A Novel Conversion Analysis for 3-dimensional Machine with Non-uniform Height and Material

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This paper presents a novel analysis method for a 3-dimensional (3-D) flux machine. 2-dimensional (2-D) conversion method is proposed to take into account the 3-D structure which has non-uniform height and material according to the stack length. In the proposed 2-D model, virtual material which is expressed by the permeability and relative stack length of the corresponding materials is generated. Various magnetic characteristics are calculated and the correctness and usefulness of the proposed method are verified by using 3-D analysis.

***Index Terms*—Equivalent magnetic material (EMM), 2-D conversion analysis, 3-D flux machine, Non-uniform height and material.**

I. Introduction

Recently, 3-dimentional (3-D) topologies with various magnetic flux paths have been proposed for high power and torque density [1-2]. The 3-D numerical analysis is necessary to analyze accurate characteristics of the 3-D machines; however, the 3-D analysis can be inefficient and time-consuming as a modeling and solving process. This paper presents a novel 2-D analysis method to effectively account for the 3-D structure with different stack length and heterogeneous magnetic materials. The equivalent magnetic materials (EMMs) with virtual permeabilities are generated from each magnetic material and the EMMs are used in 2-D analysis process. The magnetic characteristics, such as magnetic flux density, electromotive force (EMF), and iron losses, are calculated and compared with 3-D analysis results.

II. 3-D Test Model

Fig. 1 shows an example machine with 3-D flux path. The radial and axial cores are united, and integrated coil windings are inserted into the slots of the united stator core. Fortunately, the model can be divided and calculated by radial and axial parts, separately [3]. The EMFs of the 3-D integrated and separated results are in good agreement with each other, as shown in Fig. 2. However, 3-D analysis is still necessary for each radial and axial part which has non-uniform height and material according to the stack length. For the radial part, the stack lengths of the rotor core, PM, and stator teeth are the same, whereas the length of the stator yoke is shorter than these stack lengths. Furthermore, the soft magnetic composite (SMC) is combined at the top of the laminated silicon steel sheet (SSS) in the stator teeth, as shown in Fig. 3.

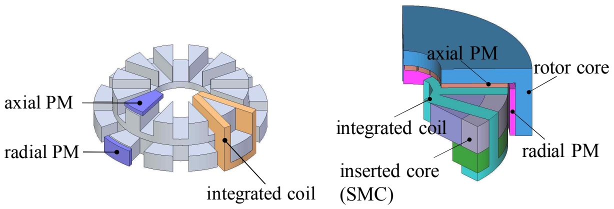

Fig. 1. Test machine with 3-D flux path.

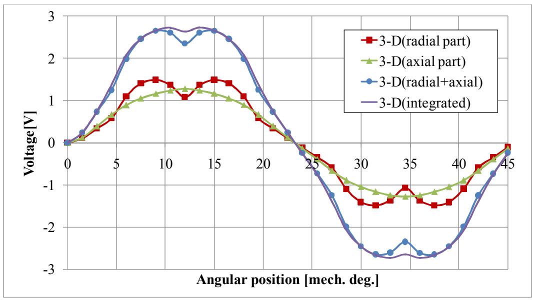

Fig. 2. EMF comparison of the separated and integrated 3-D analyses.

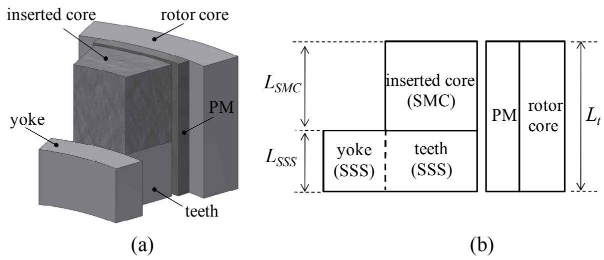

Fig. 3. Radial part of the test machine. (a) 3-D view. (b) Cross-sectional view. L_{SMC} and L_{SSS} are the lengths of the SMC and SSS, respectively.

III. Proposed Analysis Method

An equivalent magnetic circuit (EMC) model is employed to express the proposed 2-D analysis method [4]. Assuming that the magnetic flux densities of the SMC and SSS are distributed uniformly and the lengths of magnetic paths are the same, the reluctance of the stator teeth can be divided into two parallel parts corresponding to each material, as shown in Fig. 4. For the teeth reluctances, the general expressions are given by

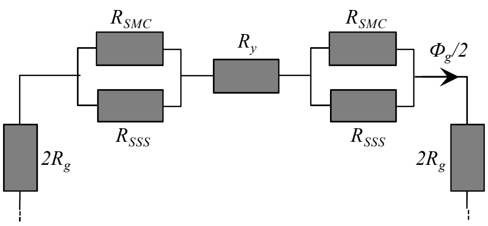

Fig. 4. EMC model for the stator core of the radial part.

$$R_{SMC} = \frac{l_t}{\mu_{SMC} w_t L_{SMC}}, \tag{1}$$

$$R_{SSS} = \frac{l_t}{\mu_{SSS} w_t L_{SSS}}, \tag{2}$$

where μ_{SMC} and μ_{SSS} are permeabilities of the SMC and SSS, and w_t and l_t are width and length of the teeth, respectively. For the 2-D analysis, the stack lengths of the overall parts of the analysis model should be equal. If the stack lengths of the rotor, stator teeth, and stator yoke are fixed to the reference length of L_t, the teeth reluctance can be expressed as follow:

$$R_{teeth} = \frac{l_t}{\mu_{EMM} w_t L_t} \tag{3}$$

where μ_{EMM} is the equivalent permeability for the teeth, which have a stack length of L_t. From Fig. 4 and (1)-(3), the teeth reluctance can be calculated as

$$R_{teeth} = R_{SSS} \parallel R_{SMC} = \frac{l_t}{w_t(\mu_{SSS} L_{SSS} + \mu_{SMC} L_{SMC})}. \tag{4}$$

