Analysis of a Hybrid Excitation Synchronous Generator Using Three-Dimensional Magnetic Field Finite Element Method

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This paper presents the study about a novel structure hybrid excitation synchronous generator (HESG), which consists of a permanent magnet part as the major component, and an electrically-excited part as the assistant component, and hence possesses the advantages of both the PM and electrically-excited generators. To accurately determine the machine parameters, three-dimensional (3-D) finite element analysis is conducted to solve the magnetic field distribution, which is quite complicated and 3-D, particularly in the electrically-excited part. An equivalent electrical circuit is derived to calculate the generator performance, such as the external characteristic or the relation between the output voltage and the load. A HESG prototype has been constructed and the experimental results validate the theoretical calculations.

Key Words: Hybrid excitation synchronous generator, Magnetic field finite element analysis, External characteristic.

1. Introduction

Because of the simple structure, high efficiency and high reliability, the rare earth permanent magnet (PM) generator has been a strong interest of research in the past decades [1]-[3]. However, the PM generator has difficulty in adjusting its output voltage as the excitation field is almost fixed, and this has greatly limited the application of PM generators [4]. This paper presents a novel structure hybrid excitation synchronous generator (HESG), which possesses the advantages of both PM and electrically-excited generators. The HESG includes two components: the major one is a PM generator, the assistant is similar to an electrically-excited generator, and both components share the same armature. The assistant component is used to regulate the output voltage with a small excitation current.

The magnetic field distribution in the HESG, particularly in the electrical excitation component, is really complicated and three-dimensional (3D). In the design of an electrical machine with 3D magnetic flux, numerical methods like the finite element analysis (FEA) is necessary for accurately computing the machine parameters and performance [5]. In this paper, 3D finite element magnetic field analysis is carried out for computing the key machine parameters such as winding flux, back electromotive force (*emf*), and inductance. To calculate the generator's performance such as the external characteristic, i.e. the relationship of the output voltage against the output current, an equivalent electrical circuit is derived.

An HESG prototype of 1.5 kVA has been designed, constructed, and tested. The calculated and measured external characteristics at different power factors agree well to each other. The assistant component has been successfully applied to regulate the output voltage.

2. Structure and Major Dimensions

The topology of the HESG prototype is shown in Fig. 1, where (1) is the shaft, (2) non-magnetic clapboard, (3) winding holder, (4) excitation winding, (5) axial magnetic pole, (6) magnetic shaft sleeve, (7) radial magnetic pole, (8) stator core, (9) magnetic insulation plate between the main and assistant components, (10) rotor PMs, and (11) rotor core. The major dimensions of main part include a stator inner diameter of 104 mm, a rotor outer diameter of 100.2 mm, an axial core length of 106 mm. The rotor has 4 poles, each consists of 3 NdFeB PM segments with a width of 51.4 mm and an average height of 8.7 mm along the radial magnetization direction. The armature length for the assistant component is 16 mm, in which an *emf* is

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induced by the electrical excitation for regulating the external characteristic of the HESG. The generator is rated as an output power of 1500 VA, phase voltage of 230 V, phase current of 2.17 A, when the rated speed is 1500 rpm.

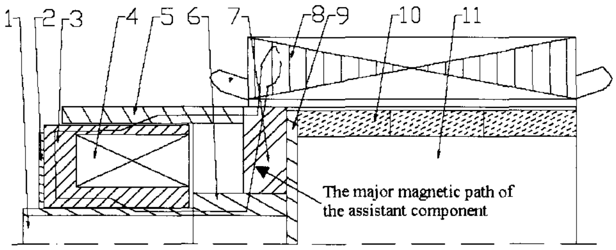

Fig. 1. Structure of the HESG prototype

3. Computation of Major Parameters

3.1 3D Magnetic field FEA

By taking into account the details of the machine structure and dimensions and the non-linearity of ferromagnetic materials, the FEA of magnetic field can accurately determine the magnetic field distribution and hence the parameters and performance of the generator. For simplification, the FEA analyses of the major PM part and the assistant electrically-excited part are performed separately. The magnetic circuits of the two parts are basically independent to each other, but the leakage flux between them may cause partial coupling, which are found negligible by 3D magnetic field FEA.

Considering the structural symmetry, only one pole pitch is required for field solution. Fig. 2 illustrates the plots of magnetic flux density vectors produced by an electrical excitation current.

