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Rotor Loss Analysis in Permanent Magnet High-Speed Machine Using Coupled FEM and Analytical Method

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Abstract - This paper deals with the method to calculate the rotor eddy current losses of permanent magnet high-speed machines considering the effects of time/space flux harmonics. The flux harmonics caused by the slot geometry in the stator is calculated from the time variation of the magnetic field distribution obtained by the magneto-static finite element analysis and double Fast Fourier Transform. And, using the analytical approach considering the multiple flux harmonics and the Poynting vector, the rotor losses is evaluated in each rotor composite. Using this method is simple and workable for any kind of stator slot shape for rotor loss analysis.

Keywords: Rotor eddy current losses, permanent magnet high-speed machines, double Fourier Transform, Poynting vector

1. Introduction

ELECTRO magnetic losses are proportional to the volume of the machine, consequently, the smaller the machine in size the smaller the power loss. On the other hand, the increase in the frequency will increase the losses that may nullify the reduction by the volume reducing effect. The mechanical power loss due to friction and windage will certainly increase rapidly with the increase in speed, but will reduce due to reduction in the rotor diameter. Taking into account the overall surface of a high-speed machine that is smaller than that of the same power machine with normal speed, heat transfer in a high-speed machine is more difficult than it in a normal speed machine. This makes the cooling of a high-speed machine more difficult, hence, requiring special considerations[1]-[3].

The rotor speed for high-speed machines is normally above 30,000 r/min and may exceed 100,000 r/min. The frequency of flux variation in the stator teeth and core can be more than 1 kHz. Therefore, it is generally necessary to secure the magnets on to the rotor shaft by means of a retaining sleeve, in order to resist high centrifugal forces. However, the retaining sleeve and the magnets are exposed to high order flux harmonics, which cause parasitic eddy current losses. The effects on rotor losses are caused by changes in rotor speed, rotor material choices, airgap length, stator winding design, and stator slot design. Therefore, the most important design consideration in the choice of permanent magnet high-speed machine is the need to minimize eddy current losses in the sleeve and magnet due to slotting harmonics. But, the losses in the rotor elements due to slotting harmonics are not to easy to determine[2][3].

On the basis of the coupled FEM and analytical method, this paper deals with the rotor loss analysis in permanent magnet high-speed machine. The method contains two main steps: first step, using a 1 slot-pitch magneto-static finite element analysis, the flux density distribution in the machine is calculated. And the traveling wave harmonics data caused by the slot geometry is generated by double

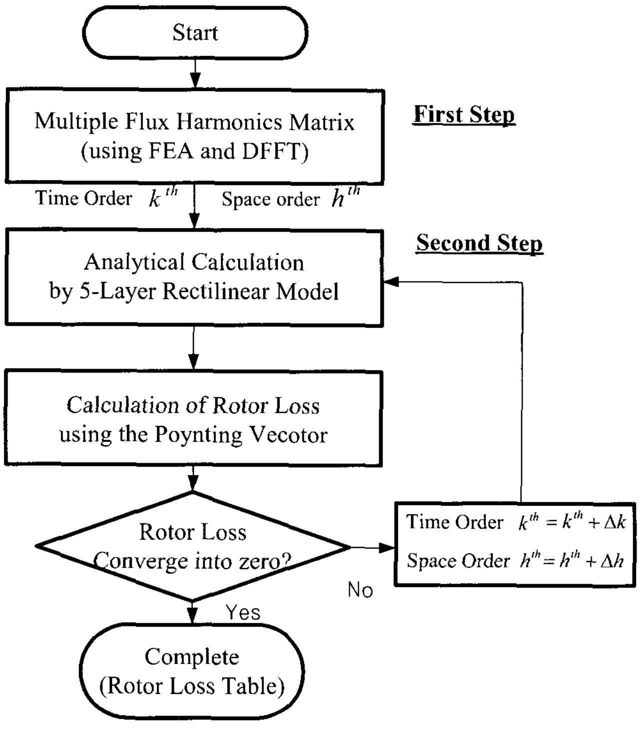

Fig. 1 Process of rotor loss analysis

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Fast Fourier Transform (DFFT). Second step, rotor losses are computed with the proposed rectilinear current sheet model considering the multiple traveling wave harmonics and the Poynting vector. These analysis strategies are described in more detail in [1]-[3].

Fig. 1 shows the process of rotor eddy current loss analysis of the permanent magnet high-speed machine.

