Magnetic Slot Wedge Application Analysis in Double-fed Asynchronous Motor-generator by Finite Element Method

Yang Xiao[1], *Student member, IEEE*, Libing Zhou[1], Jianjun Liu[1,2], Jin Wang[1], *Member, IEEE*, and Yiming Ma[1]

[1] State Key Laboratory of Advanced Electromagnetic Engineering and Technology,
Huazhong University of Science and Technology, Wuhan 430074, China, xiaoyang@hust.edu.cn
[2]Dongfang Electric Machinery Co., Ltd, Dongfang Electric Corporation, Deyang 618000, China, zhongchang08@163.com

To eliminate high order space harmonics in double-fed asynchronous motor-generator, magnetic slot wedge application is introduced. A field-circuit finite element analysis model is proposed for precisely analysis the effect of magnetic slot wedge. And performance estimation methods using simulation result from finite element model are presented. By applying proposed model and methods to prototype, effects of magnetic slot wedge on machine performance are investigated. The advantages of magnetic slot application are proved by calculation results. Comparison and discussion of different wedge group provides guidance of magnetic slot wedge design.

Index Terms**—AC motors, parameter estimation, finite element analysis, air gaps, electromagnetic fields**

I. INTRODUCTION

DOUBLE-FED asynchronous motor-generators (DFAMG) have been used in adjust-speed pump storage plant in Japan and Europe since 1990s. With the increasing of renewable energy and opening of electricity market in china, it is significant to develop pump storage plant for power system stability improvement, power flow optimization and power energy management. And application of adjust-speed DFAMG could increase the efficiency of pump-turbine and improve the ability of operation control.

In large capacity DFAMG, both stator and rotor have open slots for winding assembly, causes tooth harmonic flux in the air gap. To reduce tooth harmonic flux, the application of magnetic slot wedge should be considered as it has been widely used in high efficient motor and also in large turbo-generator. To precisely analysis the application of magnetic slot wedge in DFAMG, finite element (FE) method should be applied to estimate performance and calculate parameters of machine as presented in [1][2].

In this paper, the magnetic slot wedge application in a DFAMG prototype is analyzed. The field-circuit coupled FE model to consider non-linear of machine and the influence of control on voltage harmonics are introduced. The performance estimation methods of magnetic slot wedge application in DFAMG are presented. Different types of magnetic slot wedge are discussed and the result demonstrates the advantage of magnetic slot wedge application in DFAMG.

II. ANALYSIS METHOD

A. Field-circuit coupled FE analysis model

As fed from grid and converter in stator and rotor side respectively, the performance of DFAMG is determined by both machine design and control method. To consider the influence of harmonic voltage especially rotor harmonic produced by rotor side converter, a field-circuit coupled FE model includes 2-D FE model and external circuit model of rotor converter, control system and power grid is considered in this model.

For simplification, the end leakage inductances of stator and rotor windings are calculated analytically and coupled from external circuit. The power grid is modeled as ideal voltage source connected with stator. An ideal model of three-level neutral-point clamped converter is applied. Traditional vector control and SVPWM modulation method is used in external circuit model. The schematic diagram of field-circuit coupled model is shown in Fig.1.

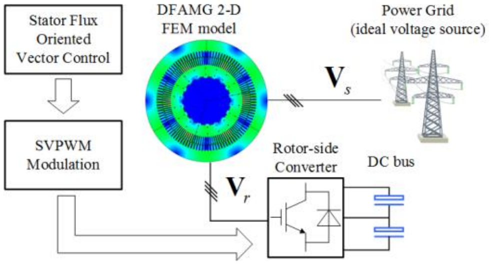

Fig. 1. Schematic diagram of field-circuit coupled FEM model of DFAMG

Two operation conditions are simulated in this paper: no-load and on-load condition both at slip s=0.1. The control goal in on-load condition are output active power P=3MW and stator power factor cosφ =0.9. The stator and rotor voltage waveforms in on-load condition are shown in Fig. 2.

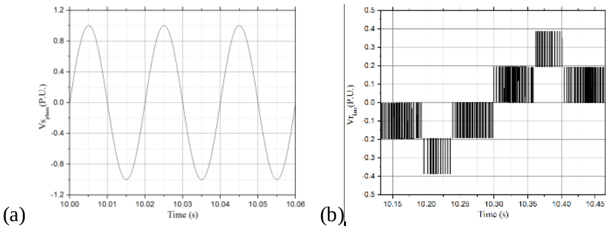

Fig. 2. Voltage waveform of DFAMG in per-unit expression (P.U.) (a) stator phase-to-ground voltage (b) rotor line-to-line voltage

B. Performance estimation method

To analysis the influence of magnetic slot wedge application in DFAMG, some performance of machine should be estimated and compared by fore-mentioned model.

The no-load rotor excitation current is determined by both rotation slip and mutual inductance between stator and rotor winding by no-load FE simulation.

The transient 2-D FE model is connected with circuit model.

Carter's coefficient and space harmonic flux density are computed after Fourier analysis of air gap flux density when the physical quantities of machine are in steady state in the simulation.

