Design of Small Permanent Magnet Generator Using 2D FEMM

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Abstract - **This paper deals with the design of small permanent magnet generator using 2D FEMM. The design will present the parameter computation and performance prediction of a permanent magnet (PM) synchronous generator based on numerical magnetic field analyses. The finite element method is employed to accurately determine the magnetic field distribution and key parameters of the machine, such as the winding flux, back electromotive force, winding inductance. An equivalent electrical circuit is applied to predict the generator performance such as the external characteristic.**

Keywords-component; Permanent magnet(PM); Finite Element Analysis (FEA); synchronous generator.

I. 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 application, including isolated diesel engine, wind turbine, hybrid vehicle, and electric ship [2-3].

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.

II. GENERATOR DESIGN

Figure. 1 illustrates the magnetically relevant parts of a PMSG prototype The laminated stator core has 24 slots, in which three phase double-layer windings are placed (not shown for clarity).Each coil has 50 turns so the number of turns of each phase winding is 400. The rotor core and shaft are made of mild steel and four pieces of NdFeB PMs are mounted and bound on the surface of the rotor. The stator core has an inner diameter of 144.83 mm, an outer diameter of 165 mm, and an axial length of 124.1 mm. The main air gap length is 0.08 mm. The generator is designed to operate at 1500 rpm, or a frequency of 50 Hz, producing a rated power of 2 kW at a phase current of 2 A and a phase voltage of 413 V with a power factor of 0.8.

The rotor structure of the machine addressed in this paper is the surface-mounted magnet type as shown in Figure. 1. The main advantage of this topology is that all of the magnetic flux produced by the magnets links the stator, and therefore, takes part in energy conversion. The design uses arc magnets glued on the rotor to prevent them coming off at high speeds.

Additional magnet retention can be provided using wire wrapping, or stainless steel. The winding is distributed so that the output voltage of the machine is close to a sine wave.

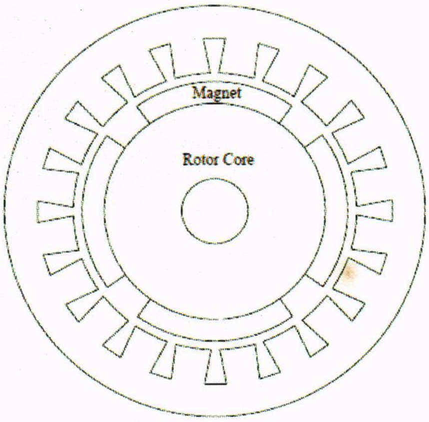

Figure 1. Permanent magnet synchronous generator with surface mounted magnets on the rotor

Table I
MAJOR PARAMETERS AND DIMENSIONS OF THE PMSG

Dimensions and parameters	**Quantities**
Rated output power (W)	2000
Rated phase voltage (V)	413
Rated phase current (A)	2
Rated power factor	0.8
Number of phases	3
Number of poles	4
Rated speed (rpm)	1500
Stator outer diameter (mm)	165
Stator inner diameter (mm)	144.83
Air gap length (mm)	0.08
Permanent magnets	NdFeB, 32 MGOe
Width of PM (mm)	3.3
Number turns of a phase winding	400

III. METHADOLOGY

FEMM is a 2D Finite Element Analysis (FEA) freeware package, which is suitable for modeling of electromagnetic devices during the design stages. It enables designers to visualize the invisible flux lines and determine the flux densities in parts of interest, thereby providing valuable insight into possible design enhancements. The design process will produce detailed design of the generator. It will also produce the theoretical predictions by means of the equivalent circuit parameters and the performance of the machine. The main objective of this project would be to verify the theoretical predictions by means of a finite element analysis with the FEMM software.

