PARAMETER DETERMINATION AND PERFORMANCE ANALYSIS OF A PERMANENT MAGNET SYNCHRONOUS GENERATOR BY MAGNETIC FIELD FINITE ELEMENT ANALYSIS

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Abstract

This paper presents the accurate determination of key parameters and performance analysis of a permanent magnet synchronous generator (PMSG) by finite element magnetic field analysis, providing a sound basis for the machine design and optimisation. Parameters such as the winding flux, back electromotive force, and inductances are accurately calculated based on a series of numerical field solutions and improved formulations. An equivalent electrical circuit is employed to derive the equation of the external characteristic, the most important performance of the synchronous generator. The theoretical calculations and analyses have been validated by the experimental results on the PMSG prototype.

1. Introduction

With the development of high performance rare earth permanent magnet (PM) materials, PM synchronous generators (PMSGs) have attracted a strong interest of research, as they possess a number of advantages such as high efficiency, high power-to-volume ratio, and high reliability. Furthermore, compared to the conventional electrically excited generators, PMSGs have the advantages such as the absence of brushes, slip rings, excitation coils, dc power supply and field winding copper loss [1]. As a result, a large number of PMSGs were investigated in the last decade by various researchers for different applications, including isolated diesel engine, wind turbine, hybrid vehicle, and electric ship [2-6].

In spite of the many advantages, the PMSG has difficulty in adjusting the external characteristic due to the almost fixed excitation field produced by the rotor PMs [7]. Therefore, it is very important to achieve satisfactory performances, e.g. a small inherent voltage regulation rate, in the design stage of the PMSG. Other techniques such as hybrid structures with both PMs and electrically excited coils are also being investigated for improving the performance of PM generators [8].

This paper aims to present the parameter determination and performance analysis of a surface-mounted PMSG. For the design and analysis of an electrical machine, accurate prediction of the machine parameters is crucial. In this paper, key machine parameters such as winding flux, back electromotive force (*emf*), and inductances are obtained based on magnetic field finite element analysis (FEA) solutions and improved formulations. Numerical analyses of magnetic field, e.g. FEA, can take into account the detailed structure and dimensions of the machine and the non-linearity of the ferromagnetic materials, and hence can accurately compute the machine parameters and performance.

An equivalent electrical circuit is employed to calculate the external characteristic, which is validated by the experimental results on the PMSG prototype.

2. PMSG Prototype

Figure 1 illustrates the magnetically relevant parts of a PMSG prototype, and Table 1 lists the major dimensions and parameters. Four NdFeB PMs (type: NTP230/72) are radially magnetised and are mounted on the surface of the rotor. Considering the almost fixed magnetic field, the rotor core uses solid steel (type: #10 steel) and is mounted on a steel shaft. The stator core is made of electrical steels (type: D21), with 24 slots for the 3 phase windings (not shown for clarity). The phase winding is of double layer overlap type and each coil has 86 turns, so the number of turns of a phase winding can be computed as 688.

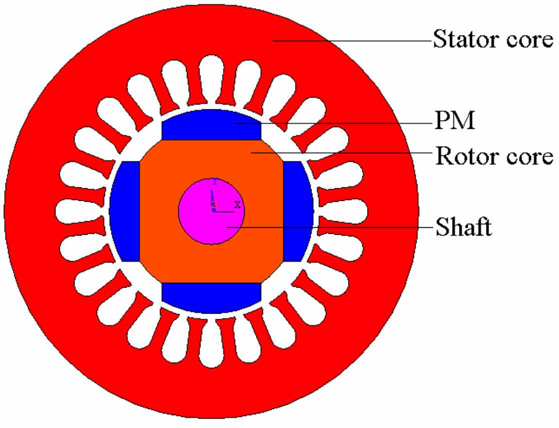

Figure 1 Magnetically relevant parts of a PMSG prototype

Table 1 Major parameters and dimensions of the PMSG

Dimensions and parameters	Quantities
Rated output power (W)	500
Rated phase voltage (V)	139
Rated phase current (A)	1.5
Rated power factor	0.8
Number of phases	3
Number of poles	4
Rated speed (rpm)	1500
Stator outer diameter (mm)	138
Stator inner diameter (mm)	72
Axial length of stator core (mm)	80
Air gap length (mm)	2
Permanent magnets	NdFeB, NTP230/72
Width of PM (mm)	33
Average length of PM along magnetisation (mm)	8.7
Axial length of PM (mm)	72
PM arc coefficient	0.65
Number of turns of a phase winding	688