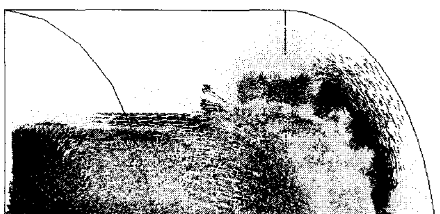

Fig. 2. Plots of flux density vectors due to the excitation current

From Figs. 1 and 2, it can be seen that when a current is fed to the excitation winding, a flux is generated flowing along: the core of the excitation winding holder - radially through the air gap between the winding holder and the axial magnetic pole - axially through the axial magnetic pole - radially via the main air gap and stator teeth under N pole - circumferentially through the stator yoke - radially via the stator teeth and main air gap under S pole - radially through the radial magnetic pole - axially through the magnetic shaft sleeve and the air gap between the sleeve and the excitation winding holder - back to the winding holder to form a closed loop. The magnitude and direction of the magnetic flux can be controlled by the magnitude and direction of the excitation current.

3.2 Winding flux and back emf

The PM flux, defined as the flux linking a phase winding produced by the rotor PMs, can be obtained by the no-load magnetic field distribution of the major part. As shown in Fig. 3, the curve of PM flux is obtained by rotating the rotor for 12 steps for one pole pitch, i.e. 15° electrical per step.

By the discrete Fourier transformation, the fundamental of the flux is found to be ϕ_1=4.889 mWb, and the corresponding back *emf* is 267.3 V, by

$$E_1 = \sqrt{2}\pi f_1 N k_{N1} \phi_1 \qquad (1)$$

where f_1=50 Hz is the power frequency, N=264 the number of turns of one phase winding, and K_{N1}=0.933 is the winding factor. The 3rd harmonic and its multiples do not contribute to the line voltage, so their effect can be ignored. The other non-negligible harmonics include ϕ_5=0.0194 mWb and ϕ_7=0.0728 mWb, but their effects on the output voltage have been minimized by the winding design, e.g. the span of coil is chosen as five sixths of pole pitch. The induced 5th and 7th *emf* harmonics, 3.4 V and 2.0 V respectively, have little contribution to the magnitude of the output voltage although they do affect the voltage waveform. The rms value of the back *emf* can be calculated to be about 267.5 V, by

$$E_0 = \sqrt{E_1^{\,2} + E_5^{\,2} + E_7^{\,2} + \cdots}\,. \qquad (2)$$

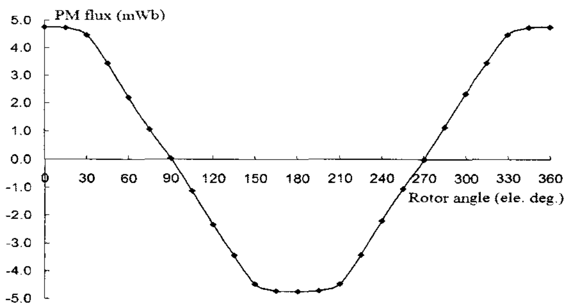

Fig. 3. Winding flux produced by the rotor PMs

3.3 Winding inductance

The winding inductance is one of the key parameters determining the generator performance. The behavior of an electrical circuit is governed by the incremental inductance rather than the secant inductance [6]. In this paper, the phase winding incremental inductances of the generator is calculated by a modified incremental energy method [7], which includes the following steps: (1) For a given rotor position θ, conduct a non-linear field analysis considering the saturation due to the PMs to find out the operating point of the motor, and save the incremental permeability in each element; (2) Set the remanence of PMs to zero, and conduct a linear field analysis with the saved permeabilities under perturbed stator current excitations, i.e. assigning the 3 phase winding currents as (i_a,i_b,i_c) = $(\Delta i,\Delta i,0)$, $(\Delta i,0,\Delta i)$, $(0,\Delta i,\Delta i)$, $(\Delta i,0,0)$, $(0,0,\Delta i)$, and $(0,\Delta i,0)$, respectively; (3) Find out the co-energy for each excitation; and (4) Calculate the incremental inductances by

$$L_{aa}(\theta)=L_{bb}(\theta)=L_{cc}(\theta)=\frac{2W_c(\Delta i,0,0,\theta)}{(\Delta i)^2} \tag{3a}$$

$$L_{ab}(\theta)=L_{ba}(\theta) =\frac{W_c(\Delta i,\Delta i,0,\theta)-W_c(0,\Delta i,0,\theta)-W_c(\Delta i,0,0,\theta)}{(\Delta i)^2} \tag{3b}$$

$$L_{bc}(\theta)=L_{cb}(\theta) =\frac{W_c(0,\Delta i,\Delta i,\theta)-W_c(0,\Delta i,0,\theta)-W_c(0,0,\Delta i,\theta)}{(\Delta i)^2} \tag{3c}$$

$$L_{ca}(\theta)=L_{ac}(\theta) =\frac{W_c(\Delta i,0,\Delta i,\theta)-W_c(0,0,\Delta i,\theta)-W_c(\Delta i,0,0,\theta)}{(\Delta i)^2} \tag{3d}$$

Fig. 4 shows the calculated self and mutual incremental inductances of the three phase windings at different rotor positions, including those of the major armature part, the assistant armature part, and the end winding. The end winding inductance is about 10 % of the armature one.

