Eddy Current Reduction in High-Speed Machines and Loss Analysis with Multislice Time-Stepping Finite-Element Method

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Abstract — Eddy-current in high-speed permanent magnet (PM) machines is a critical factor affecting the machine's efficiency or even demagnetizing the PMs because of overheating problems. It is necessary and important to accurately estimate the eddy-current loss and search for the optimal design to minimize the loss and improve the machine's performance. In this paper, the axial segmentation of PMs is proposed to cut off the eddy-current axial paths. Secondly, a conductive shield is adopted to smoothen the time varying magnetic fields in both the conductive sleeve and the PMs to reduce the eddy-current loss. A nodal method based network-field coupled multi-slice time-stepping finite element method (TS-FEM) is presented to analyze the steady-state and dynamic characteristics of the high-speed PM machine; its merit is that sub-block matrixes of the circuit equations can be established more conveniently when compared with that of mesh method. The analysis of eddy-current loss in the rotor is described in details.

I. INTRODUCTION

For high-speed permanent magnet (PM) machines, a high-strength conductive retaining sleeve outside the rotor is usually used to ensure safe and reliable operation. Due to the relatively high eddy-current loss in the conductive materials, overheating or demagnetization may appear to downgrade the machine's efficiency. In order to minimize the eddy-current loss, the PMs can be segmented into several slices to cutoff the eddy current paths. A thin shield with high conductivity materials, such as copper, is also inserted between the containing sleeve and the PM to reduce the effect of the time varying fields in the PMs and the sleeve [1].

Generally the eddy-current loss is computed using 2-dimensional (2D) finite-element method (FEM) on the assumption that i) the machine has an infinite axial length and ii) the voltage drop between the two terminals of the solid conductor is zero [2]. However these assumptions are unrealistic in practice. A 3-dimensional (3D) eddy-current FEM model can be established to accurately analyze the eddy current loss in the machines. However, the computing time is excessive and pre- and post- processing of the modeling is complex. A mesh method based network-field coupled multislice time-stepping finite-element method (NF-TS-FEM) is proposed to estimate the eddy-current loss in the PMs of the electric motors [3]. Compared with the 3D FEM model, the computing time of the proposed algorithm is greatly reduced. However, in the eddy-current region, because of the additional unknown i introduced into the branch equations, the modeling of machine is complicated. If the network is complex, it is also inconvenient to establish the mesh-to-branch incidence matrix. In this paper, a nodal method based NF-TS-FEM is proposed to analyze the eddy-current loss in high-speed PM machines. The PMs, sleeve, shield are divided into several "conductor bars", each of which is dealt as a solid conductor. Compared with mesh method based NF-TS-FEM, the proposed modeling is considerably simplified and easy to implement.

In this paper, the PMs are axially split into several segments to cut off the eddy-current paths and reduce the eddy-current loss. A copper shield is proposed to smoothen the time varying field to further minimize the eddy-current loss in the rotor of the high-speed PM machine. A nodal method based NF-TS-FEM is utilized to optimize the design of the conductive shield and segmentations of the PMs.

II. NODAL METHOD BASED NF-TS-FEM

To accurately analyze the eddy-current loss in the rotor of the high-speed PM machine and avoid time consuming and complicated 3D dimension modeling, a nodal method based NF-TS-FEM is proposed to accurately analyze the eddy-current loss in the machine.

Based on the Maxwell's equations, the field equations in the airgap and iron core domains is [4]

$$\nabla \cdot (\nu \nabla A) = 0 \tag{1}$$

where A is the axial component of the magnetic vector potential and υ is the reluctivity of the material.

In the rotor conductor domain, the PMs, sleeve or shield are divided into several "solid conductor bars" and the application of Maxwell's equations in these domains will give rise to:

$$\nabla \cdot (\nu \nabla A) - \sigma \frac{\partial A}{\partial t} + \frac{d_f \sigma}{l} u_{bar} = 0 \tag{2}$$

where, u_{bar} is the voltage difference between the two terminals of one solid conductor bar, d_f is the signature to represent forward or return paths.