3. Parameter Determination by Magnetic Field FEA

From the magnetic field FEA solutions, many machine parameters can be accurately determined. For example, the PM flux, defined as the flux linking a phase winding produced by the rotor PMs, can be obtained according to the no-load magnetic field distribution as shown in Figure 2, which illustrates the plots of **B** (flux density) vectors at no-load at the zero rotor angle, defined as the position as shown in Figure 1.

The curve of PM flux against rotor angle can be obtained by the FEAs at a series of rotor positions as plotted in Figure 3. It can be seen that the PM flux waveform is close to a sinusoid. Discrete Fourier analysis reveals that the largest harmonic (5^{th} or 7^{th}) is only 0.32% of the fundamental component.

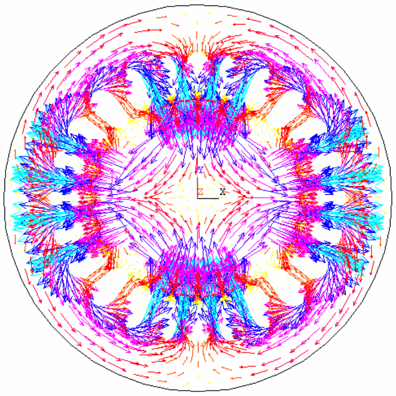

Figure 2 Plots of magnetic flux density vectors at no-load

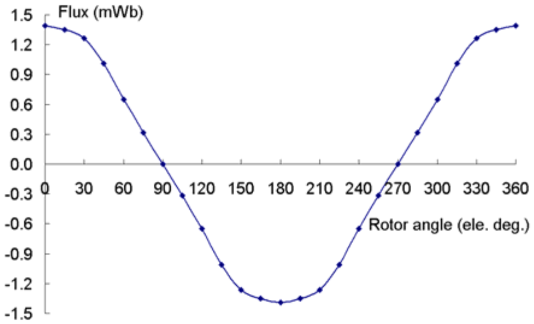

Figure 3 PM flux against rotor angle

When the rotor rotates, a back *emf* will be induced in the phase winding and can be obtained by differentiating the PM flux against time as

$$e_1 = \frac{d\lambda_1}{dt} = Nk_{w1}\frac{d\phi_1}{dt} = Nk_{w1}\frac{d\phi_1}{d\theta}p\omega_r \tag{1}$$

where λ_1, ϕ_1, N and k_{w1} are the flux linkage, flux, number of turns and winding factor of the phase winding (all refer to the fundamental component), θ is the rotor angle in electrical radians, p=2 the number of pole-pairs and ω_r the rotor speed in mechanical radian per second.

For the fundamental component, the rms value of the back *emf* can be derived from (1) as

$$E_1 = \sqrt{2}\pi f_1 N k_{w1} \Phi_1 \tag{2}$$

where f_1 is the frequency of the back *emf* and Φ_1 the magnitude of the fundamental component of PM flux.

The winding inductance is another important parameter in determining the performance of the electrical machine. The behaviour of an ac electrical circuit is determined by the incremental (differential) inductance rather than the apparent (secant) inductance [9]. In this paper, the incremental self and mutual inductances of the 3 phase windings are computed by a modified incremental energy method [10-11], which consists of 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 the operating point of the motor, and save the incremental permeability in each element; (2) Set the remanence of PMs to be zero, and conduct linear field analyses 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) Calculate the magnetic co-energy for each current excitation; and (4) Calculate the incremental inductances by

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

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

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

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

Figure 4 shows the computed self and mutual incremental inductances of the 3 phase windings.

