Voltage Source FEA for Hysteresis Motor using Preisach Model

Sun-Ki Hong, Seok-Hee Lee and Hyun-Kyo Jung

Abstract - In this paper, voltage source FEA for hysteresis motor considering magnetic hysteresis characteristics is presented. The Preisach model is used as a hysteresis model. System matrix whose unknown variables are vector potentials and currents is formulated for voltage source. The stiffness matrix is maintained constant by using M-iteration method. Therefore the calculation time and efforts are reduced with Choleski direct method. Current waveform can be calculated for arbitrary voltage waveform considering hysteresis effects.
Keywords - finite element analysis, Preisach model, voltage source, hysteresis motor.

1. Introduction

Hysteresis motor is a self-starting synchronous motor that uses the hysteresis characteristics of magnetic materials. It is known that the magnetic characteristics of the motor could be easily affected by space harmonics due to the effects of the slot, current and winding distributions. To consider those effects, it would be desirable to adopt the finite element method (FEM) which can consider hysteresis effect [1]. With respect to the hysteresis model, the Preisach model is one of the most powerful tools to describe the hysteresis behavior [2]. Usually electrical machines are fed by voltage source and current becomes unknown. Most of the hysteresis motor is driven by voltage source inverter, however, so far the FEA for hysteresis motor does not consider this problem.

In this paper, to analyze the voltage driven hysteresis motor, voltage source FEM considering hysteresis characteristics is proposed. The hysteresis model is magnetization-dependent Preisach model [3,4]. The circuit equation and Ampere's equation are formulated together to calculate the current. FEM considering hysteresis effect is combined with circuit equation. System matrix whose unknown variables are vector potentials and currents is formulated for voltage source. The Choleski direct method which divides the stiffness matrix to L and U matrix is used for convenience and time saving because the stiffness matrix is not changed until the next time step by using M-iteration method [1] which adopts the pseudo-permeability. The proposed method is applied to a hysteresis motor, which is 2 phases 4 poles motor and has hysteresis ring as a rotor, and current waveforms are simulated according to the applied voltage of sinusoidal and square waveforms. Hysteresis loops according to the depth of the hysteresis ring are also simulated and it shows that the hysteresis loops are different according to the radial depths of the hysteresis ring although in the same ring. The simulated results of the applied voltage and current are compared with the measured data and we could get acceptable results. Therefore it is found that this process can be applied other electrical systems which need accurate analysis considering hysteresis phenomena under voltage source.

2. Hysteresis Motor

Hysteresis motor consists of stator and hysteresis ring which is a part of the rotor. The hysteresis ring is usually made of semi-hard magnetic material. Fig. 1 shows the basic structure of the motor. The performance of the motor is determined by the hysteresis characteristics of the hysteresis ring and the output of the motor is propotional to the hysteresis loop area. The hysteresis ring is usually made very thin to ignore the rotational hysteresis effects [5]. The hysteresis ring is affected by the rotational magnetic field caused by the stator windings. It is assumed that only the circumferential component of the flux acts on the

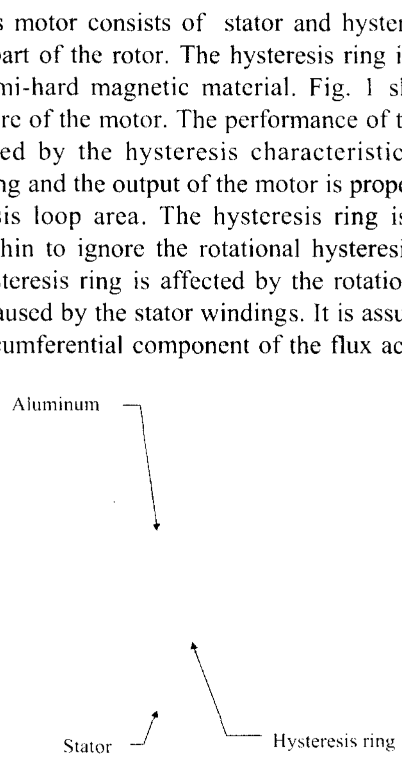

Fig. 1 Structure of hysteresis motor

This work has been supported by Korea Science & Engineering Foundation.

Manuscript received: June 5, 2001 accepted: Sep. 19, 2001.

