Magnet eddy current loss calculation method for segmentation analysis on Permanent Magnet Machines

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Abstract

Eddy current losses generated in the rotor of permanent magnet machines may lead to an excessive magnet heating. This can cause the magnets to get fully demagnetized so it is very important to analyze the losses on them. In high power application usually it is necessary to design solutions to reduce eddy current losses. The most common technique is the magnet segmentation. Analytical calculation of magnet eddy current losses may give some inaccuracies on the results and FEM analysis may be too time-consuming in some design steps. A new method that combines FEM and numerical calculations to evaluate the losses for different magnet segmentation is presented in this paper.

I. Introduction

Permanent magnet (PM) machines have been increasingly used in a wide variety of applications such as train traction, elevation, electric and hybrid vehicle or power generation [1-3]. Until now, in such applications where a high power is desired, induction machines (IM) have been preferred due to their great robustness. But with the latest trends in energy efficiency, a technological leap towards permanent magnet synchronous motors (PMSM) has been stimulated, due to their high power density and efficiency. However, the use of magnets implies a precise design of the thermal behavior of the rotor, because a high temperature in the magnet reduces its performance and increases the risk of magnet demagnetization. The magnet is heated due to the hot components of the machine (stator core, stator winding). In addition, the magnets are exposed to a time varying magnetic field which induces eddy current (EC) losses on them. Even though these rotor losses are not in general an efficiency problem, they can lead to magnet overheating. A high temperature reduces the magnet performance and increases the risk of magnet demagnetization. Therefore, it is important to understand the causes of EC losses in the magnets.

The demagnetization problem analysis can be separated in two phases: First, the losses have to be computed or calculated and then a thermal model has to be employed in order to evaluate if these losses overheats the magnet.

The aim of this article is to investigate the EC losses induction mechanism due to spatial distribution of the stator windings in surface permanent magnet synchronous machines (SPMSM) with a technique which mixes analytical and computing tools. In addition, the magnet circumferential segmentation [4], [5] is studied and the reduction of permanent magnet losses is analyzed.

The EC losses in SPMSM can be resistance limited [4-10], or not-resistance limited [11], [12]. The resistance limited eddy currents are characterized by low frequency components which lead to typically a uniform distribution of the losses across the radial axe of the magnet. In other words, the losses are not induced in a skin depth due to the low frequency of the harmonics which induce the losses. The opposite case is the non resistance limited eddy current losses. In this case the losses are induced in a narrow area of the magnet (skin depth) due to the high frequency harmonics involved in the eddy currents induction.

In this study, only resistance limited losses will be considered. In the literature, the resistance limited EC losses in the magnets are studied either analytically [5], [7-9], [13], which may lead to some inaccuracies because they do not take into account the non-linearity effects of the BH curve of the stator and rotor core, or by finite element analysis (FEM) [14-16]. In this case, the results are more accurate, but computation may be quite time-consuming. Moreover, the FEM analysis time increases even more when loss reduction mechanisms such as segmentation are analyzed. A fast design tool for the correct segment number selection is desirable for a rapid machine design.

In this paper, the FEM models have been combined with existing analytical tools in order to achieve a PM losses calculation method that lets us analyze the effect of different magnet segmentations. This solution considers the non linear BH curve of the magnetic steel, and at the same time it requires an easy and quick FEM analysis.

II. EC loss analysis

A. Obtaining the magnetic field by means of FEM simulations

Finite element simulations give accurate results but they can be excessively time consuming depending on what magnetic effects want to be considered. In order to analyze the effect of different magnet segmentations, one simulation per configuration must be carried out, which is quite tedious. The idea presented in this paper is to do a 2D FEM simulation for a non-segmented magnet machine and measure the magnetic field generated by the stator winding for different magnet radius. In the case of non resistance limited EC losses, the flux density distribution on the magnets do not change with the different segmentations because the reaction magnetic field of EC is negligible.

For this, a path is created drawing the trajectory that a magnet will take through a whole rotation period at a certain radius. The magnet, at the initial time step, will be at a corner of this path and at the last one it will be at the other corner. This way, for each simulation time step, a data array will be saved containing the flux density on the path. Part of this data array will correspond to the magnet and the rest will correspond to the air.

