Finite Element Analysis of Local Flux Density Variation in the Synchronous Motor for Core Loss Estimation Considering Current Harmonics

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This research deals with how to analyze flux density changes within the iron core, to predict core loss when operating 3phase permanent magnet synchronous motor by PWM sine wave. When creating sinusoidal current by PWM, large amount of harmonics is mixed in the current; which requires a significant amount of time for analysis. This research suggests a method to calculate flux density changes from each element in a short time, using non-linear FEA and linear FEA concurrently, based on 2-D magneto static FEA.

***Index Terms*— electric motor, finite element analysis, magnetic cores, magnetic flux density**

I. Introduction

CORE LOSS in a synchronous motor increases more when rotating speed becomes faster. Loss in high-velocity is mostly taken up by core loss, and motor output is significantly limited by this factor [1], [2]. Therefore, core loss at load condition must be predicted as accurately as possible, starting from the designing stage.

To predict core loss at load condition, a complete cycle of magnetic flux density vector variation should be computed by FEA for each element. Core loss at its total can be obtained by Fourier-transforming the loci of the flux density vector [3], [4] and adding core loss for each frequency order separately.

However, there are higher current harmonics in case of electric current provided by PWM inverter, and to reflect such current harmonics in the analysis, location of the rotor must be changed at multiple times, more than twice the number of the harmonic number, to conduct non-linear FEA.

Since such analysis requires too much time, this research will discuss a method to analyze PWM current in a short time, using non-linear FEA and linear FEA concurrently.

II. Method of Analysis

Electric current provided to motor from PWM inverter includes higher current harmonics, which can be depicted as (1).

$$i(t) = I_1 \sin(\omega t - \phi_1) + I_2 \sin(2\omega t - \phi_2) + I_3 \sin(3\omega t - \phi_3) + I_4 \sin(4\omega t - \phi_4) + \cdots \quad (1)$$

In the method suggested by this research, the analysis process can be largely divided by two stages. The first stage is non-linear FEA using only the fundamental harmonic, and the second stage is linear FEA using all current harmonics. In the second stage, each element is linearized using the analysis results obtained in the first stage.

A. Stage I: Non-linear FEA with Fundamental current wave

As shown in (2), the fundamental harmonic includes only the first term of (1).

$$i_{\text{fund}}(i) = I_1 \sin(\omega t - \phi_1) \quad (2)$$

Since it is necessary to have loci of magnetic flux density vector in one cycle of electrical angle for each element to obtain core loss, non-linear FEA is conducted using (3) [5], while changing rotor location in certain intervals under current input as in (2).

$$\nabla \times \frac{1}{\mu}\left(\nabla \times \mathbf{A}\right) = \mathbf{J} + \nabla \times \left(\frac{\mu_0}{\mu}\mathbf{M}\right) \quad (3)$$

Where μ is permeability, **A** is magnetic vector potential, **J** is current density and **M** is magnetization. In Stage I, **M** is always 0 in the element at iron core.

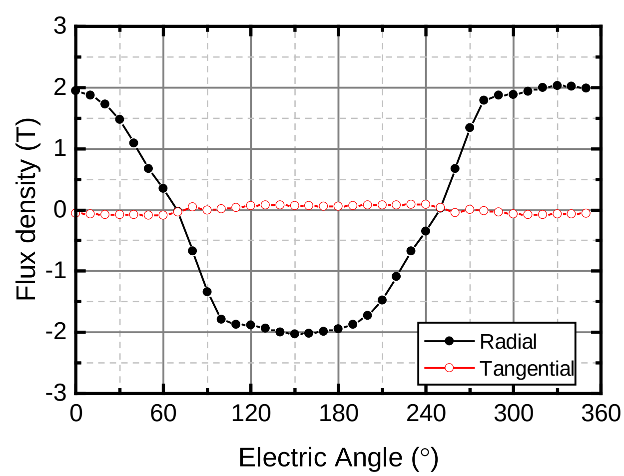

Fig. 1. Flux density variation in an element

As the result of Stage I, flux density vector values sampled at regular intervals can be obtained in all elements, as shown in Fig. 1. From these values, values in between the intervals can be predicted using methods such as spline interpolation, and the predicted values are used for linearizing each element in the second stage.

