Simplified 3D Modeling for Skewed Rotor Slots with End-ring of Cage Induction Motors

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This paper proposes a novel 3D modeling method for skewed rotor slots with end-ring of cage induction motors in order to achieve sufficient accuracy within acceptable computational costs. Its validity is clarified in the analysis of the induction motor with semi-closed rotor slots. In addition, the inter-bar current analysis is performed by using the proposed model combined with a homogenization method.

***Index Terms*—Finite element analysis, induction motor, inter-bar current, skewed rotor slots**

I. Introduction

HIGHLY accurate electromagnetic field analysis is required for the development of high-efficiency electric machines. In order to evaluate the characteristic of induction motors appropriately, it is desirable to consider effects of skewed rotor slots and end-ring in the three-dimensional (3D) magnetic field analysis. However, 3D analysis is not easy from the standpoint of calculation costs.

Therefore, some effective methods for skewed rotor slots have been suggested. The 2D multislice method [1] is widely used as a quasi-3D modeling for skewed rotor slots. This method is regarded as stepwise modeling of skewed rotor slots with some 2D meshes. In [2], the simplified 3D multilayer method was proposed, which can consider skewed rotor slots more simply and directly by using nonconforming mesh connection technique. However, these methods need the modification of the conductivity in the secondary conductors to take into account of the end-ring effect and leakage inductance of primary winding.

In this paper, we propose a novel 3D modeling method for skewed rotor slots with end-ring and clarify its validity in the analysis of cage induction motors with semi-closed rotor slots. Additionally, we perform the inter-bar current analysis of a cage induction motor by using the proposed model combined with the homogenization method [3] to consider laminated iron core with low computational cost.

II. Method of Analysis

Fig. 1(a) shows the proposed model for a cage induction motor with semi-closed rotor slots. In the proposed model, 3D mesh is generated by extruding 2D mesh along the axis direction and only the rotor mesh is skewed according to skew angle. The mesh for the iron core is divided into some layers in the axial direction. On the other hand, the number of layers along the axis direction for end-ring and upper/lower air region is one. This model can consider skewed rotor structure and the effect of end-ring and end-winding directly. In order to connect the fixed and moving parts of the mesh, we use the nonconforming mesh connection technique with the sliding interface located on the center of the air-gap between the stator and rotor [4]. Three models whose mesh of the iron core is divided into 1, 3, or 5 layers are investigated. Contrary to normal 3D mesh, the number of layers along the axis direction is much smaller (at most 5 layers) in the proposed approach.

For comparison, we also investigate the full 3D model. Fig. 1(b) shows the full 3D mesh. The iron core of this model is divided into 12 layers.

The hysteresis loss and the eddy current loss are calculated from the time series data of the flux density in each element as post-processing of the finite element analysis [5]. In the loss calculation, the waveform of the flux density for one cycle in the rotor is reproduced based on the polyphase time-periodic condition [6].

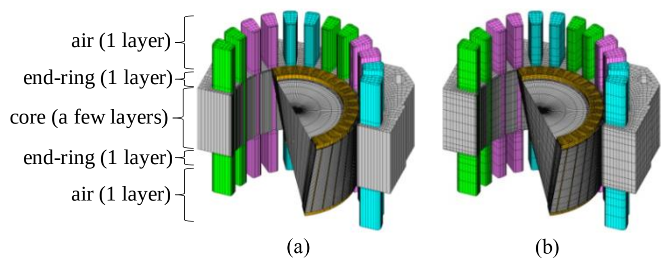

Fig. 1. Analyzed model. (a) Proposed model, (b) Full 3D model.

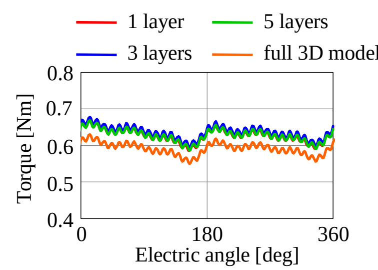

Fig. 2. Torque waveform.

III. Validity of Proposed Model

Fig. 2 shows the torque waveform. Even one-layer model can obtain the result close to the reference solution obtained from the full 3D mesh.

Fig. 3 shows the comparison of losses. As the number of layers increases, the iron loss gradually increases and the secondary copper loss decreases and the total loss approaches to the reference value. Even in one-layer model, the total loss agrees well with the reference value.

Table I shows the comparison of the average computational time per step. The calculation costs of the proposed model are drastically improved compared with the full 3D model. Therefore, one-layer model can obtain sufficiently accurate results with low computational cost.