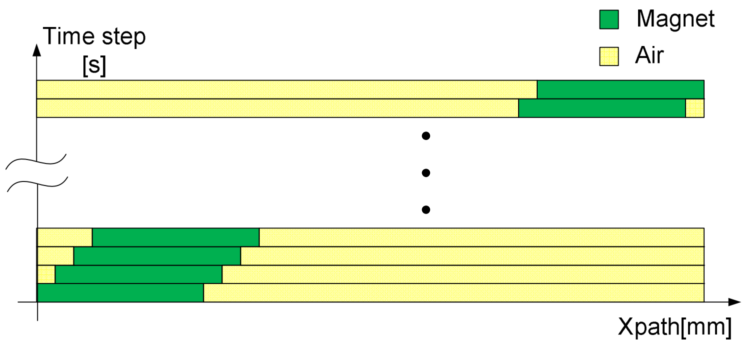

Figure 1 Structure of the data acquisition from FEM simulation

A more simple approach would be to do a path that moves along with the magnet, saving only the information related to the flux density in the magnet, but the used software was not able to do this.

B. Converting the field to the rotor reference frame

Once we have the magnetic field in a certain radius, the field must be transformed to the moving rotor frame. This way, we have a data matrix that represents the magnetic field that sees the magnet along its arc through a whole period of time as shown in Figure 2.

This FEM simulation only has to be carried out once for every machine that is being analyzed, because the magnet segmentation does not affect the flux density in the magnets. Thus, we achieve a high precision in the computation of the flux density, which is quite tough to obtain analytically, and the eddy current losses that occur in the magnets for a given segmentation can be obtained by applying the equations explained in the next section.

C. Calculating the EC losses

The magnetic field on the magnets will be bigger at a radius close from the airgap, and it will weaker as the radius is smaller. For simplicity, the flux density will be assumed to be the same through a certain radial section of the magnet (small section). For this reason, depending on the height of the magnets, a single FEM computation of the magnetic field at a certain radius will be enough. As the magnet height increases, more paths at different radii will need to be analyzed.

For the calculation of the magnet losses, first the induced eddy-current density in the permanent magnet arc segments has to be obtained. This is done by solving the following equation, which is derived from Maxwell's second equation:

$$Jm(t,\theta) = -\frac{1}{\rho} \cdot \int \frac{\partial B(t,\theta)}{\partial t} \cdot r \, d\theta + C \qquad (1)$$

Where ρ is the electrical resistivity of the PMs, θ is the magnet arc, r is the radius and C is an integration constant which ensures zero net total current flow in each magnet segment at any instant:

$$\int Jm \cdot r \, d\theta = 0 \qquad (2)$$

Finally, the power losses per segment are obtained from the following equation:

$$P = \frac{L}{T} \cdot \int_{0}^{T} \int_{\alpha_1}^{\alpha_2} \int_{R_1}^{R_1} \rho \cdot Jm^2 rdr\, d\theta\, dt \qquad (3)$$

Where L is the machine axial length and T is the time period, α_1 and α_2 are the magnet segment arc limits and R_1 and R_2 are the inner and outer radius of the magnet.

In this way, with only one 2D FEM simulation, we can calculate the permanent magnet losses for any magnet circumferential segmentation with a considerably good accuracy. Repeating the computation for a large amount of segmentation possibilities the best solution can be obtained.

III. Application Example

A. Verification of the method by 2D-FEM

As an example, a 3 pole-pair 36 slot surface mounted permanent magnet machine has been simulated on FEM-2D to confirm the validity of the proposed method. Both the stator and the rotor are made of laminated steel and the residual flux density (B_r) of the magnets is 1.1T and the relative permeability (μ_r) 1.09. More characteristics of the machine are shown on Table I.

The number of time steps per simulation is 1000 and the number of points of the path is 1420 of which 420 correspond to the magnet surface. This way, the magnet will move forward one path point every time step. A picture of the machine and its corresponding path is shown in Figure 2 (left).

Table I

Phases	3 phases
Poles	6 poles
Number of stator slots	36
Frequency	89,4Hz
Feeding current	245Aeff
Magnet type, Magnetization	Ne-Fe-B, 1.1T μ_r=1.09
Conductivity of magnet	$1{,}47.10^{-6}$ Ω.m

After converting the flux density to the rotor reference frame, the magnetic field on a magnet at a certain radius for every instant in a period is obtained, as shown on Figure 2 (right). With this data, the current density and the power losses due to eddy currents can be obtained.