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torque of the motor and the area of the hysteresis loop is proportional to the output. In analytic methods, the hysteresis loop of the ring is assumed in the middle of the ring. However the states of the hysteresis are different from each depth. For an more accurate analysis of the motor, it is necessary to analyze the hysteresis loop in any depth according to the applied voltage using FEM considering hysteresis effect.

3. Voltage Source Finite Element Analysis

In conventional FEA, the current density is used as input source [6]. However most electrical machines are driven by voltage source, therefore the current in coil becomes unknown. Some studies [7,8] have considered hysteresis for current source and some studies have considered voltage source, however those considering both look not developed yet. Especially for hysteresis motor which should be considered for the hysteresis characteristics, the FEA considering hysteresis effect for voltage source is required for accurate analysis.

In this study, finite element formulation is derived from (1) and (2) in the voltage source FEA. The discrete form of equation (2) becomes (3).

$$\nabla \times \frac{1}{\mu}(\nabla \times \vec{A}) = \vec{J} \tag{1}$$

$$V = Ri + N\frac{d\Phi}{dt} \tag{2}$$

where V: input voltage, R: winding resistance, i: current, N: winding turns, Φ : linkage flux.

$$V = Ri + \frac{N}{\Delta t}(\Phi - \Phi') \tag{3}$$

where Δt : time step size, Φ' : linkage flux of previous time step.

In equation (2), the linkage flux of current time step can be calculated from the vector potential in coil region as shown in (4).

$$\Phi = \frac{d}{S}\sum_{e}\left(\frac{A_1^e + A_2^e + A_3^e}{3}\Delta^e\right) \tag{4}$$

where d is axial length, Δ^e is the area of triangle element and S is coil area. From (3) and (4), the voltage equation becomes (5) where N is the number of turn, d is the depth of z-axis and α is the current direction.

$$\frac{N}{\Delta t}\frac{d}{S}\sum_{e}\alpha\left(\frac{A_1^e + A_2^e + A_3^e}{3}\Delta^e\right) + Ri = V + N\frac{\Phi'}{\Delta t} \tag{5}$$

From (1) to (5), element matrix equation can be formulated to (6).

$$[S^{e\prime}]\{A^{e\prime}\} = \{g^{e\prime}\} \tag{6}$$

where for the equivalent current density of magnetization J_{mi}^e,

$$[S^{e\prime}] = \begin{bmatrix} s_{11}^e & s_{12}^e & s_{13}^e & s_{I1}^e & s_{I2}^e \\ s_{21}^e & s_{22}^e & s_{23}^e & s_{I1}^e & s_{I2}^e \\ s_{31}^e & s_{32}^e & s_{33}^e & s_{I1}^e & s_{I2}^e \\ s_{I1}^e & s_{I1}^e & s_{I1}^e & 0 & 0 \\ s_{I2}^e & s_{I2}^e & s_{I2}^e & 0 & 0 \end{bmatrix},$$

$$\{A^{e\prime}\} = \begin{Bmatrix} A_1^e \\ A_2^e \\ A_3^e \\ I_1' \\ I_2' \end{Bmatrix}, \qquad \{g^{e\prime}\} = \begin{Bmatrix} J_{m1}^e \\ J_{m2}^e \\ J_{m3}^e \\ 0 \\ 0 \end{Bmatrix}.$$

From the element matrix equation (6), the resulting system equation becomes (7).

$$\begin{bmatrix} [S] & [S_I] \\ [S_I]^T & [R'] \end{bmatrix}\begin{bmatrix} [A] \\ [I'] \end{bmatrix} = \begin{bmatrix} [J_m] \\ [V'] \end{bmatrix} \tag{7}$$

where, $I' = -\Delta t I / d$, $S_I = \frac{\alpha \cdot N \cdot \Delta^e \cdot d}{3 \cdot \Delta t \cdot S}$, and because the motor has 2 phase,

$$[R'] = \begin{bmatrix} -\frac{d}{\Delta t}R_1 & 0 \\ 0 & -\frac{d}{\Delta t}R_2 \end{bmatrix}, \quad [V'] = \begin{bmatrix} V_1 + \frac{N_1}{\Delta t}\Phi'_1 \\ V_2 + \frac{N_2}{\Delta t}\Phi'_2 \end{bmatrix}.$$