Therefore, μ_{EMM} can be determined with (3) and (4) as

$$\mu_{EMM} = \frac{L_{SSS}}{L_t}\mu_{SSS} + \frac{L_{SMC}}{L_t}\mu_{SMC}. \tag{5}$$

From (5), magnetic flux density of EMM, B_{EMM}, can be expressed as a function with respect to the H as follow:

$$B_{EMM}(H) = \frac{L_{SSS}}{L_t} B_{SSS}(H) + \frac{L_{SMC}}{L_t} B_{SMC}(H). \tag{6}$$

Defining $B_{SSS}(H_1)$, $B_{EMM}(H_1)$, and $B_{SMC}(H_1)$ which are magnetic flux densities at an arbitrary magnetic intensity H_1 as a, b, and c in Fig. 5, iron loss density of EMM can be expressed by

$$P_{EMM}(b) = \frac{L_{SSS}}{L_t} P_{SSS}(a) + \frac{L_{SMC}}{L_t} P_{SMC}(c). \tag{7}$$

According to (6) and (7), the stator teeth is converted to virtual material for 2-D analysis, and the iron loss can be calculated from the corresponding dimensions and 2-D results. Fig. 6 shows *B–H* curve of the applied SMC, SSS, and EMM from (6).

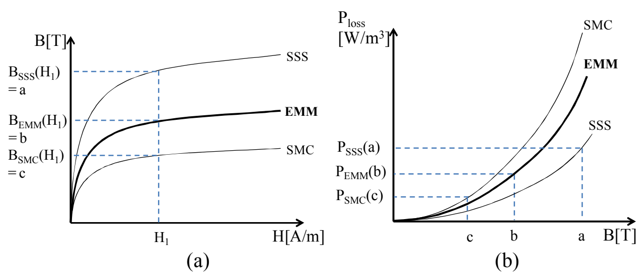

Fig. 5. *B–H* (a) and *B-P* (b) curves estimation method for EMM.

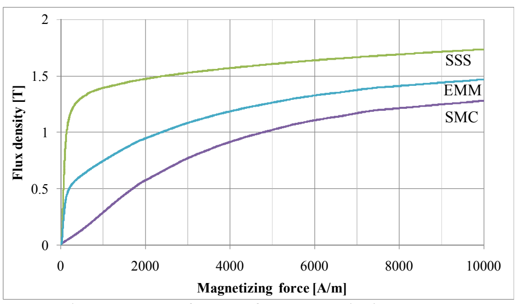

Fig. 6. Generated *B–H* curve of EMM for 2-D analysis.

The no-load magnetic field using the proposed 2-D analysis method is calculated and compared with the 3-D analysis results in Fig.7. As shown in Fig. 8, the teeth flux densities and EMFs are almost identical to each other, which shows that the 3-D machines with a non-uniform height and material according to the stack length can be analyzed by the 2-D analysis method using the proposed equivalent-material conversion method.

In a following paper, we will present detailed process and results using the proposed analysis methods. Furthermore, iron loss analysis considering each 3-D part will be calculated and discussed with 3-D numerical results.

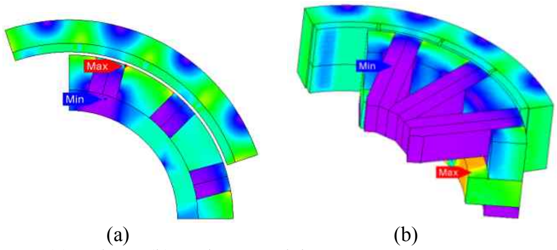

Fig. 7. 2-D (a) and 3-D (b) analyses model.

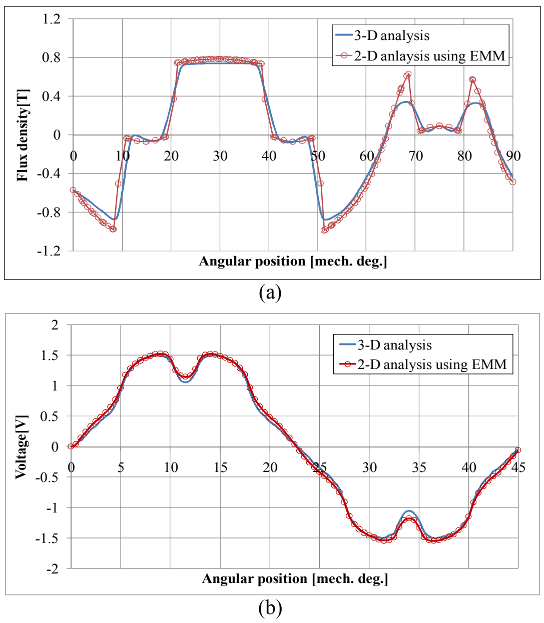

Fig. 8. 2-D and 3-D analyses comparison. (a) Radial flux density of teeth. (b) EMF.

IV. References

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