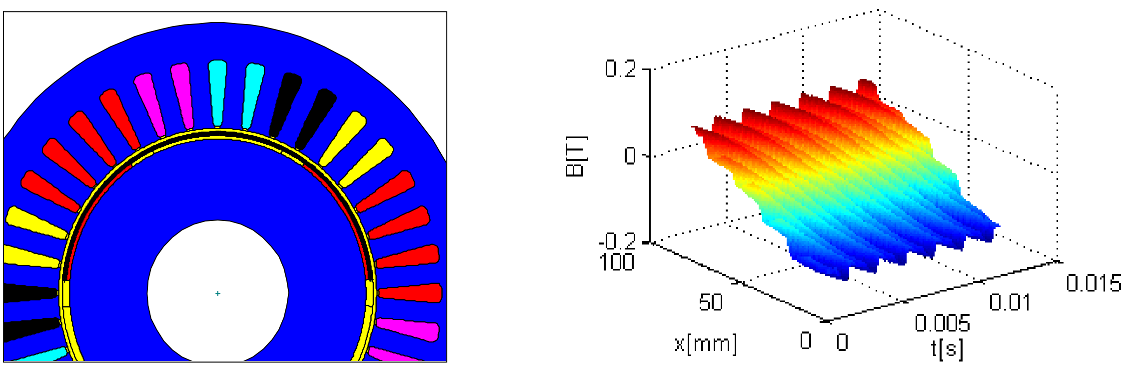

Figure 2 Path drawn in the analyzed machine (left) and magnetic field along the magnet arc through a whole rotation period (right)

First, the current density has to be obtained by applying equations (1) and (2). The result is a current density distribution through the arc of the magnet, composed by one or several magnet segments, at a certain radious.

In Figure 3, the current density at a certain time instant obtained for three different magnet segmentations are shown. The segmentations employed are 1, 4 and 10 segments respectively. Results obtained with the proposed method are superimposed to those obtained by a finite element analysis. As it can be seen, the proposed method is quite accurate when compared to the results obtained by FEM.