4. FEA Considering Hysteresis Characteristics

The hysteresis model applies to each element of hysteresis region because the magnetic history of each element is different. In combining FEM with the hysteresis model, finite element formulation is derived from (8),

$$\begin{aligned} B &= \mu_0 H + M = \mu_0 H + \mu_0 \mu_{sp} H + M' \\ &= \mu_0(1 + \mu_{sp})H + M' \end{aligned} \tag{8}$$

where, M' is the pseudo-magnetization and μ_{sp} is the pseudo-permeability. From (8), the input to FEA are the permeability $\mu_0(1+\mu_{sp})$ and M' pseudo-magnetization. As mentioned before, the stiffness matrix is not changed although time step increases, because μ_{sp} which is included in stiffness matrix is constant. Instead, M' included in the forcing matrix is varied, therefore once the stiffness matrix is divided into L and U matrix, no more effort for the stiffness matrix is needed at one step.

If the flux density is calculated with the pseudo permeability and pseudo-magnetization, field intensity and magnetization is calculated by magnetization-dependent Preisach model. Then new magnetization and pseudo-magnetization are obtained from this field intensity. Fig. 2 shows the total calculation procedure combined with voltage source FEM including hysteresis model.

If the finite element solution was obtained, hysteresis loops can be obtained according to the circumferential direction. Then the torque of the motor is calculated by

$$\tau = \frac{1}{2\pi} p V_r E_h \tag{9}$$

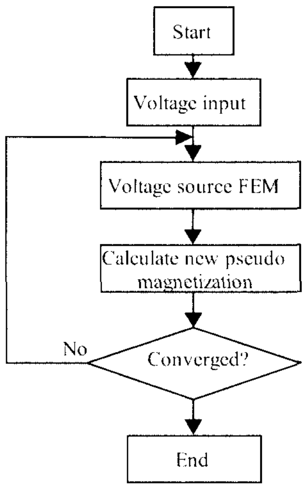


Fig. 2 Flow chart of voltage source FEA considering hysteresis characteristics.

where p : number of pole pairs, V_r : volume of hysteresis ring, E_h : area of the hysteresis loop.

5. Simulation and Results

Table I and II are the specifications of the tested motor. Because the number of poles is 4, the hysteresis ring makes two major hysteresis loops.

Table 1 Stator Specification

no. of phase	2	No. of poles	4
no. of winding	2280	Winding factor	0.85
no. of slot	16	Inner diameter	30[mm]
Effective thickness	28 [mm]		

Table 2 Rotor Specification

outer diameter	29.6 [mm]	Thickness	3.5 [mm]
axial length	28.1 [mm]	Air gap	0.2 [mm]

Fig. 3 shows the equi-potential lines when the rms value of the voltage source is 110 [V]. A half of the motor is analyzed because of the symmetry. In the analysis flow, the convergence to the solution is checked using the following equation.

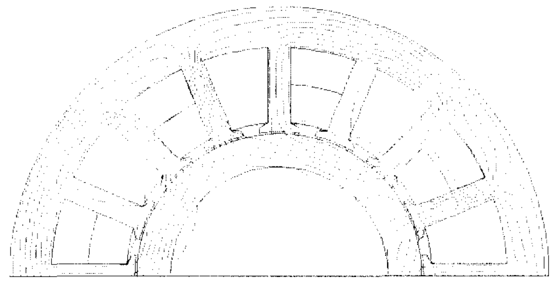


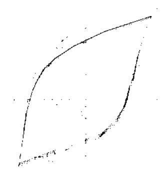
Fig. 3 Equipotential lines of the hysteresis motor with 110 [Vrms].

$$\frac{H_i^{(n+1)} - H_i^{(n)}}{H_i^{(n+1)}} < \varepsilon \tag{10}$$

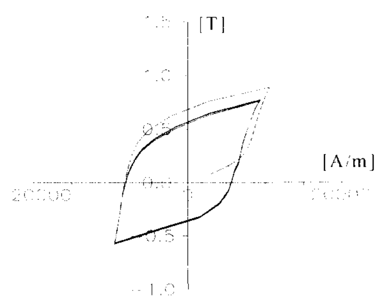
where, n is the iteration step, $i = x$ or y component, ε : convergence criterion.

As is shown in the figure, the results are for the half of the motor because the motor has 4 poles and each 2 poles are periodical.