4. External Characteristic

To predict the generator performance such as the external characteristic, an equivalent electrical circuit is derived as shown in Fig. 5, where V_1 is the rms value of the output phase voltage, I_1 the value of output phase current, R_1=6.8 Ω the phase winding resistance, $\omega_1=2\pi f_1$ the angular frequency, and L_1 the synchronous inductance which equals the self inductance plus half of the mutual inductance. For simplification, the winding inductances can be considered as constants, *e.g.* the average values. From Fig. 4, the average self-inductance of a phase winding is 34.7 mH, and the average mutual inductance between two phase windings is 13.2 mH.

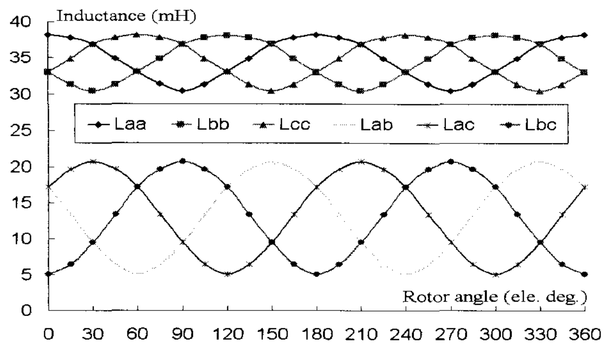

Fig. 4. Computed self and mutual inductances of three phase windings

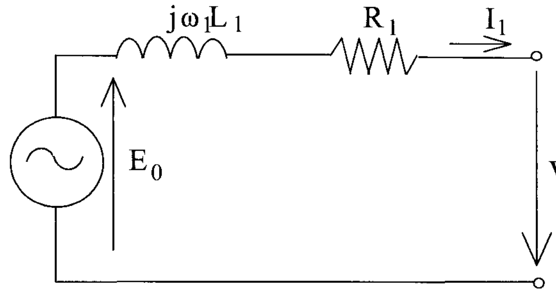

Fig. 5. Per phase equivalent electrical circuit

From Fig. 5, the external characteristic can be derived as

$$V_1=\sqrt{E_1^{\,2}-(X_1I_1\cos\varphi-R_1I_1\sin\varphi)^2} -R_1I_1\cos\varphi-X_1I_1\sin\varphi, \tag{4}$$

where $X_1=\omega_1L_1$ is the synchronous reactance, and φ is the angle between V_1 and I_1. Fig. 6 plots the calculated external characteristics of the HSEG with power factor $\cos\varphi$=1 and $\cos\varphi$=0.8.

The designed HESG prototype has been constructed and tested. Fig. 6 also plots the measured external characteristics of the HESG, showing that the experimental results agree well with the calculations. The difference, which increases with the armature current, may be caused by the effect of armature reaction on the back *emf*. The error is more evident when $\cos\varphi$=0.8 than that at $\cos\varphi$=1.

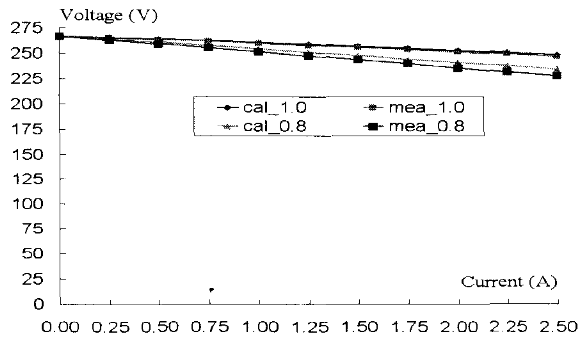

Fig. 6. Calculated and measured external characteristics

5. Voltage Regulation

The *emfs* induced in the stator windings, E_0, include two parts: that caused by the rotor PMs of the main part, and that caused by the excitation current of the assistant part. The two *emfs* have no phase difference and can thus be quantitatively added [8].