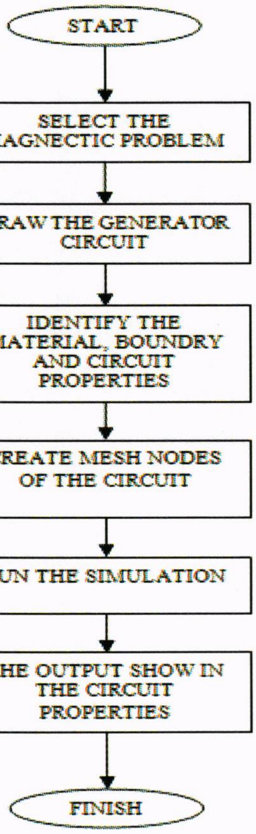

Figure 2. Work flow of the FEMM software

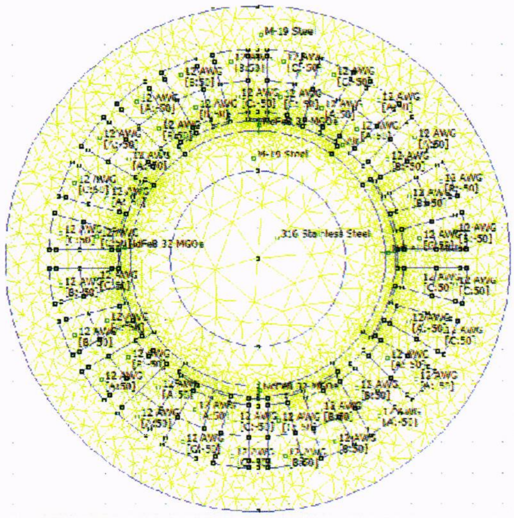

Figure 3. Mesh created in the nodes

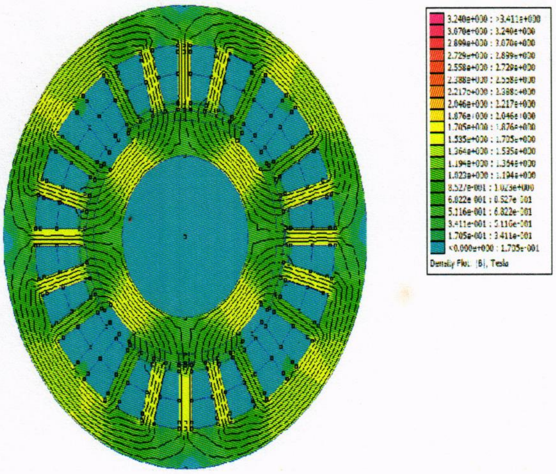

Figure 4. Density Plot of Permanent Magnet Generator

III. 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. 4, 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 5.

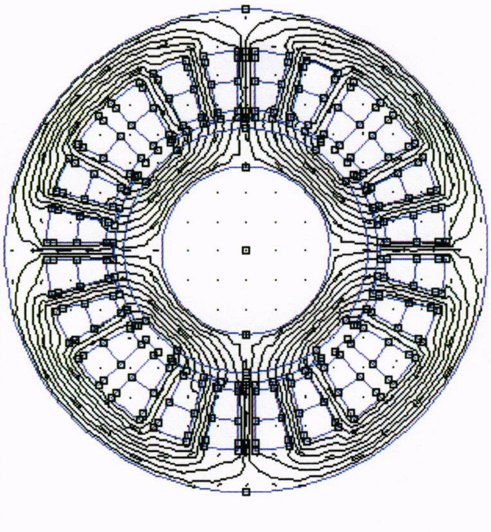

Figure 5. Plot of magnetic flux density vectors

The waveform of the PM flux can be obtained from the no-load field solutions at different rotor positions. To increase the computational accuracy and efficiency, the stator and rotor are meshed separately from the middle line of the air gap. When the rotor rotates to a specified position, the meshes are stitched together along the middle air gap line. Fig. 6 plots the waveform of PM flux linkage versus rotor position, which is not an ideal sinusoid.

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

$$e1\frac{d\lambda}{dt} = Nkw1\frac{d\vartheta}{dt} = Nkw1\frac{d\vartheta}{dt}\rho\omega r \qquad (1)$$

where $\lambda 1$, $\varphi 1$, N and $kw1$ 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 ωr the rotor speed in mechanical radian per second.

Table II. Data of flux linkage and rotor angle

Flux linkage(Wb)	Rotor angle (elec deg.)
1.99291	0
1.34531	30
-0.38997	60
-1.77766	90
-1.23124	120
0.516683	150
1.87749	180
1.34549	210
-0.39011	240
-1.77792	270
-1.23124	300
0.516683	330
1.87749	360

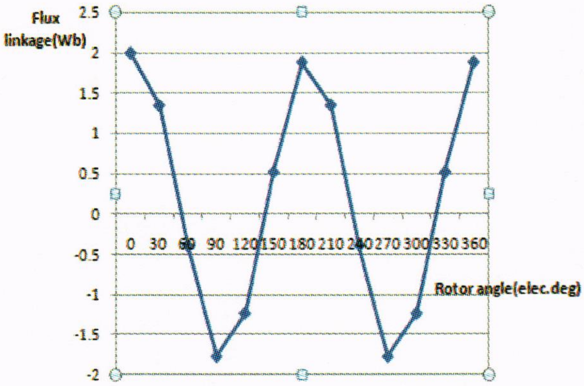

Figure 6. Flux linkage versus rotor angle

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

$$E = \sqrt{2}\pi f N k w \Phi \tag{2}$$

where f is the frequency of the back *emf* and Φ the magnitude of the fundamental component of PM flux.

$$\Phi = \frac{\lambda}{N} = \frac{1.99291}{400} = 4.982m \tag{3}$$

$$kw = kp.kb \tag{4}$$

$$kp = \sin p\frac{\pi}{2} = sin\frac{5}{6}\left(\frac{\pi}{2}\right) = 0.966 \tag{5}$$

$$kb = \frac{\sin\frac{\beta}{2}}{n\sin\frac{\gamma}{2}} = \frac{\sin\frac{60}{2}}{2\sin(\frac{\pi}{6}/2)} = 0.966 \tag{6}$$

$$kw = 0.933$$

So

$$E = \sqrt{2}\pi(50Hz)(400)(0.9330)(4.982m)$$
$$= 413.05V$$

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.

