2, 3, head part using the existing analytical calculation method of parameters included in the analysis of branch, the linear part using two-dimensional electromagnetic field finite element analysis.

2) The higher order harmonic component of armature current and vector magnetic potential is ignored, only the effect of fundamental wave is considered.

3) The nonlinear characteristics of rotor material are considered, but the material

hysteresis loss, the eddy current loss of the motor stator lamination and distortion errors of axial symmetry are ignored.

4) The electrical conductivity of the generator material is constant value.

5) The change of the tooth harmonic is not consider, the cartesian coefficient characterization of the cogging effect gas gap.
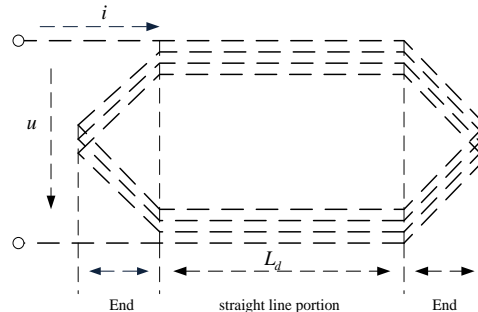

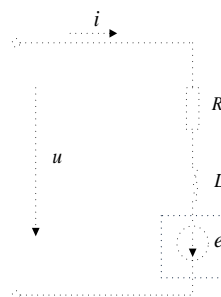**Figure 2. Structure Diagram of Winding Model of AC-Excited Generator**

Figure 3. Equivalent Circuit of Winding Model of AC-Excited Generator

The partial differential equation of boundary value problems of the motor transient electromagnetic field can be represented by the type (3) [12], the coupling problem of the electromagnetic field and mechanical movement is described

$$\nabla \times \left(\frac{1}{\mu} \nabla \times A \right) + \sigma \left[\frac{\partial A}{\partial t} - v \times (\nabla \times A) \right] = J \qquad (3)$$

Type: μ is medium permeability, A is the vector magnetic potential, σ is medium conductivity, v is medium velocity relative to the reference coordinate system, J_s is the source of externally imposed current density.

4. The Analysis of Air-Gap Magnetic Field of AC Excitation Generator

On the small capacity of AC excitation generator, air-gap magnetic field is analysis by using field-circuit coupled method. The main parameters of the generator are as follows: The rated power is 2.2 KW. The rated voltage is 220V. The number of stator slot is 45. The number of rotor slot is 36. The number of poles is 6. According to structure parameters of the motor, the field-circuit coupled model of the generator is established. The model is shown in Figure 4.
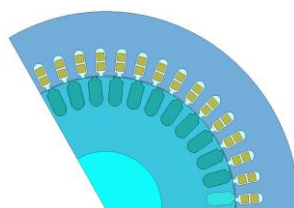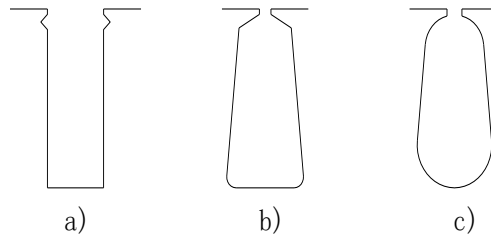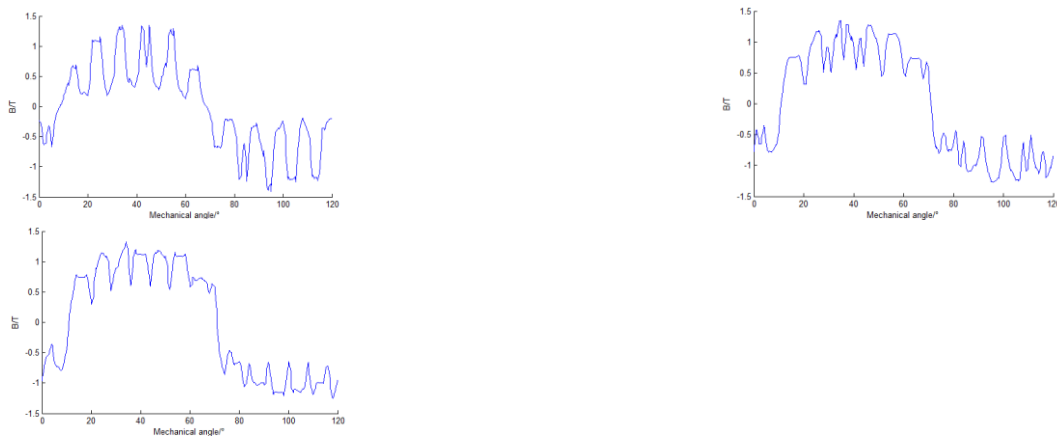
Figure 4. The Model of AC-Excited Generator

