Comparison on Eddy Current Losses for Halbach Array Permanent Magnet Type Cylindrical Linear Oscillatory Actuator according to Voltage Source Waveform

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Abstract — This paper deals with the calculation and comparison on eddy current losses for Halbach array permanent magnet type cylindrical linear oscillatory actuator (LOA) mover according to voltage source waveform. On the basis of the magnetic vector potential and a two-dimensional (2-d) cylindrical coordinate system, this paper derived analytical procedures and solutions of eddy current losses using Poynting theorem. And then, this paper obtained amplitude of each harmonic using fast Fourier transform (FFT) analysis of phase current waveform. The eddy current losses obtained from amplitude of harmonic and analytical solutions are compared with results obtained from non-finite element method (FEM). Particularly, this paper shows that the eddy current losses of cylindrical LOA according to square voltage waveform are more significant than those according to sinusoidal voltage waveform.

I. INTRODUCTION

Recently more attention is paid to minimizing losses for higher efficiency of permanent magnet (PM) machine [1]. The eddy current losses of PM machines are induced in the permanent magnets and also rotor back-iron due to the time and space harmonics in the air-gap field produced by slotting effects as well as non-sinusoidal stator mmf and phase current waveforms. The amount of the eddy current losses is usually considered negligible. However, despite the relatively small amount of the eddy current losses compared with the stator copper and core losses, it may cause significant heating of the PM, due to relatively poor heat dissipation from the rotor, and result in partial irreversible demagnetization. For the case when our cylindrical LOA are driven by voltage source, it can be considered the influence of time harmonic contained in the phase current on the eddy current losses according to two driving method such as sinusoidal and square voltage waveforms.

A method for calculating the eddy current losses in permanent magnet brushless machines equipped with surface-mounted magnets has been developed by many researchers [2]-[4]. Zhu [2] calculated the eddy current losses induced in surface-mounted permanent magnet brushless machines using improved analytical technique accounting for the eddy current reaction field derived in terms of magnetic scalar potential and 2-d polar coordin ate system and proved the validation of analytical method by presenting experimental results obtained from thermometric measurements. However, his model neglected the air-gap stator slotting for simplicity. Flynn

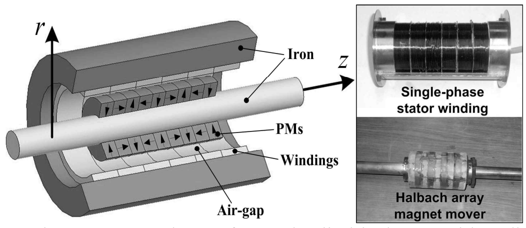

Fig. 1. The structure and manufactured cylindrical LOA with Halbach array mover and stator winding.

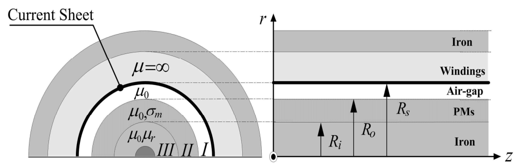

Fig. 2. Analytical model for the calculation of eddy current losses induced in mover.

[3] presented the methodology for evaluating and reducing rotor losses of the high-speed machines for flywheel application considering current fed by the inverter using 2-d rectilinear model. However, his analytical techniques are not compared with other methods such as experimental works or FEM. Irenji [4] predicted the rotor losses induced in high-speed surface-mounted PM motors according to load conditions using 2-d FEM, 2-d rectilinear model, and 2-d FFT analysis. His methods can be judged to be reasonable, but are quite complicated and time-consuming.

As a conclusion, those methods can be easily adapted to the cylindrical LOA shown in Fig. 1, which has mover with Halbach array magnet, slotless stator with single-phase winding, coil-wrapped hollow bobbin and iron core. So, this paper employed analytical technique proposed by [2] for the prediction of eddy current losses induced in our cylindrical LOA with Halbach array mover. Although stator slotting effects are neglected in [2], since the stator of our model is slotless, analytical methods proposed in [2] are more suitable. Thus, more reasonable calculations of eddy current losses are expected by considering only space harmonic and time harmonic due to winding distribution and current waveform.

