Proceedings of the Seventeenth International Workshop on Rare-earth Magnets and Applications,
Newark, Delaware, USA, 18-22 August 2002

MODELLING OF EDDY-CURRENT LOSSES IN A SURFACE-MOUNTED NDFEB PERMANENT-MAGNET GENERATOR

W. WU, J.B. DUNLOP, AND S.J. COLLOCOTT

CSIRO Telecommunications & Industrial Physics, PO Box 218, Lindfield, NSW 2070, Australia

In a surface-mounted sintered NdFeB permanent-magnet generator, the magnets are usually thin (typically 4 mm), and hence the armature reaction, due to the time harmonics in the stator currents, is high. NdFeB magnets are conducting (resistivity typically 1.6 μΩm) and experience eddy-current losses. Therefore, the combined eddy-current losses in the NdFeB magnets and a solid iron rotor may become significant. An increase in temperature from eddy-current losses can demagnetize the magnets, and high temperature may weaken structural adhesives, leading to the magnets detaching from the rotor backing-iron. A two-dimensional time-stepping finite element method is employed to examine the eddy-current losses under a typical stator phase current with a rectifier load. The calculated results are given. It is found that the eddy-current losses are dependent on the magnet thickness, air gap, magnet width, and rotor backing-iron structure (solid or laminated). The modelled generator, with 4 mm magnets and a 1.5 mm air gap, has eddy-current losses of more than 1% of its rated power output. The eddy-current loss in the rotor can be reduced by either increasing the magnet thickness and air gap length simultaneously, or using segmented magnets for each pole and laminated rotor backing-iron. The increase in magnet thickness and air gap length effectively reduces the effect of armature reaction, while segmenting the magnets and laminating the rotor backing-iron effectively reduces the eddy-current loop areas. Interestingly, laminating the rotor backing-iron on its own leads to a significant increase in eddy-current losses in the magnets and in the total eddy-current loss.

1 Introduction

Usually, eddy-current losses in the magnets and the rotor backing-iron of a permanent-magnet (PM) generator are neglected, since the fundamental air-gap field rotates in synchronism with the rotor, and the armature reaction, due to the time harmonics in the stator currents and the space harmonics in the winding distribution, is generally small. However, in a surface-mounted sintered NdFeB permanent-magnet generator (see Figure 1), the magnets are usually thin (typically 4 mm), and hence the armature reaction is high. NdFeB magnets are conducting (resistivity typically 1.6 μΩm) and experience eddy-current losses. Therefore, the combined eddy-current losses in the NdFeB magnets and a solid iron rotor may become significant.

High eddy-current losses in the magnets and rotor backing-iron can lead to an increase in temperature. High temperature can demagnetize the magnets, and may weaken structural adhesives, leading to the magnets detaching from the rotor backing-iron.

Many authors have presented predictions of rotor losses by using analytical methods [1] and finite element analysis [2]. Several techniques have been proposed to reduce the eddy-current losses in the magnets [3], for example, using a shielding cylinder around the magnets, segmenting and side-insulating the magnets etc. However, the effect of the rotor backing-iron structure (solid or laminated) on the total eddy-current losses has not been considered.

This paper presents a two-dimensional time-stepping finite element method to examine the eddy-current losses in a surface-mounted NdFeB PM generator under a typical stator phase current with a rectifier load. The PM generator and its moving boundary finite element model are described. The calculated results for eddy-current losses, for different magnet thickness, air gap length, magnet width (segmenting magnets per pole) and rotor backing-iron structure (solid or laminated), are given. Methods for reducing the eddy-current losses in the rotor are suggested.

2 PM Generator

The PM generator studied has a radial-flux, outer-rotor, slotted-stator and surface-mounted magnet topology, as shown in Figure 1. The permanent magnets are bonded to the inner surface of a steel drum that rotates around a stationary stator with conventional three-phase windings. An advantage of this arrangement is that the centrifugal force of the rotating magnets applies a pressure to the bonding media, therefore increasing the reliability of the glued joint.

The generator was developed for a stand-alone high-speed, high-efficiency generator system, in which the PM generator, attached to an internal combustion engine, supplies power to an electronic converter [4]. The 3-phase AC voltage from the generator is rectified into a DC link by a full-wave (FW) diode rectifier and then converted to a constant-frequency, constant-voltage AC output by an H-bridge inverter.