In the rotor domain, the key is to model the PMs, shield and sleeve by a network having N bars along the circumferential direction and M slices along the axial direction, as shown in Fig. 1. It can be seen that the eddy-current flow forms a complete loop which enhances the accuracy in the computation of the eddy-current loss. The inter-bar resistance and the end resistance are respectively given by $R_i = b_P / N\sigma l_M h$, $n = 1,2,\ldots,N$, and $R_k = 2R_i$, where $l_M = l_P / M$ is the axial length of the n^{th} bar of the m^{th} slice, l_P is the axial length and b_P is the width. The depth of penetration of the PMs and rotor iron core is

$\delta = \sqrt{2/\omega\mu\sigma}$. If $\delta < h_P$, it yields $h = \delta$; otherwise, if $\delta > h_P$, it yields $h = h_P$, where h_P is the thickness of the PMs, shield and sleeve.

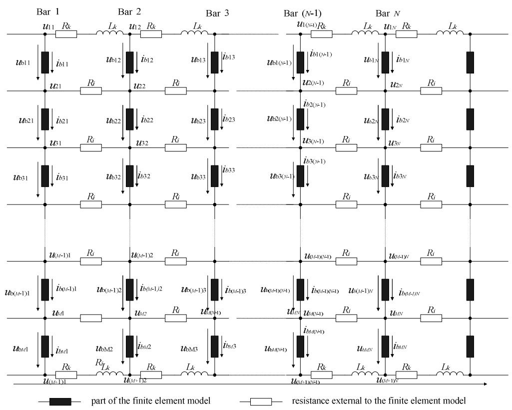


Fig. 1. Nodal method based network model for the rotor.

The relationship between the branch voltage u_b and the nodal voltage u_n is :

$$\begin{bmatrix} u_{bm1}\\ u_{bm2}\\ u_{bm3}\\ \vdots \\ u_{bmN}\end{bmatrix} = \begin{bmatrix}1&0&0&&0\\0&1&0&&0\\0&0&1&\cdots&0\\&&\vdots&\ddots&\\0&0&&0&1\end{bmatrix}\begin{bmatrix} u_{m1}\\ u_{m2}\\ u_{m3}\\ \vdots \\ u_{mN}\end{bmatrix} - \begin{bmatrix}1&0&0&&0\\0&1&0&&0\\0&0&1&\cdots&0\\&&\vdots&\ddots&\\0&0&&0&1\end{bmatrix}\begin{bmatrix} u_{(m+1)1}\\ u_{(m+1)2}\\ u_{(m+1)3}\\ \vdots \\ u_{(m+1)N}\end{bmatrix} \tag{3}$$

Using the Galerkin Method, the coupled field and circuit equations in the magnetic field region is written as:

$$\begin{bmatrix} C_{11} & C_{12} & C_{13}\\ 0 & C_{22} & 0\\ 0 & 0 & C_{33}\end{bmatrix}\begin{Bmatrix} A\\ e\\ u_f\end{Bmatrix} + \begin{bmatrix} D_{11} & 0 & 0\\ C_{12}^T & 0 & 0\\ C_{13}^T & 0 & 0\end{bmatrix}\begin{Bmatrix} \dfrac{\mathrm{d}A}{\mathrm{d}t}\\ \dfrac{\mathrm{d}e}{\mathrm{d}t}\\ \dfrac{\mathrm{d}u_f}{\mathrm{d}t}\end{Bmatrix} = \begin{Bmatrix} 0\\ 0\\ -\dfrac{1}{lp}i_f\end{Bmatrix} + \begin{Bmatrix} P_A\\ 0\\ 0\end{Bmatrix} \tag{4}$$

Using the back Euler's equation, after coupling the branch equations of external circuits, it has,

$$\begin{bmatrix} C_{11}+\dfrac{D_{11}}{\Delta t} & C_{12} & C_{13} & 0\\ C_{12}^T & \Delta t C_{22} & 0 & 0\\ C_{13}^T & 0 & \Delta t C_{33} & 0\\ 0 & 0 & 0 & -\dfrac{\Delta t}{lp}G_e\end{bmatrix}\begin{Bmatrix} A^k\\ e^k\\ u_f^k\\ u_e^k\end{Bmatrix} = \begin{Bmatrix} 0\\ 0\\ -\dfrac{\Delta t}{lp}i_f^k\\ -\dfrac{\Delta t}{lp}i_e^k\end{Bmatrix} + \begin{Bmatrix} P_A+\dfrac{D_{11}}{\Delta t}A^{k-1}\\ C_{12}^T A^{k-1}\\ C_{13}^T A^{k-1}\\ -\dfrac{\Delta t}{lp}P_e\end{Bmatrix} \tag{5}$$