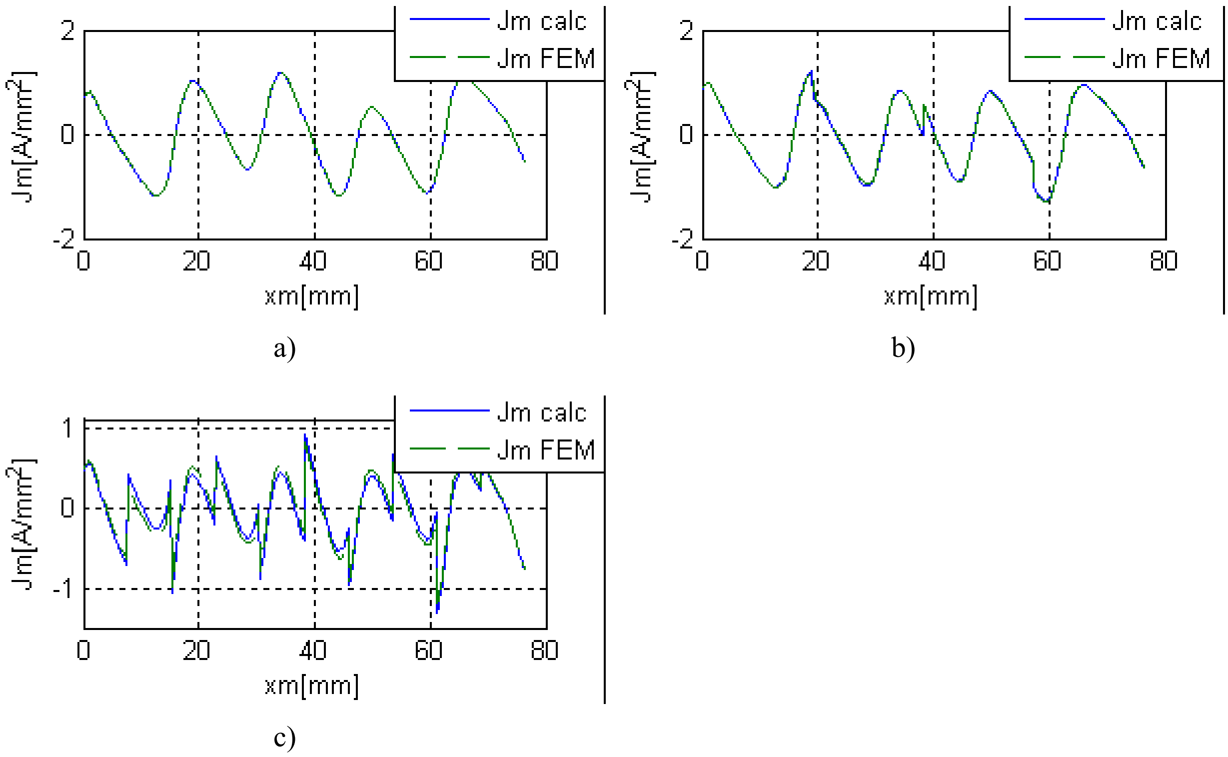

Figure 3 Current density calculated with the explained method and with FEM in one magnet. a) One segment, b) 4 segments and c) 10 segments.

In Figure 4 eddy current losses in one magnet are shown for the previous three segmentations. The losses are calculated by means of equation (3). As the current density is only calculated for a certain radius, a radially uniform current density distribution is assumed through the magnet. This way, the flux density measurement from FEM at one single radius is enough for the total magnet EC losses calculation.

As it can be seen, the results show a high degree of accuracy when comparing them to the ones obtained with FEM.

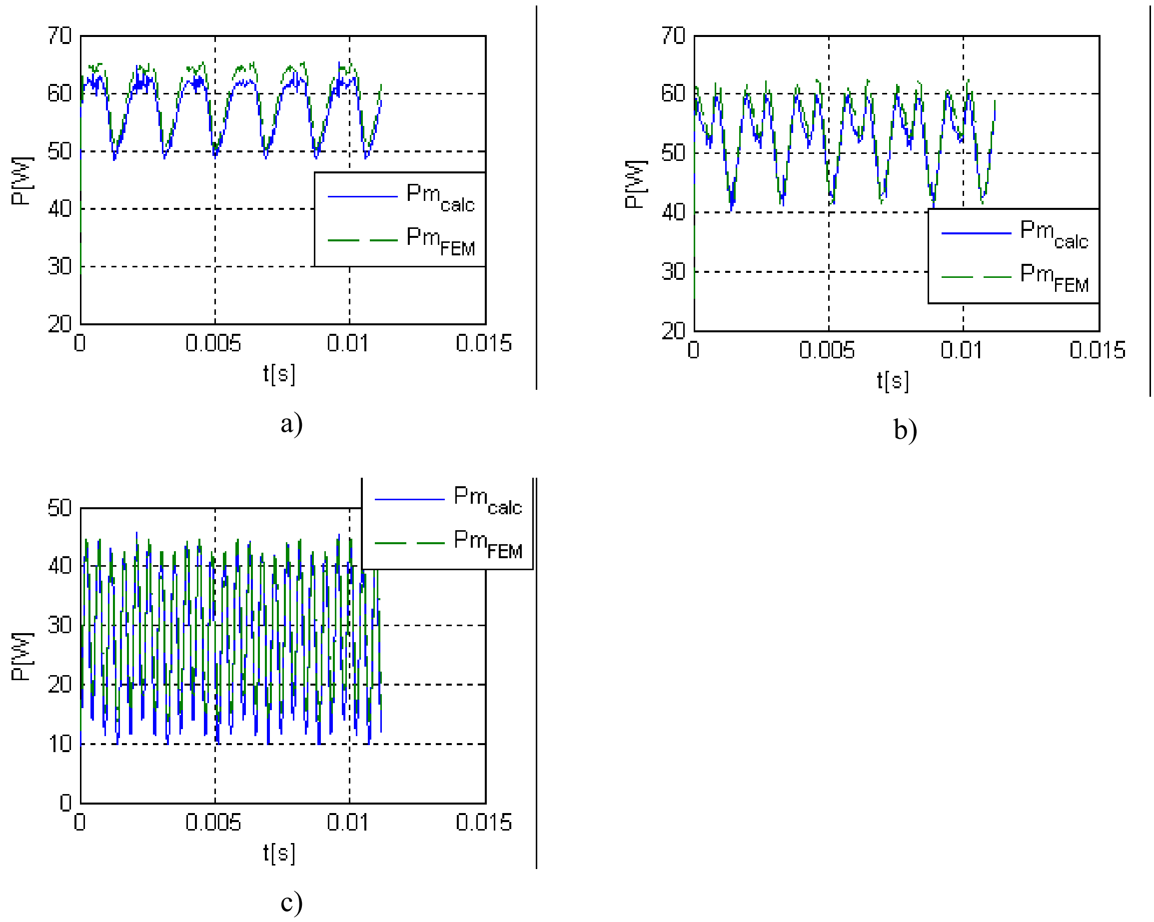

Figure 4 PM losses calculated with the explained method and with FEM in one magnet. a) One segment, b) 4 segments and c) 10 segments.