2. Coupled FEM and Analytical Method

2.1 One-Slot Finite Element Method and DFFT

The commercial finite element analysis package ANSOFT MAXWELL has been used for 2-D magneto static analysis, allowing nonlinear material properties and structural details to be considered.

Fig. 2 describes the concept of employing a 1 slot-pitch model for finite element analysis. The analysis model is a 5kW, 40,000rpm permanent magnet high-speed machine with an 18-slot stator carrying a distributed winding, and a 2-pole rotor with diametrically magnetized sintered NdFeB magnets which produce an essentially sinusoidal airgap flux density distribution. As shown in figure, the total of 30 models, representing 30 rotor positions with a rotor step of 0.66 mechanical degrees, were analyzed.

The normal flux density harmonics were calculated by use of double Fast Fourier Transform (DFFT) of normal flux density data on the surface of the sleeve [3]. The data is obtained from 30 finite element solutions corresponding to different rotor positions.

Fig. 3-5 show the time and space distribution of normal flux density over the retaining sleeve surface for no-load condition, stator-mmf only condition and on-load condition, respectively. The total of 30 models, representing 30 rotor positions with a rotor step were generated and analyzed.

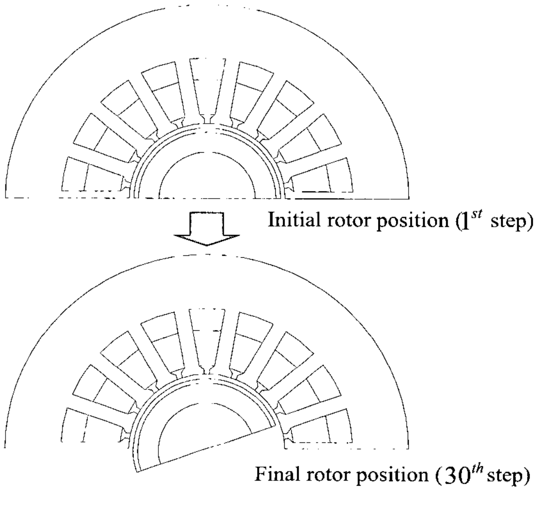

Fig. 2 1 slot-pitch model for finite element analysis

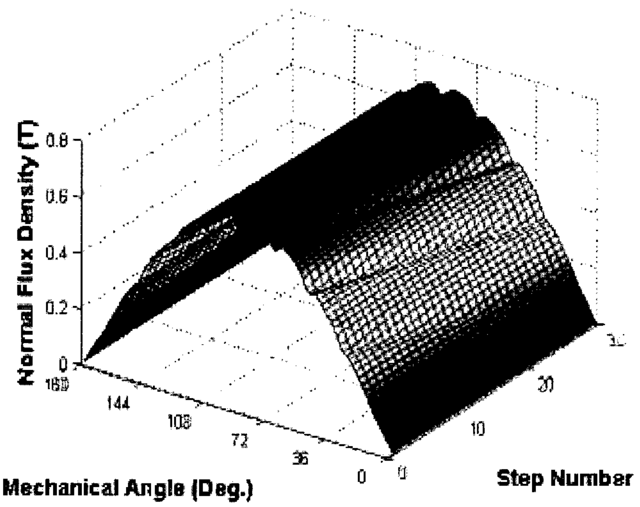

Fig. 3 Time/Space distribution of the normal flux density for no-load condition

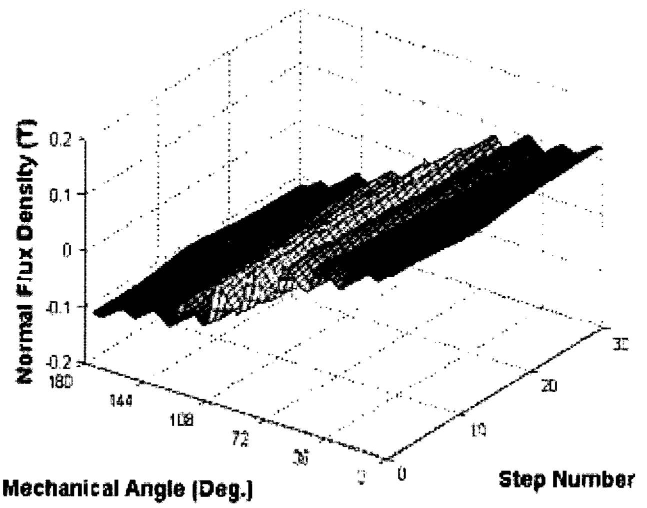

Fig. 4 Time/Space distribution of the normal flux density for space-mmf only condition