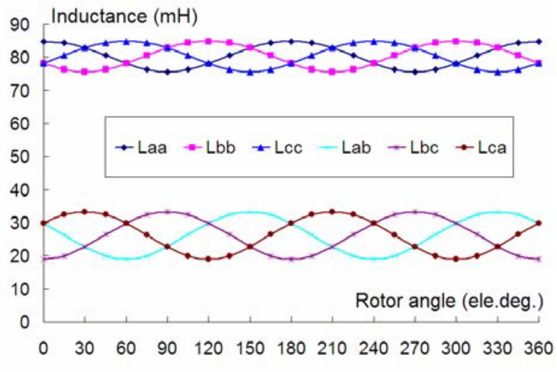

Figure 4 Self and mutual inductances of the 3 phase windings

4. Generator Characteristics

The most important performance of a generator is the external characteristic, i.e. the relationship of output terminal voltage against load current, which can be predicted by an equivalent electrical circuit as shown in Figure 5, where V_1 is the output voltage, I_1 the phase current, R_1 the phase resistance, ω_1 the electrical angular frequency, and L_1 is the synchronous inductance, which equals the self inductance plus half mutual inductance here.

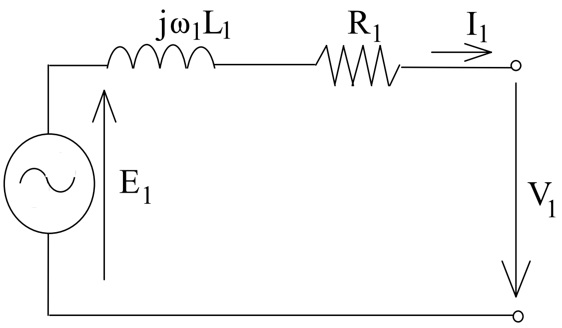

Figure 5 Per-phase equivalent electrical circuit of a PMSG

From the above circuit, the external characteristic can be derived as

$$\begin{aligned}V_1=&\sqrt{E_1^{\,2}-I_1^{\,2}(\omega_1L_1\cos\varphi-R_1\sin\varphi)^2}\\&-I_1(\omega_1L_1\sin\varphi+R_1\cos\varphi)\end{aligned} \tag{4}$$

where φ is the power factor of the load.

From Figure 4, it can be seen that the inductances actually vary against the rotor angle and these variations may affect the machine performance, particularly the dynamic characteristics. However, it might be sufficient to predict the steady state characteristics by using the average values of the inductances [11]. For this PMSG, the average self inductance is 80.6 mH and the average mutual inductance is 26.4 mH.

According to (4), the external characteristics of the generator can be obtained. Figure 6 illustrates the computed external characteristics of the PMSG with both a resistive load ($\cos\varphi$=1) and an inductive load ($\cos\varphi$=0.8 lagging) when the generator runs at the rated speed of 1500 rpm. The corresponding experimental results are also plotted in the figure, validating the theoretical calculations.

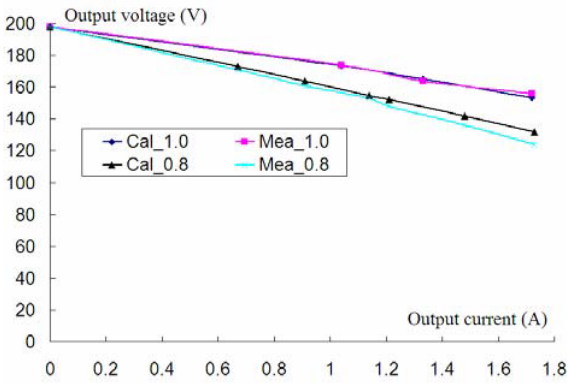

Figure 6 Calculated and measured external characteristic of the PMSG prototype

5. Conclusion

This paper present the parameter computation and performance analysis of a PMSG by using magnetic field FEA. Key generator parameters such as PM flux, back *emf* and winding inductance are determined based on FEA solutions. The external characteristics of the PMSG are predicted by an equivalent electrical circuit and verified by the experimental results on the prototype.

6. References

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