Fig. 7 shows the adjustment of the external characteristic of HESG. It is well known that the output voltage decreases when the load current increases. It is also found that the voltage characteristic curves with different E_0 are almost parallel lines. If the excitation current of the assistant part and hence E_0 are adjusted according to the load current, the output voltage of the HESG can be kept constant when the load changes.

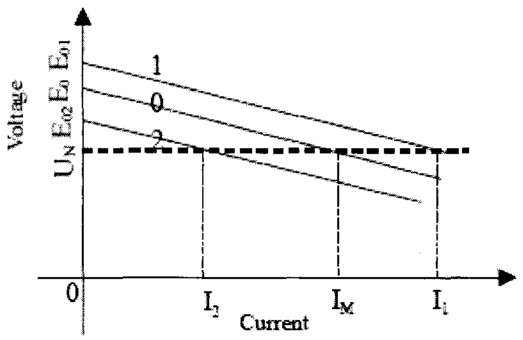

Fig. 7. Theory of voltage regulation

6. Conclusion

This paper presents the development of a novel structure hybrid excitation synchronous generator by 3D magnetic field FEA. The advantages of the HESG include: simple structure and high reliability as it is brushless, capability of regulating the output voltage of PM generator, and high efficiency.

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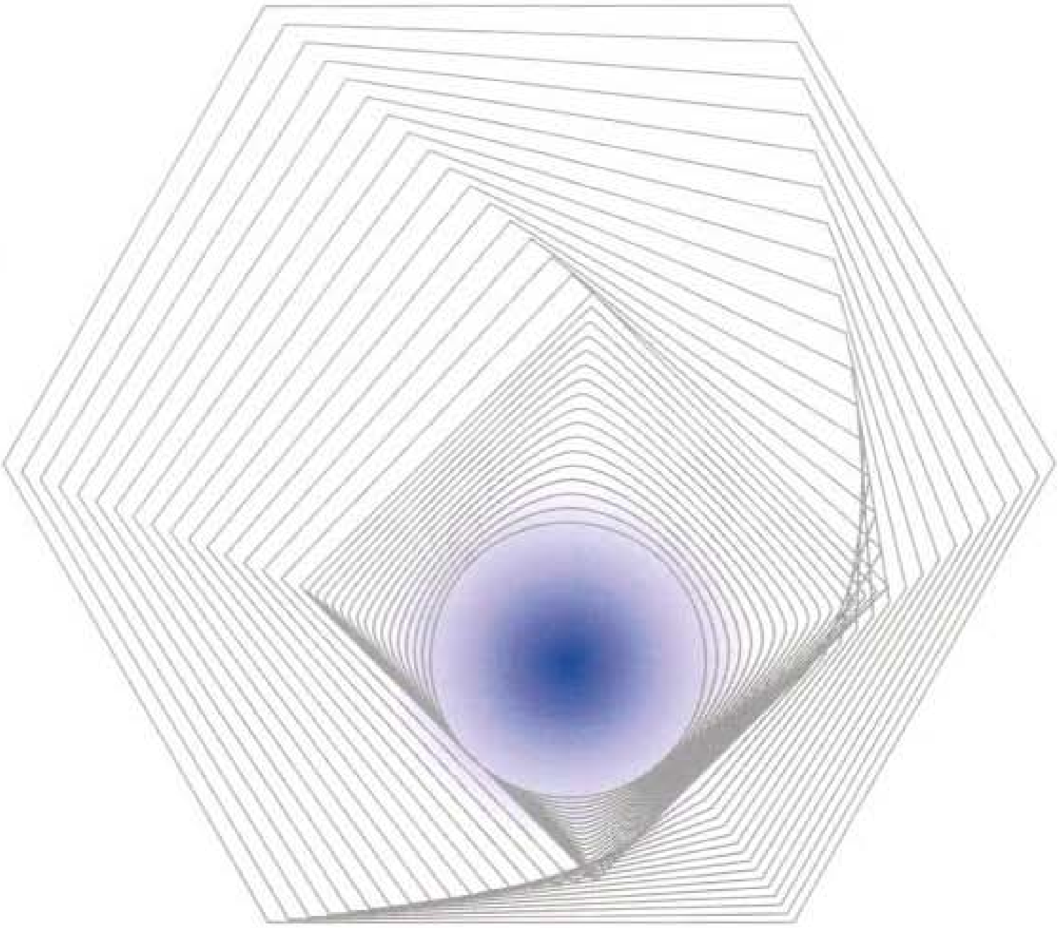

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