The permanent magnets used for the generator were sintered NdFeB magnets with a remanence of 1.19 T at 20 °C and a maximum energy product of 280 kJ/m^3. The resistivity of sintered NdFeB magnets is 1.6 μΩm. The thickness of magnets is 4 mm and the air gap length 1.5 mm.

Before rectification, the nominal power of the generator is 3.6 kW at a speed of 3000 rpm. Eight poles were chosen which corresponds to an output frequency of 200 Hz, at a rotor speed of 3000 rpm. The designed efficiency is 95%, with an assumption that the rotor eddy-current losses are 1% of the output power. This assumption may be appropriate for a generator with hard ferrite magnets, in which the use of a thick magnet (typically 10 mm) results in a small armature reaction. Ferrite magnets are insulators, and free from eddy-current losses. The eddy-current losses in the NdFeB magnets and the rotor backing-iron are analyzed using finite element analysis.

3 Finite Element Analysis

3.1 Fundamental equation

The fundamental equation of a two-dimensional magnetic field can be written by using the magnetic vector potential, *A*, as follows:

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right)=-J_s-J_M-J_e\,. \qquad (1)$$

where μ is the permeability, J_S the current density in the stator winding, J_M the equivalent magnetizing surface current density of the permanent magnets. The eddy-current density, J_e, is given by

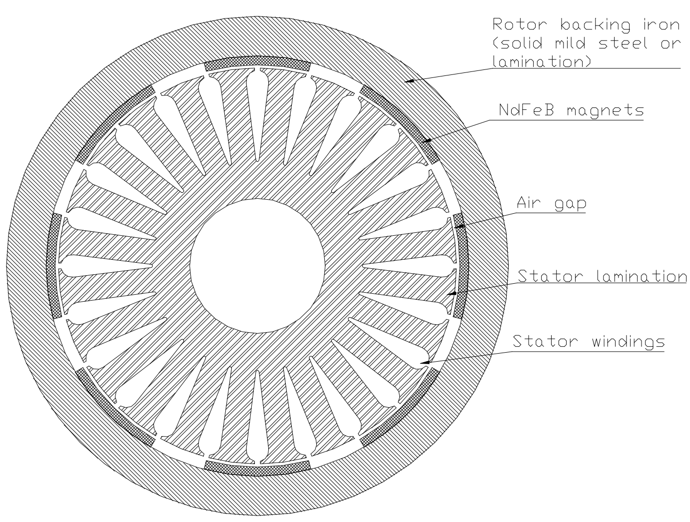


Figure 1. Cross-sections of the surface-mounted PM generator.

$$J_e = -\frac{1}{\rho}\left(\frac{\partial A}{\partial t} + grad\,\phi\right) \tag{2}$$

where ρ is the electrical resistivity and ϕ the time-integrated electric scalar potential. In a two-dimensional field, the total current in the sectional area of each magnet and the conducting rotor backing-iron should be zero, i.e.,

$$\int J_e ds = \int -\frac{1}{\rho}\left(\frac{\partial A}{\partial t} + grad\,\phi\right) ds = 0 \tag{3}$$

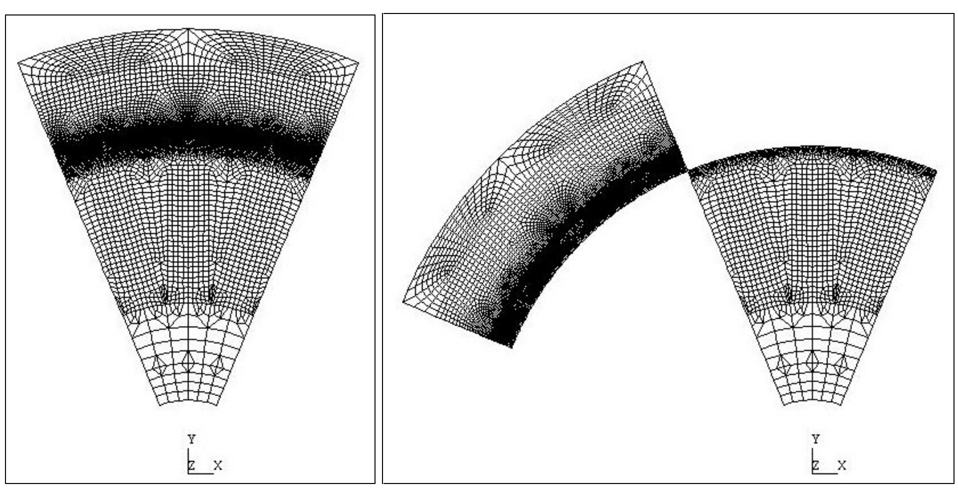
The two-dimensional magnetic field can be calculated by coupling Equations (1) to (3) with field boundary conditions.