a)   b)   c)

(a) Open Slot   (b) Trapezoidal Slot   (c) Pear-Shaped Slot

Figure 5. Three Different Kinds of Channel

4.1. The Air-Gap Magnetic Field under Influence of Rotor Slot Shape

The rotor slot shape of the motor general has three types: open slot, trapezoidal slot, and pear-shaped slot, as shown in Figure 5.As a result of the different rotor slot shape, air gap flux density produced by excitation current is not the same. Under the premise of the same air gap flux density fundamental wave, it is set up that field-circuit coupled model of ac excitation generator with three different rotor slots. Analyzing the three models, the three different air-gap flux density of ac excitation generator is obtained, as shown in Figure 6.

(a) The Air Gap Flux Density of Open Slot (b) The Air Gap Flux Density of Trapezoidal Slot (c) The Air gap Flux Density of Pear-Shaped Slot

Figure 6. Air-Gap Flux Density of AC-Excited Generator with Different Slot of Rotor

As can be seen from the Figure 6, three air-gap flux density of ac excitation generator are non-sinusoidal, because three permeances of air gap the motor are different. The three air-gap flux density in Figure 6 is harmonic analyzed. The variety of harmonic content of air gap flux density is shown in Table 1.

Table 1. Harmonic Content of Harmonic Content of Different Slot of Rotor

slot	The ratio of every harmonic amplitude and the amplitude						
	1	5	7	11	13	17	19
open slot	100	7.735	6.686	38.290	27.882	1.962	2.039
trapezoidal slot	100	9.549	6.877	19.281	4.089	2.102	2.314

pear-shaped slot	100	8.717	6.008	12.498	6.376	1.643	1.880

As can be seen from Table 1, In the air gap flux density of open slot, the 11 times harmonic component and the 13 times harmonic component are high. In the air gap flux density of trapezoidal slot, the 5 times harmonic component and the 11 times harmonic component are high. In the air gap flux density of pear-shaped slot, the 11 times harmonic component is high. The 11 times harmonic component of pear-shaped slot is less than open slot and pear-shaped slot. Comprehensive consideration, pear-shaped slot is suit as rotor slot the AC excitation generator.

4.2. The Air-Gap Magnetic Field under Influence of the Air Gap Size

The size of air gap will also affect the air gap permeance, thus the air gap flux density waveform of AC excitation generator and the air gap flux density harmonic content is different also. It is set up that field-circuit coupled model of ac excitation generator with three different air gap size. Analyzing the three models, the three different air-gap flux density of ac excitation generator is shown in Figure 7.
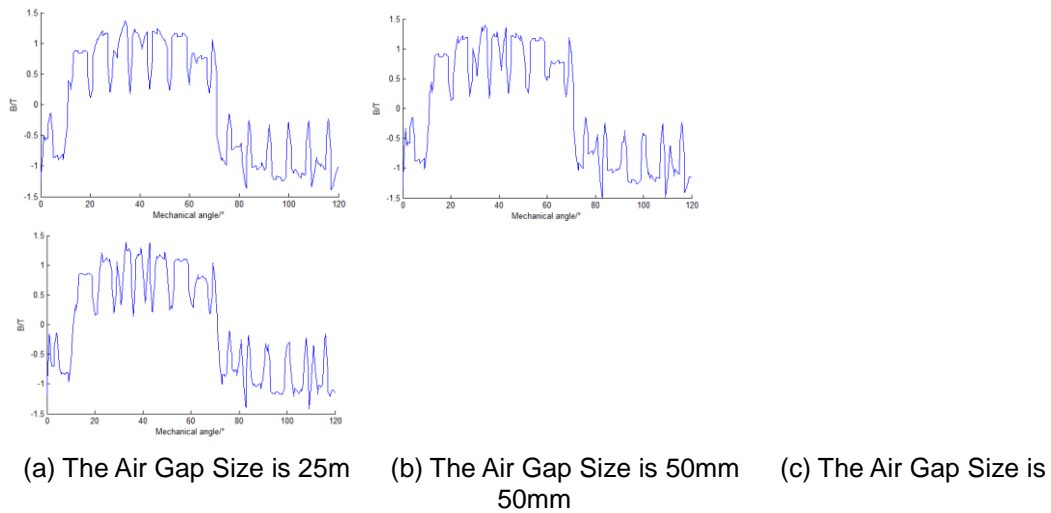