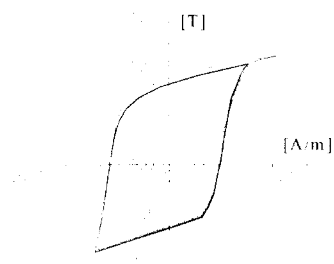
Fig. 4 shows the hysteresis loop variations for time steps according to their ring depths. As seen in the figures, the hysteresis loop at the outside of the ring is a little larger than that at the inside of the ring because the applied field is a little different according to the depths. From the calculation results, the torque is computed using the hysteresis loop area.



(a) Most inner point of the ring



(b) Middle point of the ring



(c) Most outer point of the ring

Fig. 4 Hysteresis loops according to the ring depths.

Fig. 5 shows the current waveform when 110 [V_{rms}] 60[Hz] sine wave voltage source is applied. Within a few cycles after the voltage source is applied, the current wave form is stabilized. From this result, the peak current value can be estimated from this proposed method.

Fig. 6 shows the current waveform when square wave voltage source is applied and the amplitude is 110 [V_{rms}]. In the equivalent circuit method, it is very difficult problem to analyze the motor under the square wave or arbitrary voltage wave form input.

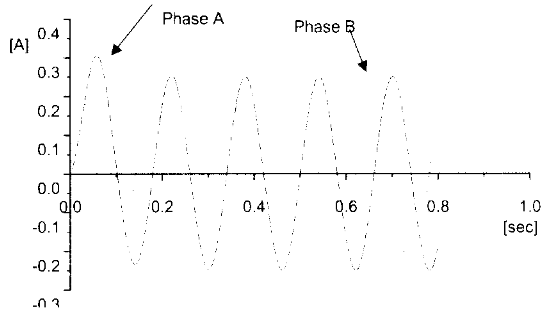


Fig. 5 Current waveform for sinusoidal voltage source.

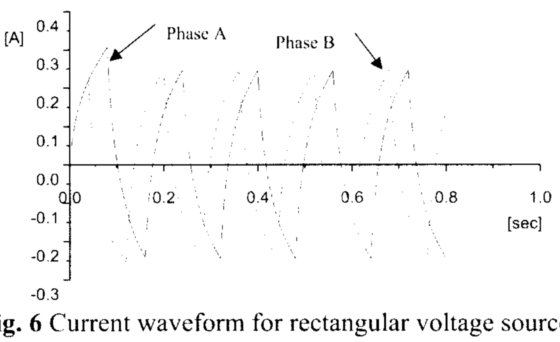


Fig. 6 Current waveform for rectangular voltage source.

Fig. 7 shows the measured and simulated current values according to the sine wave input voltage. The measured values are a little larger than the simulated value. That main reason may come from the iron losses because the FEA does not consider about that. However the trend explains the good agreement between the measured and simulated data. If the input current is known, the torque can be calculated accurately by the FEM considering hysteresis characteristics[1].

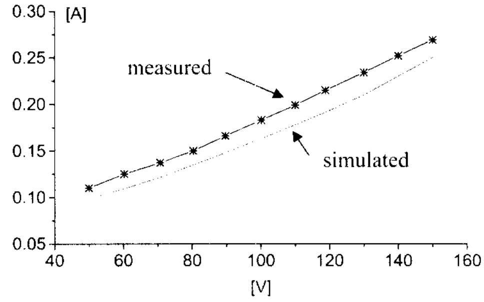


Fig. 7 Current vs. input voltage for sine wave voltage source

6. Conclusions

In this paper, voltage source FEA considering hysteresis model is presented for accurate analysis of the hysteresis motor. Magnetization-dependent Preisach model is adopted to consider hysteresis effect. System matrix whose unknown variables are vector potentials and currents is formulated for voltage source. The stiffness matrix is maintained constant by using M-iteration method, therefore the calculation time and efforts are reduced using direct method. Hysteresis loops according to the voltage and depths of the hysteresis ring are calculated to evaluate and estimate the hysteresis motor performances. Through the comparison between the simulation results and the experimental ones, it is found that the proposed method can get very reasonable results. The proposed method can be applied to other magnetic systems where voltage source is applied and hysteresis characteristics must be considered.

Acknowledgment

This work has been supported by Korea Science & Engineering Foundation.

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