3.2 Finite element model

The two-dimensional time-stepping finite element analysis was conducted by using a commercial package, ANSYS. Only one pole pitch of the generator need be studied, as the machine is periodically symmetrical for each pole under load conditions. The meshes for the stator and rotor were generated separately. A half slot pitch of the stator with half the air gap was meshed and mirrored to form one slot, and then copied to form one pole pitch. The same approach was applied to the rotor meshes. The rotor with half air gap meshes was rotated by the specified rotor position angle and joined to the stator mesh along the inner side of the half air gap by using coupling equations. One requirement of this method is to mesh the common side of the half air gap attached to the stator and rotor with the same number of divisions. There is then no need to re-mesh the model whenever the rotor rotates, which eliminates numerical errors due to an asymmetric mesh.

Figure 2 shows the meshes for two specified rotor positions. The nodes on the two radial edges are coupled by odd periodic boundary conditions. Surrounding air inside and outside the generator was modeled to a distance of 5 times the air gap radially, with no flux density beyond these boundaries.

Since eddy currents in the magnets and rotor backing-iron flow near their inner surfaces, the mesh size for the region of interest should be less than their skin depth. For a frequency of 200 Hz, the skin depths of the magnet and solid rotor backing-iron are approximately 43 mm and 0.44 mm, respectively. It can be seen from Figure 2 that very dense meshes were used for the magnet and the rotor backing-iron.



(a) Rotor at 0° (electrical) (b) Rotor at 180° (electrical)

Figure 2. Finite element meshes.

The magnetic non-linearity of the stator lamination and rotor backing-iron (lamination or solid mild steel) was represented by their single-valued B-H characteristics. Since the induction curve of the NdFeB magnets is linear, they can be simply approximately as fixed permeability in all directions and a remanence in the magnetised direction. The winding was modelled as air.

The finite element model of one pole region consisted of 17445 elements and 17332 nodes. The magnetic field over a complete electrical cycle was calculated in 241 discrete equidistant time steps by rotating the rotor position and simultaneously changing the stator excitation. The instantaneous eddy currents in each element in the conducting regions of magnets and the solid rotor backing-iron were calculated and the total eddy-current losses were determined as the sum of Joule loss in each element. Since the magnets have been treated as an equivalent current source, the results accounted for the eddy-current loss component caused by the variation of the magnet working point due to the stator slotting.

4 Results and Discussion

Assuming a typical phase current of the rectifier load as shown in Figure 3(a), the transient performance of the generator was calculated in each time step. For a generator with one 4 mm thick NdFeB magnet segment for each pole and a 1.5 mm air gap, Figure 3 shows the variation of the induced phase emf, electromagnetic power and eddy-current losses with the rotor position at a speed of 3000 rpm. It can be seen that, although the rotor rotates in synchronism with the fundamental component of the stator field, the time harmonics in the stator currents and the space harmonics due to the stator slotting cause a magnetic flux fluctuation in the magnets and rotor backing-iron, resulting in eddy-current losses.

The eddy-current losses are dependent on the magnet thickness, air gap, magnet width, and rotor backing-iron structure (solid or laminated). Figure 4 shows the flux plots of the generator with 4 mm magnets and solid rotor backing-iron. Table 1 gives the calculated results of eddy-current losses under full load at 3000 rpm, for different magnet thickness, air gap length, magnet width, and rotor backing-iron structure (solid or laminated). It is found that a generator with 4 mm NdFeB magnets and a 1.5 mm air gap would produce eddy-current losses of 47.4 W (average) at 3.6 kW output, which is higher than the assumed 1%.