B. Segmentation number selection

The proposed method has been applied to the machine described in Table I. A circumferential segmentation from one single segment to 16 segments has been applied so that the effects of the segmentation in the eddy current losses could be analyzed.

Time-wise, the loss calculation for each segmentation try is done in less than 10 seconds. For the total time, the time consumed in the initial FEM simulation must be added. If this was intended to be done with a FEM simulation for each segmentation try, the time employed would be much higher. First the geometry with the required segmentation would have to be drawn, then the simulation would need to be carried out and finally the results would need to be analyzed. And this has to be done for every desired segmentation tries. So the saved time by employing the proposed method is considerably high.

Figure 5 shows the total eddy current losses on the magnets depending on the number of segments for the proposed machine. By analyzing the figure, it can be noted that the loss reduction has an increasing tendency until it arrives to 8 magnet segments. From there on, although the losses are still reduced, the reduction has a decreasing tendency.

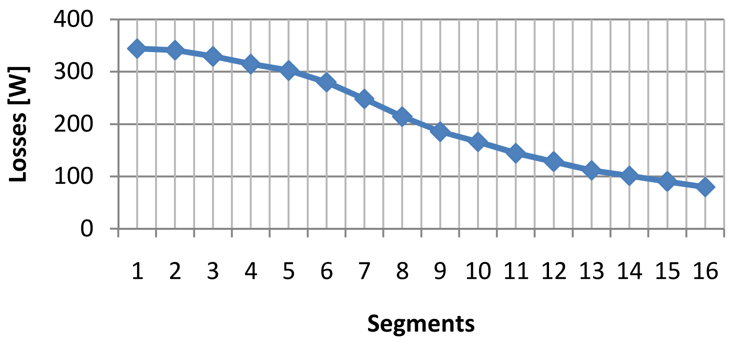

Figure 5 Reduction of the eddy current losses by circumferential segmentation of the magnets.

C. Segmentation length selection

Usually uniform segments are employed to reduce EC losses. However the possibility of having unequal magnet segments for one pole is opened. This possibility is hardly evaluated by FEM due to the number of possibilities which will require a different FEM model for each one. With the method proposed in the paper the evaluation of different segments' length can be easily carried out. As an example three segments have been selected and the optimum magnet length has been looked for. For simplicity the two segments in the corner have been considered to be equal. Although the three segments' variation can be considered with this model, the segments variation under this restriction clearly show that the unequal magnet length can reduce the magnet losses.

Figure 6 shows the losses on the 3 segment magnet machine. The red bar represents the losses when the three segments are equal. For the other bars, the width of the two segments in the corners is the same and it is changed from 1/12th to 0.45 of the total width of the magnet.

As it can be seen in Figure 6, if a segment length of 0.1 in the corners is chosen (which makes the center segment 0.8), the total losses can be reduced in a 6% compared to the equally segmented configuration. This can lead to a study of alternative segmentation methods where the width of each segment is changed randomly and the results are studied, in order to achieve an optimum loss reduction.

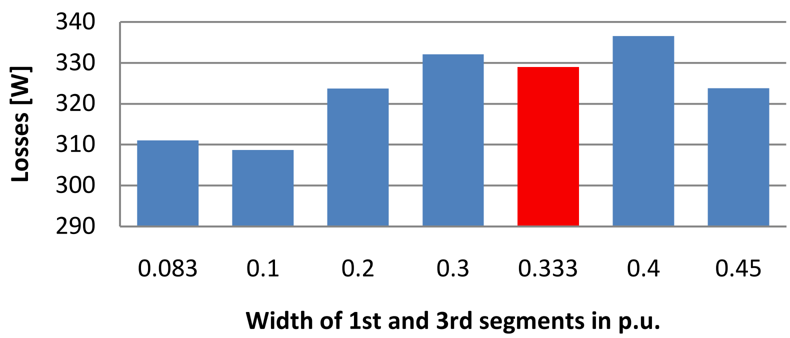

Figure 6 Three segment magnets with different width segments.