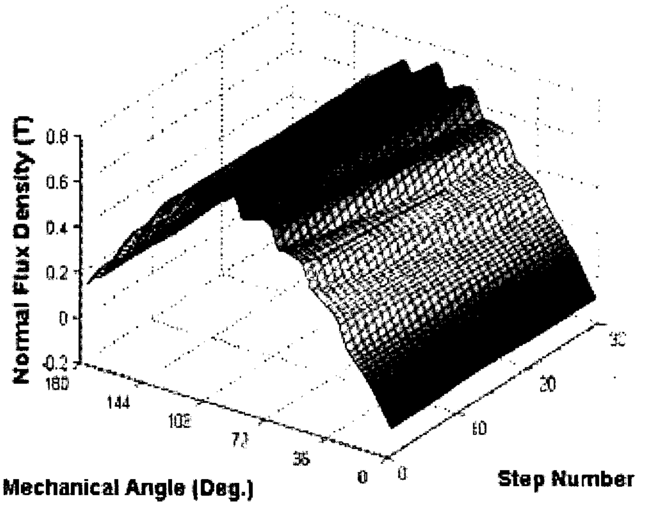

Fig. 5 Time/Space distribution of the normal flux density for On-load condition

Table 1 Amplitude of Flux Harmonics for No-Load Condition

Space order	Time order		
	0	18	36
1	0.669589	0.000011	0.000013
5	0.000071	0.000017	0.000011
13	0.000028	0.000150	0.000035
17	0.000007	0.009952	0.000014
19	0.000011	0.010751	0.000014
35	0.000003	0.000009	0.005710
37	0.000021	0.000005	0.005447

Table 2 Amplitude of Flux Harmonics for Stator-mmf Only Condition

Space order	Time order		
	0	18	36
1	0.107793	0.000136	0.000017
5	0.004570	0.002381	0.000905
7	0.001898	0.001093	0.000375
13	0.001276	0.002456	0.000696
17	0.000030	0.019159	0.000105
19	0.000009	0.010715	0.000070
35	0.000015	0.000002	0.005134
37	0.000012	0.000034	0.001559

Table 3 Amplitude of Flux Harmonics for On-Load Condition

Space order	Time order		
	0	18	36
1	0.681987	0.000229	0.000355
3	0.005167	0.000179	0.000284
5	0.005774	0.002411	0.000900
7	0.002804	0.001140	0.000356
9	0.001499	0.000214	0.000238
11	0.001264	0.000894	0.000333
13	0.001629	0.002342	0.000690
15	0.000799	0.001127	0.000187
17	0.000614	0.022183	0.000235
19	0.001367	0.013916	0.000262
21	0.000315	0.000638	0.000026
23	0.000457	0.001143	0.000764
33	0.000676	0.000091	0.001185
35	0.000318	0.000227	0.008187
37	0.000297	0.000119	0.004150

Tables 1-3 show the most significant time and space harmonics for each operating condition. Time harmonic order is multiple of 18 because the number of slots per pole for analysis model is 9. Space even order harmonics are absent, because of the presence of odd symmetry in the flux space distribution.

Examining tables indicate that among the harmonics of time order 18, those of space 17 and 19 have highest magnitude, among the harmonics of time order 36, those of space order 35 and 37 have the highest magnitude. These are highlighted in the tables.

These harmonics are produced due to interaction of rotor fundamental harmonic with airgap permeance harmonics [6][7].

2.2 Analytical Method

The governing field equation, in terms of the Coulomb gauge, $\nabla \bullet A = 0$, is given by

$$\frac{\partial^2 A_z}{\partial x^2}+\frac{\partial^2 A_z}{\partial y^2}-j\omega\mu_i\sigma_i A_z=0 \tag{1}$$

where A_z is the magnetic vector potential, μ_i and σ_i denotes the permeability and conductivity of each layer, respectively. It is assumed that the magnet and shaft region have uniform permeability and conductivity, and the stator has zero conductivity, since it is laminated [4].