The eddy-current loss in the rotor can be reduced by either increasing the magnet thickness and air gap length, or using segmented magnets for each pole together with laminating the rotor backing-iron. An increase in magnet thickness and air gap effectively reduces the effect of armature reaction, while segmenting the magnets and laminating the rotor backing-iron effectively cuts the eddy-current loops. Interestingly, laminating the rotor backing-iron on its own leads to a large increase in eddy-current losses in the magnets and an increase in the total eddy-current loss. Although the reduction in eddy-current losses by increasing the magnet thickness and air gap length simultaneously is significant, the material cost of the magnets would be doubled. The most effective method to reduce the eddy-current losses is to increase the number of magnet segments per pole [1]. Segmenting the magnets and laminating the rotor backing-iron lead to a greater reduction in losses.

Table 1. Eddy-current losses in the rotor predicted by a two-dimensional time-stepping FEA.

Magnet thickness, mm	4.0	4.0	4.0	4.0	8.0	8.0	8.0	8.0
Air gap, mm	1.5	1.5	1.5	1.5	3.0	3.0	3.0	3.0
Rotor backing-iron, solid (S) or laminated (L)	S	L	S	L	S	L	S	L
Magnet segments per pole	1	1	2	2	1	1	2	2
Eddy-current loss in magnet, W	28.0	53.5	13.9	25.0	15.8	24.4	7.1	11.3
Eddy-current loss in the rotor backing-iron, W	19.4	0	24.5	0	6.2	0	8.5	0
Total eddy-current loss, W	47.4	53.5	38.4	25.0	22.0	24.4	15.6	11.3

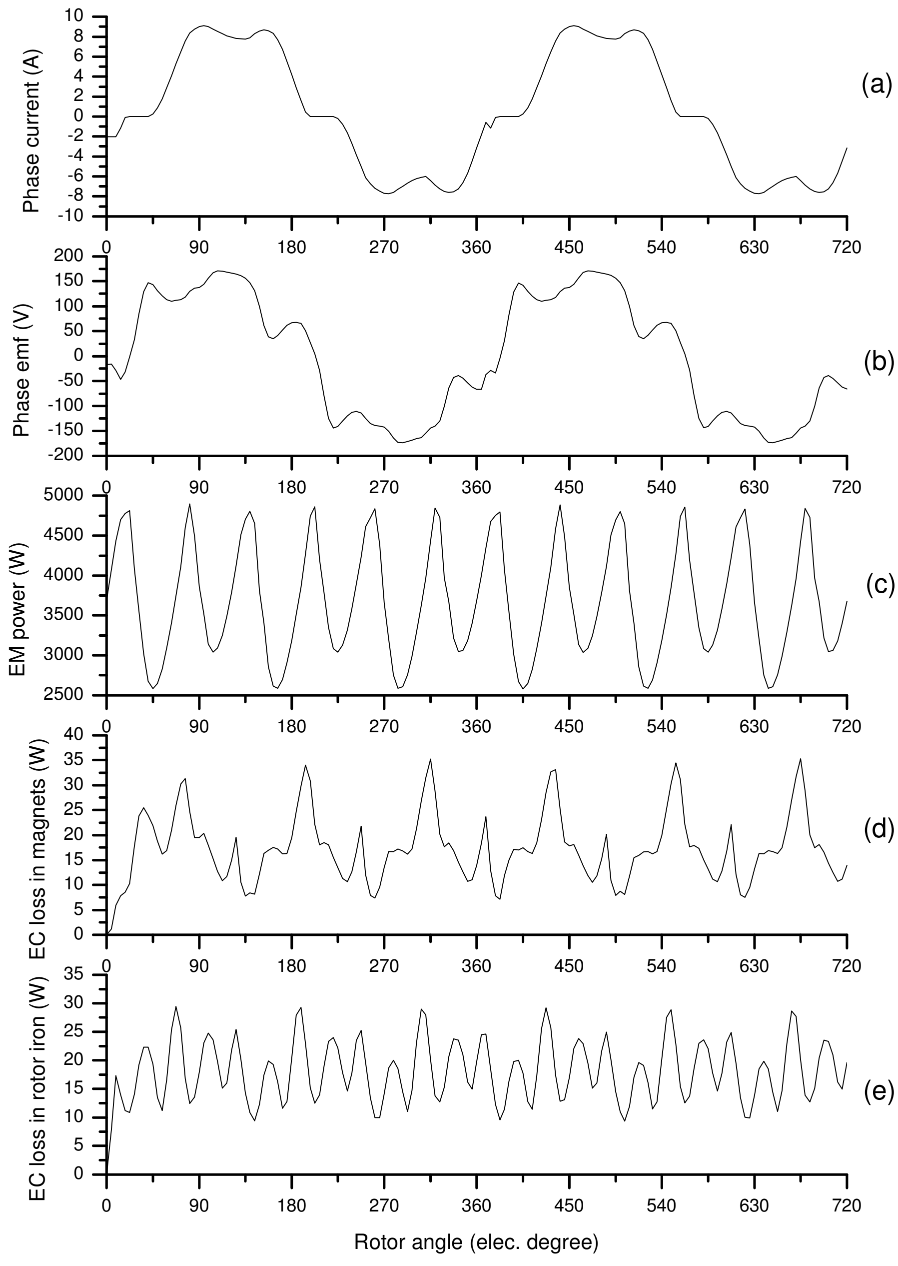
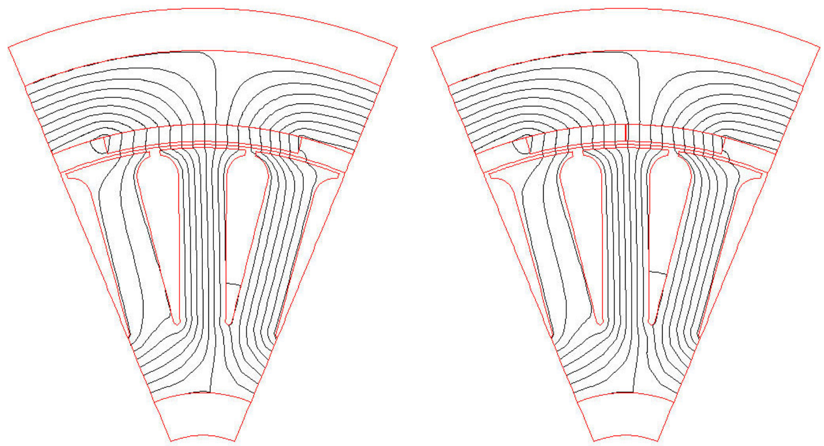