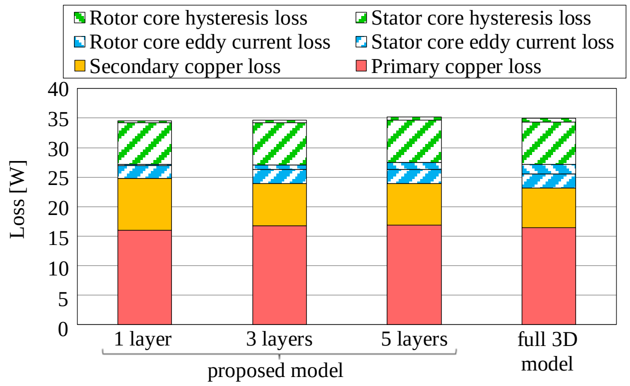

Fig. 3. Comparison of losses.

TABLE I
AVERAGE COMPUTATIONAL TIME

Analyzed model	No. of elements	Average computational time per step [sec]
Proposed model (1 layer for core)	63,415	41.3
Proposed model (3 layers)	88,781	92.0
Proposed model (5 layers)	114,147	128.8
Full 3D model (12 layers)	355,124	491.7

IV. INTER-BAR CURRENT ANALYSIS

The inter-bar current flows from a rotor bar to an iron core and the inter-bar current loss occurs when the bars are not insulated completely from the iron core in induction motors [7]. It is necessary to model a laminated iron core to consider inter-bar current loss accurately. However, it is not easy to divide the mesh considering laminated structure of electrical steel sheets from the standpoint of calculation costs. Therefore, a homogenization method is applied to the full 3D model as a simple approximate modeling technique. We investigate the inter-bar current loss by applying the homogenization method to the proposed model.

The eddy current induced by the magnetic flux parallel to the lamination is neglected in the magnetic field computation in the homogenization method. The eddy current loss generated by the perpendicular flux due to the skewed structure and end-ring effect is directly calculated by the finite element analysis. Because the inter-bar current is parallel to the lamination, the inter-bar current loss is also calculated. On the other hand, the hysteresis loss and the eddy current loss due to the parallel flux are calculated from the time series data of the flux density in each element as a post-processing.

Fig. 4 shows the distribution of the inter-bar current density vector. The inter-bar current flows from a bar to the other bar through the iron core. The inter-bar current density is high near the air-gap surface of the rotor.

Fig. 5 shows the comparison of losses in the case of the inter-bar current analysis. By considering inter-bar current, losses become larger than those when neglecting inter-bar current and approach to the measurements. Although there is an apparent difference in total loss between the one-layer model and full 3D model, the numerical results approach to the reference solution as the number of layers increases.

TABLE II shows the comparison of the average computational time per step. The proposed model can consider inter-bar current within acceptable computational costs.

The details of the proposed model and the analysis of induction motors with closed rotor slots will be reported in the full paper.

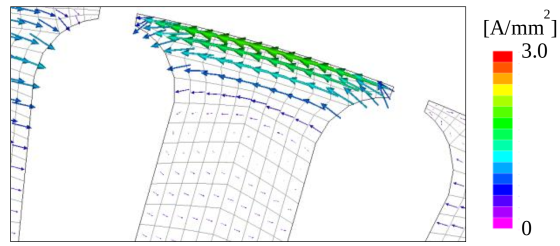

Fig. 4. Distribution of inter-bar current density vector in 3-layer model.

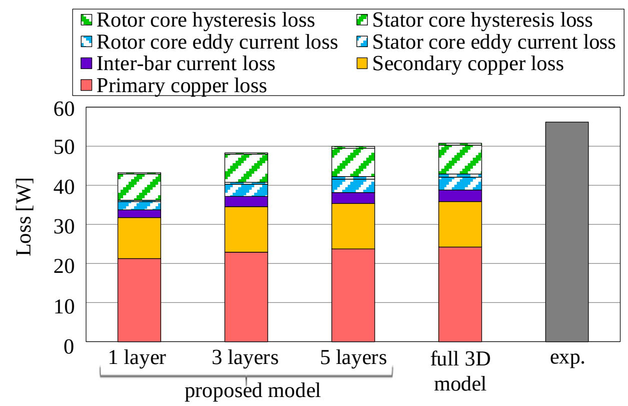

Fig. 5. Comparison of losses in inter-bar current analysis.

TABLE II
AVERAGE COMPUTATIONAL TIME IN INTER-BAR CURRENT ANALYSIS

Analyzed model	No. of elements	Average computational time per step [sec]
Proposed model (1 layer for core)	63,415	56.8
Proposed model (3 layers)	88,781	104.6
Proposed model (5 layers)	114,147	163.2
Full 3D model (12 layers)	355,124	632.7

V. REFERENCES

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