Neglecting end effect, the tangential and normal flux density in a particular layer can be obtained as follows

$$B_x=\frac{\partial A_z}{\partial y}=\alpha(C_i e^{\alpha y}-D_i e^{-\alpha y})e^{j(\omega t+qx)} \tag{2}$$

$$B_y=-\frac{\partial A_z}{\partial x}=-jq(C_i e^{\alpha y}+D_i e^{-\alpha y})e^{j(\omega t+qx)} \tag{3}$$

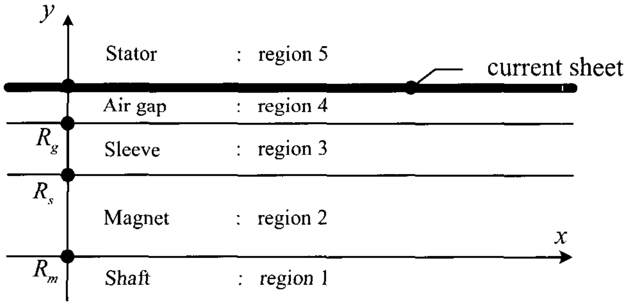

Fig. 3 Rectilinear current sheet model.

α is defined as follows

$$\alpha=\sqrt{q^2+j\omega\mu_i\sigma_i} \tag{4}$$

where, ω and q is the angular frequency and the phase constant of the traveling wave and defined as

$$\omega = 2\pi k f, \quad q = 2\pi / l \tag{5}$$

where, k is the time harmonic order, f is the input frequency and l is the wavelength of h th space harmonic order.

3. Rotor Loss Calculation

The Poynting vector is powerful means of obtaining the total power entering or leaving a region [3]. The Poynting vector, P, is defined in terms of the vector product of the electric field intensity and the magnetic field intensity over the surface of a region. For a sinusoidal electromagnetic field at steady-state, the average power transmitted through a surface is calculated using the Poynting vector in the following form

$$P = \frac{1}{2}\mathrm{Real}\left\{\left[E_{z_3}\right]_{y=R_g} \times \left[H^*_{x_3}\right]_{y=R_g}\right\} \tag{6}$$

where E_z is the amplitude of the electric field intensity in the axial direction and H_x^* is the amplitude of the conjugate of the tangential magnetic field intensity. Integrating (6) over the surface results in the total power transmitted through the surface [3].

Table 4 shows the rotor loss density under no-load condition for significant harmonics. Rotor losses are mainly due to the time harmonic order 18 with space harmonic order 17 and 18, as expected. The rotor loss density under stator-mmf only and on-load condition is in Table 5 and Table 6. As shown in tables, most significant harmonics are time order of 18, 36 with space order of 17 and 19, 35 and 37, as expected. Since, the relatively high conductivity of the retaining sleeve is used, most of the losses are in the retaining sleeve and permanent magnet, also as expected.

Table 4 Rotor Eddy Current Loss for No-Load Condition

Space order	Time order	
	18	36
1	0.0016	0.0029
5	0.0074	0.0078
13	0.0336	0.0069
17	63.5656	
19	53.1011	
35		8.7
37	0.0013	6.7
Total	P_{dens}=116.7(18th) +15.5(36th) =119.1(titanium sleeve)+13.1(magnet)	

Table 5 Rotor Eddy Current Loss for Stator-mmf only Condition

Space order	Time order	
	18	36
1		
5	114.7	
7	12.2	
13	9.0061	
17	237.895	
19	52.7469	
35		7.0849
37		0.5520
Total	P_{dens}=426.5(18th)+7.6(36th) =307.2(titanium sleeve) +125.0(magnet)+1.9(shaft)	

Table 6 Rotor Eddy Current Loss for On-Load Condition

Space order	Time order	
	18	36
1		
5	148.133	
7	13.277	
13	8.189	
15	1.2146	
17	319.019	
19	88.969	
23	0.333	
33		0.451
35		18.0165
37		3.913
Total	P_{dens}=579.4(18th)+22.4(36th) =446.8(titanium sleeve) +151.7(magnet)+3.3(shaft)	

4. Conclusion

For analysis on rotor eddy current loss, the coupled finite element method and analytical method was presented. One slot-pitch finite element model is used to calculate the traveling wave harmonics. Rectilinear current sheet model is represented by each traveling wave harmonic caused by airgap flux variation. And, the 2-dimensional diffusion equation is solved for each harmonic to calculate rotor eddy current loss. Using this method is simple and workable for any kind of stator slot shape. Moreover, it is useful to reduce the computation time and labor in rotor loss calculation for the harmonic component.

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