B. Stage II: Linear FEA with Harmonic Current Wave

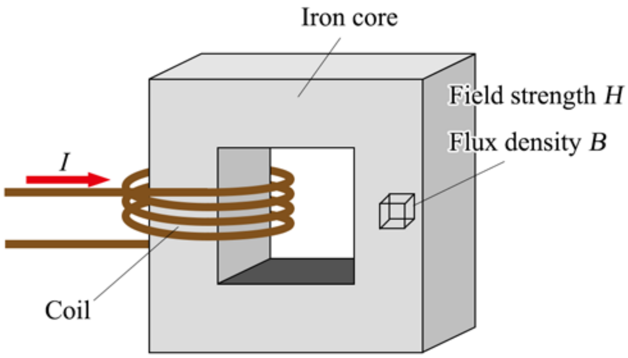

Fig. 2. Magnetic circuit

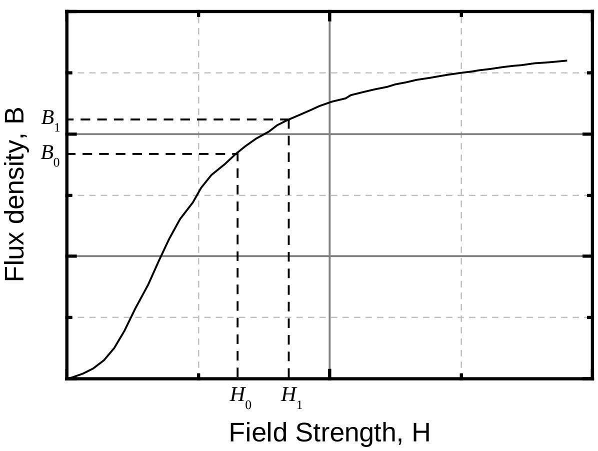

Fig. 3. B-H curve

Let's suppose a magnetic circuit, consisting iron core and coil as shown in Fig. 2. The iron core is made from a material that has single-valued B-H curve as in Fig. 3. Let's put the case that a random location within the core has field strength H_0 and flux density B_0 while current I_0 is flowing. In this situation, when the size of the current increases by ΔI, field strength and flux density is increased to H_1 and B_1 respectively, as shown in Fig. 3. If ΔI is small enough, the relationship between field strength H and flux density B can be assumed to be linear during the time when the current changes from I_0 to $I_0+\Delta I$.

In equation (1), the higher harmonics I_2, I_3, I_4… are significantly smaller than fundamental harmonic I_1; so such relationship explained above is applicable. In Stage II, each element's flux density obtained from Stage I is interpolated to linearize each element. In the analysis result obtained in Stage I, if an element has field strength and flux density with direction θ and the size of B_0 and H_0 at a certain time, the element can be linearized with a material that has permeability and residual flux density as below.

$$B = B_r + \mu H$$
$$\mu = \left.\frac{\partial B}{\partial H}\right|_{H=H_0}, \qquad B_r = B_0 - \mu H_0 \tag{4}$$

The relationship in above formula is shown in Fig.4. Permeability μ can be expressed as the tangent line slope of B-H curve at a point when $H=H_0$, and residual flux density B_r can be expressed as the point where an extended line from the tangent line meets B axis.

Each element's loci of flux density for PWM current waveform can be obtained by conducting linear FEA with current described in (1) in a model linearized as described above.

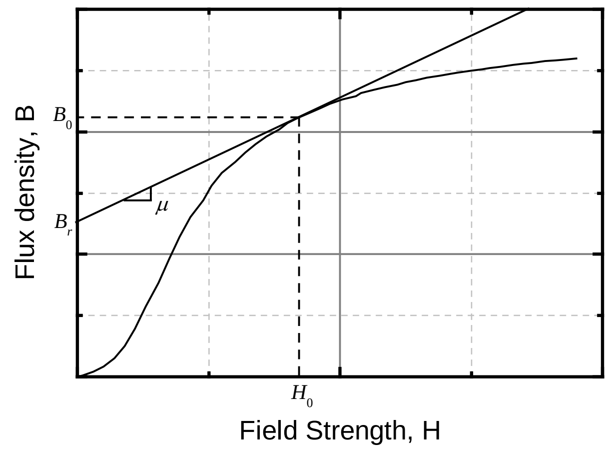

Fig. 4. Material Linearization

III. Results and Discussion

For currents consisting higher harmonics, results obtained by existing non-linear FEA method and results obtained from the suggested method will be provided and compared in a full paper.

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