Figure 3. Stator phase current (A), stator phase emf (V), electromagnetic power (W), eddy-current losses (W) in the magnets and rotor backing-iron, for a PM generator with 4 mm thick magnets and 1.5 mm air gap, rotating at 3000 rpm.



(a) One-segment magnet for each pole (b) Two-segment magnets for each pole

Figure 4. Flux plot of the generator when rotor is at 360 ° (electrical).

5 Conclusions

A two-dimensional time-stepping finite element method for predicting the eddy-current losses induced in the permanent magnets and solid rotor backing-iron of a PM generator has been presented. It has been shown that the effect of the rotor backing-iron structure (solid or laminated) on the eddy-current loss in magnets is very significant. With one magnet segment per pole, the total eddy-current loss is increased by 13% by laminating the rotor backing-iron. With two or more segments of magnet per pole, the total eddy-current loss is reduced by laminating the rotor backing-iron, although the eddy-current loss in magnets themselves actually increases compared with the solid rotor backing-iron. Increasing the magnet thickness and air gap length simultaneously can be a very effective means of reducing eddy-current losses, but increases the material cost of magnets.

6 Reference

1. K. Atallah, D. Howe, P.H. Mellor and D.A. Stone, Rotor loss in permanent-magnet brushless AC machines, *IEEE Transactions on Industry Applications*, Vol. 36, No. 6, pp1612-1618 (2000).
2. Y. Kawase, T. Ota and H. Fukunaga, 3-D eddy current analysis in permanent magnet of interior permanent magnet motors, *IEEE Transactions on Magnetics*, Vol. 36, No. 4, pp1863-1866 (2000).
3. H. Polinder and M.J. Hoeijmakers, Eddy-current losses in the segmented surface-mounted magnets of a PM machine, *IEE Proc.-Electr. Power Appl.*, Vol. 146, No. 3, pp261-266 (1999).
4. M.J. Ryan and D. Lorenz, A “power-mapping” variable-speed control technique for a constant-frequency conversion system powered by a IC engine and PM generator, *Conference Record of the 2000 IEEE IAS Annual Meeting*, Roma, Italy, pp2376-2382 (2000).