For stator and rotor leakage inductances calculation, to account for slot leakage inductance, belt leakage inductance and zig-zag leakage inductance, the leakage inductance can be calculated from equivalent circuit and EMF is obtained from (1) [3]. Leakage inductances are calculated at same on-load operation condition.

$$E_0 = \sqrt{2}\pi N_1 k_{w1} f_n (\frac{2B_{m1} l_{ef} \tau}{\pi}) \qquad (1)$$

The slot leakage inductance of stator winding can be computed by frozen permeability method in 2-D FE model by

$$L_{s\sigma} = \frac{4l_{ef}}{3} \iint_S (\int_0^B HdB)dS \qquad (2)$$

And the sum of belt and zig-zag leakage inductance of stator winding, called gap leakage inductance, is obtained by

$$L_{g\sigma} = \frac{\dot{U}_1 - \dot{E}_0 - \dot{I}_1 (r_1 + j\omega L_{s\sigma})}{j\omega \dot{I}_1} \qquad (3)$$

The total leakage inductance of stator winding is

$$L_{sl} = L_{s\sigma} + L_{g\sigma} \qquad (4)$$

For rotor leakage inductance computation, the same method is applied.

The wedge joule loss in conductive magnetic slot wedge can be obtained by (5)

$$P_{wjl} = \sum_{Q_r} \sum_{wl} \iint_{Sw} \frac{l_{sw}}{2\sigma} \mathrm{Re}(\dot{J}_{sw} \cdot \dot{J}_{sw}^{*}) dS \qquad (5)$$

Where $\dot{J}_{sw}$ is current density vector in wedge, * represents conjugate value, *wl* is the number of wedge segments in a slot, L_{sw} is the axial length of one wedge segment and Q_r is the number of rotor slot.

III. PROTOTYPE SPECIFICATION

A DFAMG prototype is analyzed in this paper with specifications presented in Table I. Three different types of magnetic slot wedge design are shown in Table II.

TABLE I
DFAMG PROTOTYPE SPECIFICATIONS

Item	Value	Item	Value
Rated Power	3MW	Rated Voltage	690V
Rated Frequency	50Hz	Poles number	6
Rated Speed	1000rpm	Operation Slip	-0.1~0.1
Air-gap Length	5mm	Stator Slots	108
Rotor Slots	126	Length	575

TABLE II
DFAMG MAGNETIC SLOT WEDGE DESIGN

Type name	Rotor wedge	Stator Wedge	Permeability(μ_r) at 0.5T
NMW	NonMag	NonMag	1(rotor)/1(stator)
MW1	SU	SU	3.2/3.2
MW2	SU	XJ	3.2/6.5
MW3	CNM	XJ	692/6.5

The electromagnetic characteristics of wedges applied in simulation are BH curves and conductivity. SU and XJ are non-conductive materials made of iron powder and epoxy material while CNM are conductive steel material. Dimension of rotor wedge with CNM is different from others and dimension design would be presented in full paper.

IV. RESULT AND DISCUSSION

The comparison of DFAMG performance with different wedge type is shown in Table III and Fig. 3.

Obviously, the application of magnetic slot wedge can decrease no-load excitation current and carter's coefficient, also significantly eliminate air-gap space harmonics especially tooth harmonics. However, it also leading to the growth of leakage inductances, which would influence the power factor of machine. In general, magnetic slot wedge is suitable for DFAMG. More detailed discussion would be presented in full paper.

TABLE III
DFAMG PERFORMANCE COMPARISON

Type name	NMW	MW1	MW2	MW3
No-load current (A)	353 A	323 A	315 A	320 A
Carter's coefficient	1.66	1.49	1.35	1.27
Stator leakage inductance (mH)	0.168	0.203	0.227	0.227
Rotor leakage inductance (mH)	0.406	0.544	0.545	0.613
Wedge joule loss (kW)	—	—	—	2.02

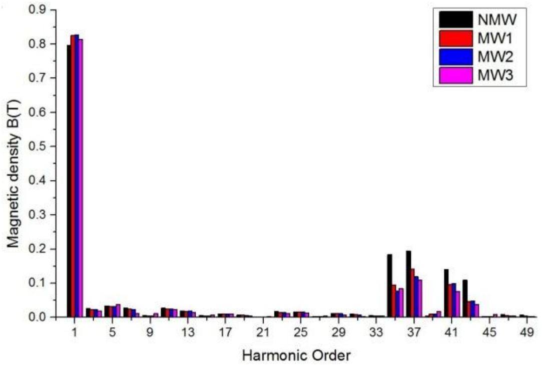

Fig. 3. Spectrum comparison of air-gap space harmonic flux density

One of the main reasons leading to magnetic slot wedge failure is the electromagnetic and mechanical stress. As epoxy wedge is brittle especially for large relative permeability product, the wedge failure risk restricts application of non-conductive wedge. Table III and Fig.3 also show that the effect of MW3 with conductive steel rotor magnetic slot wedge is acceptable. Application of conductive steel rotor slot wedge can reduce the risk of rotor wedge failure.

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