(a) The Air Gap Size is 25m   (b) The Air Gap Size is 50mm   (c) The Air Gap Size is 50mm

Figure 7. Air-Gap Flux Density of AC-Excited Generator with Different Length of Air-Gap

As can be seen from the Figure 4, the longer the air-gap size of AC excitation generator, air gap flux density harmonic content is less. Because of the air gap size affects the air gap permeance, it can offset part the air gap magnetic field waveform caused by rotor slot of the motor. The three air-gap flux density in Figure 7 is harmonic analyzed. The variety of harmonic content of air gap flux density is shown in Table 2.

**Table 2. Harmonic Content of Harmonic Content of Different Air Gap Size**

air gap size /mm	The ratio of every harmonic amplitude and the amplitude						
	1	5	7	11	13	17	19
25	100	10.998	7.830	14.292	6.600	2.498	2.889
50	100	9.334	6.528	13.086	5.626	1.963	2.408
75	100	8.717	6.008	12.498	6.376	1.643	1.880

As can be seen from Table 2, In the three air gap flux density of AC generator with different air gap size, the 5 times harmonic component, the 11 times harmonic component, and the 13 times harmonic component are high, especially, the 11 times harmonic component .

Compared three models, the size of air gap are bigger, and air gap flux density harmonic content is smaller. In order to improve the air gap flux density waveform, the air gap size can be increased in the design of AC excitation generator. Air gap size cannot too big, otherwise the magnetic flux leakage is more, and the efficiency of the motor will be reduced.

4.3. The Air-Gap Magnetic Field under Influence of the Width of Slot

The air gap permeance is not only related to channel and air gap length, but also associated with width of rotor slot. The width of the slot of AC excitation generator also affects the air gap flux density waveform. It is set up that field-circuit coupled model of ac excitation generator with three different the width of the slot. Analyzing the three models, the three different air-gap flux density of ac excitation generator is shown in Figure 8.
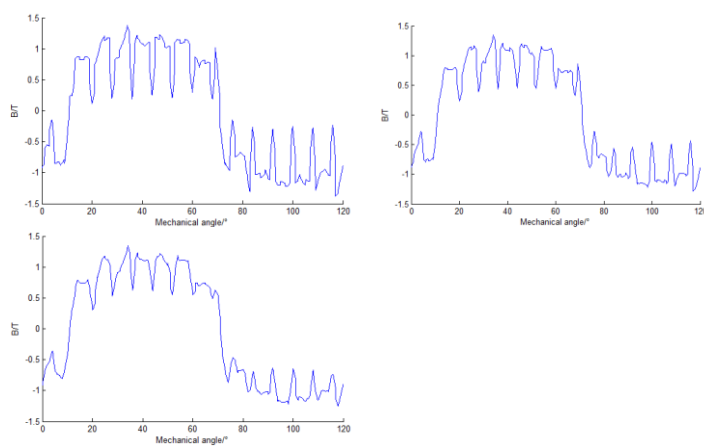
(a) The Width of Slot is 0.5mm   (b) The Width of Slot is 1mm   (c) The Width of Slot is 1.5mm

Figure 8. Air-Gap Flux Density of AC-Excited Generator with Different Width of Rotor Slot

The three air-gap flux density in Figure 8 is harmonic analyzed. The variety of harmonic content of air gap flux density is shown in Table 3.