One complicating factor in determining the inductance is the presence of the permanent magnet. Typically, one can find inductance of a coil by doing a simulation with current in the coil, applied via a "circuit property." The "flux/current" obtained by viewing the circuit's properties in the postprocessor can then be taken as inductance. However, if there is a permanent magnet, some of the linked flux is due to the permanent magnet, so assuming that "flux/current" is the same as inductance would lead to large errors in the estimation of inductance. To get the incremental inductance about an operating point established by the permanent magnet, the best way is to compute the flux linkage for a small positive-valued current and a small negative-valued current. The inductance can then be taken as the change in flux linkage divided by the difference of the two test currents.

$$L = \frac{\text{Different Between Flux Linkage}}{\text{Different Between Two Test current}} \tag{7}$$

When current = 1A, λ = 1.93720Wb

When current = -1A, λ = 1.81303Wb

$$L = \frac{1.93720\text{Wb} - 1.81303\text{Wb}}{1\text{A}-(-1\text{A})} = 0.062115 \text{ Henries}$$

For the purposes of estimating a value of end turn resistance, assume that the center of the winding is at a height of approximately 14 mm and its end-turns have a roughly half-circle shape on each side.

The mean end-turn = π ×14 mm = 44 mm
length

Depth specified for the problem = 124.1 mm

Nominal resistance=2.07861 Ω

$$Rs = 2.07861\Omega \times \frac{(124.1mm - 44\text{mm})}{124.1mm} = 2.82\Omega$$

IV. PREDICTION OF GENERATOR PERFORMANCES

The most important performance of a generator is the external characteristic, i.e. the relation between the terminal voltages against output current (load). Figure.7 shows the per-phase equivalent electrical circuit of the generator, from which the external characteristic can be derived as

$$V_1 = \sqrt{E_1^2 - I^2(\omega L\cos\varphi - R\sin\varphi)^2} - I(\omega L\sin\varphi + R\cos\varphi) \tag{8}$$

where V_1 is the terminal voltage, E_1 is the back EMF, I_1 is the load current, $\omega = 2\pi f$ is the angular frequency of electricity, L_1 is the synchronous differential inductance, R_1 is the phase resistance, and φ is the power factor angle of the load.

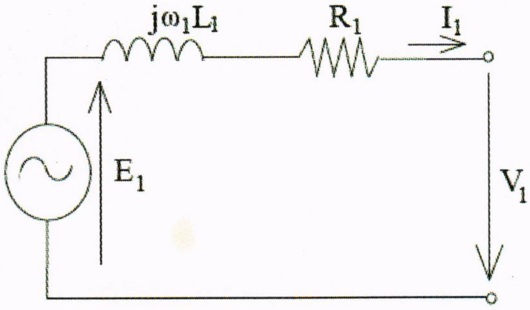

Figure 7. Per-phase equivalent circuit of PMSG

When PF load = 0.8 lagging

$$V_1 = 412.06V - 27.9V = 384.16V$$

When PF load =1

$$V_1 = 411.15V - 5.64V = 405.51V$$

According to (8), 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□=1) and an inductive load (cos□=0.8 lagging) when the generator runs at the rated speed of 1500 rpm. The corresponding experimental results are also plotted in the Figure 6.

Table III: Data of external characteristic of PMSG

Output current	PF=0.8	PF=1
0	413	413
0.3	408.79	412.11
0.6	404.54	411.14
0.9	400.295	410.089
1.2	369.04	408.95
1.5	391.79	407.735
1.8	387.54	406.433
2.1	383.29	405.047

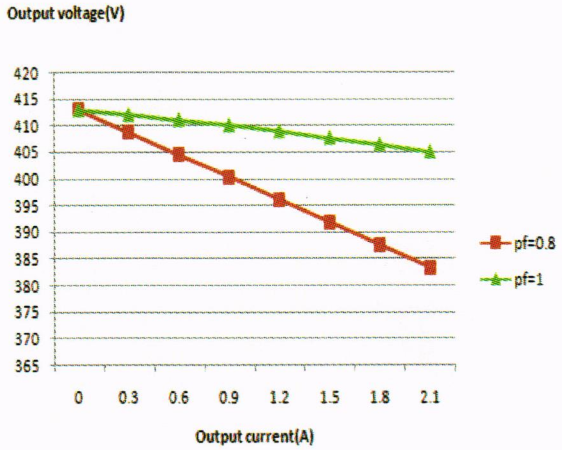

Figure 8. The computed external characteristic with both load

Lagging case

$$VR = \frac{Vnl - Vfl}{Vfl} \times 100\% \qquad (9)$$

$$VR = \frac{413.05V - 384.16V}{384.16V} \times 100\%$$

$$= 7.5\%$$

Unity case

$$VR = \frac{Vnl - Vfl}{Vfl} \times 100\% \qquad (10)$$

$$VR = \frac{413.05V - 404.5V}{404.5V} \times 100\%$$

$$= 2.11\%$$

VII. CONCLUSION

This paper presents the parameter computation of a permanent magnet synchronous generator by finite element magnetic field analysis and the performance prediction of the generator by an equivalent electrical circuit. Key machine parameters, such as winding flux, winding inductance are determined based on numerical magnetic field solutions. The analysis approaches and results can be useful for design and optimization of permanent magnet synchronous machines.

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