Design of WFSM using Sizing Method Combining 2D Equivalent Magnetic Circuit considering Nonlinear Characteristics

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This paper proposes a novel sizing method of wound field synchronous motor (WFSM) using a 2D equivalent magnetic circuit (EMC) considering nonlinear characteristics. The conventional sizing method is an analytical method predicting motor performance using a proportional formula based on size-related variables of the motor, which are shape ratio (SR), torque per rotor volume (TRV), and torque density (TD). However, accurate results cannot be obtained only from the proportional formula because the performance of the motor varies greatly depending on the magnetic saturation of the core. In particular, since the WFSM does not use a permanent magnet (PM) for the field, it is important to reflect the magnetic saturation of the field core. Therefore, in this paper, a novel sizing method of WFSM based on the 2D EMC, which is a numerical method used to fast and accurately calculate the performance of the motor considering the magnetic saturation of the core, is proposed. Using the proposed design method, it is possible to not only accurately predict the motor characteristics according to the size but also determine the motor size that satisfies the requirement performances. The validity of the proposed sizing process is verified through simulations and experiments.

***Index Terms*—2-dimensional equivalent magnetic circuit (2D EMC), shape ratio (SR), sizing method, torque density (TD), torque per rotor volume (TRV), wound field synchronous motor (WFSM)**

I. Introduction

Because unlike PMSM, wound field synchronous motor (WFSM) does not use a magnet for the field but uses an electromagnet through a coil, WFSM is an attractive alternative to permanent magnet synchronous motor (PMSM), which uses rare-earth permanent magnets (PMs) that are sensitive to international situations [1], [2]. Moreover, since WFSM structurally has the saliency, WFSM can generate not only magnetic torque but also reluctance torque. For this reason, WFSM is suitable for applications requiring high torque density or high efficiency.

Motor performance is closely related to motor size. In terms of motor design, the motor size can be expressed in terms of size-related variables of a motor such as shape ratio (SR), torque per rotor volume (TRV), and torque density (TD). In addition, using these size-related variables of the motor, the performance of the motor such as back electromotive force (BEMF), inductance, and resistance can be expressed and predicted [3], [4]. The sizing method introduced previously could only predict the motor performance linearly since it uses only proportional coefficients according to the shape changes. However, when the motor shape changes, the magnetic field distribution in the motor changes due to the nonlinear characteristics of the core, which causes a nonlinear change in the motor performance. Especially, in the WFSM, the nonlinear changes in the motor performance due to changes in the motor shape occur prominently. Therefore, in the sizing method for WFSM, it is necessary to add a method to predict nonlinear changes.

There are various methods for analyzing the magnetic field by reflecting the saturation of the core. Among various methods, an equivalent magnetic circuit (EMC) can reflect magnetic saturation as well as magnetic flux leakage through a simple circuit equation [5]. Therefore, in this paper, EMC is used to consider the nonlinear characteristics of the core.

This paper proposes a design method for WFSM using a sizing method combining the 2D EMC to consider the nonlinear characteristics, which is a design method that combines analytical and numerical methods. Using the proposed design method, it is possible to not only fast and precisely predict the motor characteristics according to the size but also determine the appropriate motor size that satisfies the required performances. This paper is composed as follows. First, the sizing method used in WFSM design is introduced. Next, the EMC used in considering the nonlinear characteristics of the core is introduced. Finally, to verify the validity of the proposed method, the proposed method is compared with finite element analysis (FEA), and an experiment is performed.

II. Sizing Method for WFSM Combining 2D EMC

In this section, the sizing method combining 2D EMC is introduced. As mentioned earlier, the previous sizing method is fast but lacks accuracy because it ignores the nonlinear characteristics of the core. For this reason, to accurately predict performance under load conditions, this paper proposes the sizing method for the WFSM combining the 2D EMC.

A. Sizing Method for WFSM

The flowchart of the proposed sizing method for WFSM is shown in Fig. 1. First, the data for the reference motor is input. The input data includes not only the shape dimensions of the reference motor but also the electrical parameters such as the BEMF, inductances, and the air-gap flux density. For accurate performance prediction according to changes in the shape of the

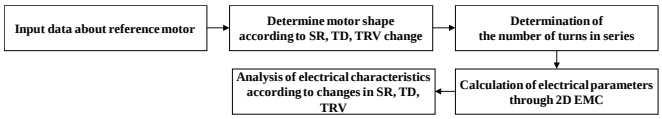


Fig. 1. Flowchart of proposed sizing method based on 2D EMC for WFSM

motor, the electrical parameters obtained through FEA are input. Second, the shape of the motor is determined using SR, TD, and TRV. Since size-related variables are functions of motor shape variables as seen below, conversely, the shape of the motor can also be determined through size-related variables.