As can be seen from Table 3, In the three air gap flux density of AC generator with different the width of slot, the 11 times harmonic component are high, Compared three models, and air gap flux density harmonic content is smaller in the width of slot is 0.5mm. In order to improve the air gap flux density waveform, the width of slot can be reduced in the design of AC excitation generator. Because the width of slot is not too small considering wire, the magnetic slot wedge can be used.

Table 3. Harmonic Content of Harmonic Content of Different Width of Rotor Slot

width of slot /mm	The ratio of every harmonic amplitude and the amplitude						
	1	5	7	11	13	17	19
0.5	100	11.332	8.010	15.669	2.068	2.841	3.064
1	100	11.707	8.562	18.635	6.195	3.050	3.352
1.5	100	12.519	9.263	19.447	2.067	3.063	3.479

5. Conclusions

On the basis of the research of structure of AC-excited generator, a field-circuit-motion

coupled analysis model for AC-excited generator is established using field-circuit-motion coupling method. Under the influence of rotor trough, the air gap size, and the width of the slot, the air gap magnetic field is studied. We draw a conclusion: 1. The pear-shaped slot is suit as rotor slot the AC excitation generator, which can improve the waveform of air gap flux density. 2. The air gap is longer, the harmonic content of the air gap flux density is less. But air gap size cannot too big, otherwise the magnetic flux leakage is more, and the efficiency of the motor will be reduced. 3. Magnetic slot wedge can improve the waveform of air gap flux density, which can reduce the wastage, noise and vibration of the AC excitation generator.

Acknowledgement

References

[1] Y. Shunchang, L. Yong, L. Hui and X. Dawei, "Asynchronous generators, Beijing: Science Press, **(2009)**.

[2] Z. Haihong, X. Liqun and Y. Xiangwu, "Review on asynchronous generators under synchronous operation mode", North China Electric Power, vol. 25, no. 10, **(2000)**.

[3] J. Bend, M. Chombt and L. Schreier, "Adjustable-speed Operation of Doubly Fed Machines in Pumped Storage Power Plants", Ninth International Conference on Electrical Machines and Drives, (conf. Publ. No. 468), **(1999)**.

[4] H. Li, W. Hua and M. Nianping, "Calculation and analysis of harmonic copper losses and iron losses of brushless doubly-fed machine", Electric Machines and Control, vol. 16, no. 3, **(2012)**.

[5] B. Heller, "Effect of harmonic magnetic field on asynchronous motor", Beijing: China Machine Press, **(1980)**.

[6] Y. Xiangyu and C. Xiaoming, "Harmonic magnetic field analysis of brushless Doubly-Fed machines for adjustable speed drives", Journal of South China University of Technology, vol. 33, no. 4, **(2005)**.

[7] Z. Lingjuan, "Investigation on the harmonic field analysis of brushless Doubly-Fed machines", Zhejiang: Zhejiang University, **(2013)**.

[8] M. Dawei and L. Pingzhou, "Design and research of 1MW high slip wound asynchronous wind generator", Journal of Haerbin University of Science and Technology, vol. 4, no. 16, **(2011)**.

[9] S. L. Ying, M. D. Wei and L. Y. Bo, "Application of mutually related field-circuit method steady-state analysis of salient pole synchronous machine", Journal of Haerbin University of Science and Technology, vol. 8, no. 6, **(2003)**.

[10] L. Ruifang, Y. Dengjun and H. Minqiang, "Field circuit and movement coupled time stepping finite element analysis on permanent magnet brushless DC motors", Proceeding of the CSEE, vol. 27, no. 12, **(2007)**.

[11] Y. Xiuke, "Field-Circuit-Motion coupled analysis for switched reluctance motor", Beijing: Shenyang University of Technology, **(2004)**.

[12] H. Minqiang and H. Xueliang, "Numerical computation method of electric machine performance and its application", Nanjing: Publishing House of Southeast University, **(2003)**.