In the rotor domain, it has,

$$\begin{bmatrix} \begin{pmatrix} C_{11}+\dfrac{D_{11}}{\Delta t} & C_{12}\\ C_{12}^T & \Delta t C_{22}\end{pmatrix} & \begin{pmatrix} C_{13} & 0\\ 0 & 0\end{pmatrix} A_{nb}^T\\ A_{nb}\begin{pmatrix} C_{13}^T & 0\\ 0 & 0\end{pmatrix} & A_{nb}\begin{pmatrix} \Delta t C_{33} & 0\\ 0 & -\dfrac{\Delta t}{lp}G_e\end{pmatrix}A_{nb}^T\end{bmatrix}\begin{Bmatrix} \begin{pmatrix} A^k\\ e^k\end{pmatrix}\\ u_n^k\end{Bmatrix} = \begin{Bmatrix} \begin{pmatrix} P_A+\dfrac{D_{11}}{\Delta t}A^{k-1}\\ C_{12}^T A^{k-1}\end{pmatrix}\\ A_{nb}\begin{pmatrix} C_{13}^T A^{k-1}\\ -\dfrac{\Delta t}{lp}P_e\end{pmatrix}\end{Bmatrix} \tag{6}$$

where A_{nb} is the node-to-branch incidence matrix and the coefficient matrix is symmetrical.

III. EXAMPLE AND ANALYSIS

Using the nodal method based NF-TS-FEM, the eddy-current losses in the rotor of the high-speed PM machine are analyzed and compared. A typical magnetic flux distribution at full load is shown in Fig. 2.

A. *With Segmentation of the PMs*

Aiming to reduce the eddy-current losses in the rotor, the PMs are segmented into 10 slices in axial, and hence the eddy-current paths are cut off in the axial direction. The calculated eddy-current losses are shown in Fig.3. Assuming the eddy-current loss of the machine with no axial segments in PM is 1 p.u, the eddy current losses of machine are reduced by 0.2 p.u. after PMs segmented into 10 slices in axial direction.

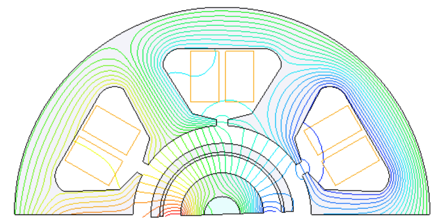


Fig. 2. Magnetic flux distribution of the high-speed machine.

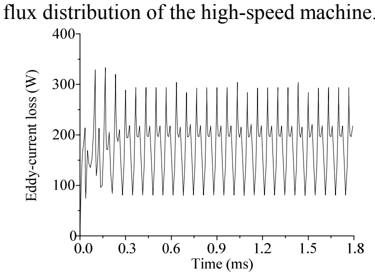
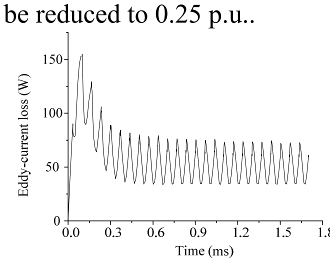


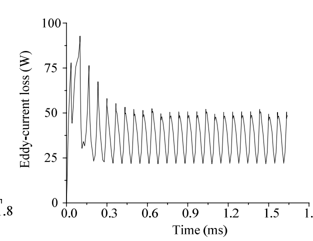
Fig. 3. Eddy-current loss with different PM segmentations with 10 segmentations.

B. *With Copper Shield*

In order to further reduce the eddy-current losses in the rotor, copper shield is used to smoothen the time varying field on the conductive sleeve and the PMs. To evaluate the effect of copper shield on eddy current loss, the eddy current loss results are analyzed, as shown in Fig. 4. With the copper shield of 0.5 mm thick the eddy-current loss can be reduced to 0.25 p.u..



(a)



(b)

Fig. 4. Eddy-current loss with different copper shield thickness. (a) 0.2 mm. (b) 0.5 mm.

IV. REFERENCES

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