$$SR = D_{ro} / D_{so} \tag{1}$$

$$TD = 4T_{\max} / \pi D_{so}^2 L_{stk} \tag{2}$$

$$TRV = 4T_{\max} / \pi D_{ro}^2 L_{stk} \tag{3}$$

where, D_{ro} and D_{so} are the rotor and stator outer diameters, respectively, T_{max} is the maximum value of the torque, L_{stk} is the stack length. Third, the number of series turns is determined to maintain the same BEMF as the reference motor. Next, the electrical parameters of the modified motor such as inductance, and flux linkage by are calculated using a proportional formula adjusted by the 2D EMC:

$$X_{\text{mod}} = X_{FEA.ref} \times k_X = X_{FEA.ref} \times \frac{X_{EMC.\text{mod}}}{X_{EMC.ref}} \tag{4}$$

where, X_{mod} and $X_{FEA.ref}$ are the electrical parameters of the modified motor and the reference motor calculated through FEA, respectively, k_X is the proportional coefficient of X, $X_{EMC.mod}$ and $X_{EMC.ref}$ are the electrical parameters of the modified and reference motors calculated through EMC, respectively. In the previous sizing method, k_X was obtained using formulas that included motor shape variables. On the other hand, in the proposed method, k_X is obtained using the value obtained from EMC to consider the nonlinear characteristics. Finally, the motor performance is obtained using the electrical parameters of the modified motor, d, q-axis equivalent circuit, and maximum efficiency control [6].

B. 2D EMC considering nonlinear characteristics

As aforementioned earlier, 2D EMC is applied to the sizing method to consider the nonlinear characteristics of the core. Fig. 2 shows EMC for the WFSM, and 2D EMC is divided into three parts; stator, air-gap, and rotor. The computation speed and analysis accuracy of the EMC vary depending on how modeling is done. As shown in Fig. 2, to enhance computation speed and analysis accuracy, the air-gap and the stator and rotor parts adjacent to the air-gap, which are related to the analysis accuracy are finely divided. On the other hand, the stator and rotor parts, which are not significantly related to the analysis accuracy, are sparsely divided. Also, to consider the slot leakage flux, the magnetic resistance is added to the slot and slot-opening of the stator and rotor. The B-H curve of the core is used for EMC, and the nonlinear characteristics of the core were reflected through the direct convergence method [7].

III. Simulation and Experimental Verification

To validate the proposed sizing method, its results are compared with FEA for various SR, TD, and TRV, as shown in Fig. 3. Since the proposed EMC has a maximum error of 3.3% for various electrical parameters, it can be seen that the 2D

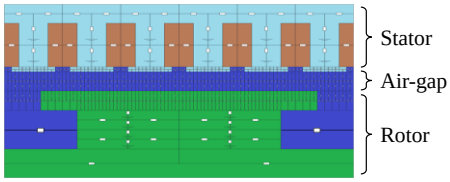


Fig. 2. 2D EMC for WFSM

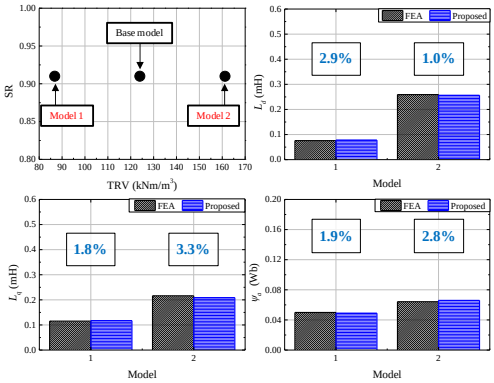


Fig. 3. Comparison between 2D EMC and 2D FEA results

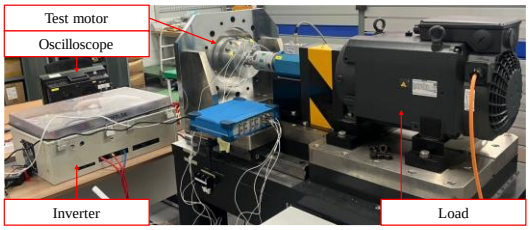


Fig. 4. Experimental setup.

EMC is well structured. The proposed method achieves similar accuracy to FEA with much less setup and computation, making it suitable for iterative analysis. Also, the motor derived through the proposed sizing method will be verified through simulation and experiment. Fig. 4 shows the experimental setup.

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