IV. Conclusions

In order to avoid magnet demagnetization due to excessive heating, Eddy current losses need to be analyzed in the design stages. This article presents a method that combines existing tools to achieve a time efficient and accurate EC loss obtaining approach for magnet segmentation analysis.

This agile method allows the designer to optimize the segment number selection in a very short time period comparing with FEM simulations. Moreover, non uniform segmentation, which can take a long time to evaluate with FEM simulations, can be easily studied with this method. This can lead to more publications in the near future.

V. References

[1] J. F. Gieras and N. Bianchi, "Electric motors for light traction,"2004.

[2] Takanori Komatsu and Akihiro Daikoku, "Elevator Traction Machine Motors," Japan: Mitsubishi Electric, 2003.

[3] C.Peter Cho, "Permanent Magnet Motors/Generators For Automotive Applications,"2009.

[4] H. Polinder, H. Polinder, and M. J. Hoeijmakers, "Eddy-current losses in the segmented surface-mounted magnets of a PM machine," *Electric Power Applications, IEE Proceedings -*, vol. 146, no. 3, pp. 261-266, 1999.

[5] K. Atallah, D. Howe, P. H. Mellor, and D. A. Stone, "Rotor loss in permanent-magnet brushless AC machines," *Industry Applications, IEEE Transactions on*, vol. 36, no. 6, pp. 1612-1618, 2000.

[6] M. Mirzaei, A. BInder, and C. Deak, "3D Analysis of Circumferential and Axial Segmentation Effect on Magnet Eddy Current Losses in Permanent Magnet Synchronous Machines with Concentrated Windings," *International Conference on Electrical Machines ICEM*, 2010.

[7] M. Markovic and Y. Perriard, "A simplified determination of the permanent magnet (PM) eddy current losses due to slotting in a PM rotating motor," Wuhan.: 2008, pp. 309-313.

[8] Z. Q. Zhu, K. Ng, N. Schofield, and D. Howe, "Analytical prediction of rotor eddy current loss in brushless machines equipped with surface-mounted permanent magnets. I. Magnetostatic field model,", 2 ed Beijing, China: Int. Acad. Publishers, 2001, pp. 806-809.

[9] W.-Y. Huang, A. Bettayeb, R. Kaczmarek, and J.-C. Vannier, "Optimization of Magnet Segmentation for Reduction of Eddy-Current Losse in Permanent Magnet Synchronous Machine," *IEEE Transactions on energy conversion*, vol. 25, no. 2, pp. 381-387, 2010.

[10] J. Wang, K. Atallah, R. Chin, W. M. Arshad, and H. Lendenmann, "**Rotor Eddy-Current Loss in Permanent-Magnet Brushless AC Machines**," *IEEE Transactions on Magnetics*, vol. 46, no. 7, pp. 2701-2707, 2010.

[11] Z. Q. Zhu, K. Ng, N. Schofield, and D. Howe, "Analytical prediction of rotor eddy current loss in brushless machines equipped with surface-mounted permanent magnets. II. Accounting for eddy current reaction field,", 2 ed Beijing, China: Int. Acad. Publishers, 2001, pp. 810-813.

[12] Z. Q. Zhu, D. Howe, and C. C. Chan, "Improved analytical model for predicting the magnetic field distribution in brushless permanent-magnet machines," *Magnetics, IEEE Transactions on*, vol. 38, no. 1, pp. 229-238, 2002.

[13] J. D. Ede, K. Atallah, and G. W. Jewell, "Effect of Axial Segmentation of Permanent Magnets on Rotor Loss in Modular Permanernt-Magnet Brushless Machines," *IEEE transactions on industry applications*, vol. 43, no. 5 2007.

[14] P. Rasilo and A. Arkkio, "Modeling the Effect of Inverter Supply on Eddy-Current Losses in Synchronous Machines," *Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, pp. 861-865, 2010.

[15] P. Sergeant and A. Van den Bossche, "Segmentation of Magnets to Reduce Losses in Permanent-Magnet Synchronous Machines," *IEEE Transactions on Magnetics*, vol. 44, no. 11, pp. 4409-4412, 2008.

[16] K. Yoshida, Y. Hita, and K. Kesamaru, "Eddy-Current Loss Analysis in PM of Surface-Mounted-PM SM for Electric Vehicles," in *12th Conference of the Computation of Electromagnetic Fields (COMPUMAG '99) Oct. 1999,* 36 ed USA: IEEE, 2000, pp. 1941-1944.