II. ANALYSIS OF THE EDDY CURRENT LOSSES

A. Analysis of Time-Varying Magnetic Field Distribution

In order to analyze the eddy current losses induced in the Halbach array mover, time-varying magnetic field distribution can be calculated using analytical model shown in Fig. 2 [5]. Moreover, the Poynting theorem is a powerful means of obtaining the total power entering or leaving a region. The Poynting vector $\boldsymbol{P}$ is defined in terms of the vector product of electric intensity and the magnetic field intensity over the surface of a region, i.e., complex Poynting vector can be used to determine the instantaneous real and reactive power crossing a surface at any particular point. The eddy current losses induced in Halbach array magnet can be calculated using the Poynting theorem as

$$P_{rotor} = \frac{1}{2}\oint_s \mathrm{Re}(\mathbf{E}\times\mathbf{H}^*)dS \quad (1)$$

where the surface $\boldsymbol{S}$ bounds the conducting regions.

III. DISCUSSION AND RESULTS

Fig. 3 (a) and (b) show measured phase current waveform according to sinusoidal voltage waveform and square voltage waveform using pulse width modulation (PWM), respectively. As shown in Fig. 3, the operation of voltage source waveform using PWM is contained in not only space harmonic but also time harmonic according to the sampling time of PWM.

Fig. 4 shows the comparison of analytical method for eddy current losses, obtained from the analytical methods and the FFT analysis results according to each harmonic order of the cylindrical LOA with measured phase current waveforms of Fig. 3. Although the amplitude of 5th harmonic order is smaller than that of 1st and 3rd harmonic orders, it observed that the eddy current losses of 5th harmonic order is higher than those of other harmonic orders. Fig. 5 shows the eddy current losses of sinusoidal voltage waveform and square voltage waveform according to non linear-FEM. It can confirmed that the eddy current losses of square voltage waveform are larger because amplitude of 5th harmonic component of measured phase current according to square voltage waveform is 3 times larger than that of according to sinusoidal voltage waveform. Therefore, despite low frequency operated in 10Hz, the eddy current losses induced in the Halbach array magnet should be predicted, for the case when the cylindrical LOA according to square voltage waveform.

IV. CONCLUSION

In this paper, calculation and comparison on eddy current losses for Halbach array permanent magnet type cylindrical LOA according to driving method have been described. Using time-varying magnetic field distribution analysis and 2-d polar coordinate system, this paper presented the analytical procedure of the eddy current losses induced in Halbach array magnet of cylindrical LOA. It is also suggested the calculation of the eddy current losses through Poynting theorem. In particular, the differences of the eddy current losses according to sinusoidal and square voltage waveform are compared with the results of non-linear FEM and presented analytical method. In this paper, the eddy current losses of square voltage waveform observed larger than those of cylindrical

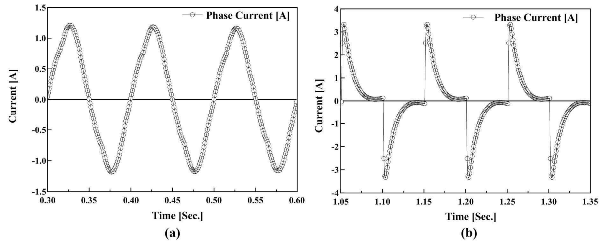

Fig. 3. Measured phase current waveform according to (a) sinusoidal voltage waveform and (b) square voltage waveform.

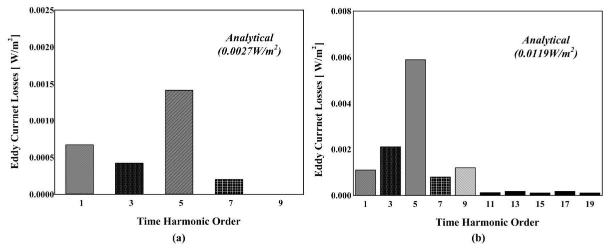

Fig. 4. The comparison of analytical method for eddy current losses according to each harmonic order : (a) sinusoidal voltage waveform and (b) square voltage waveform.

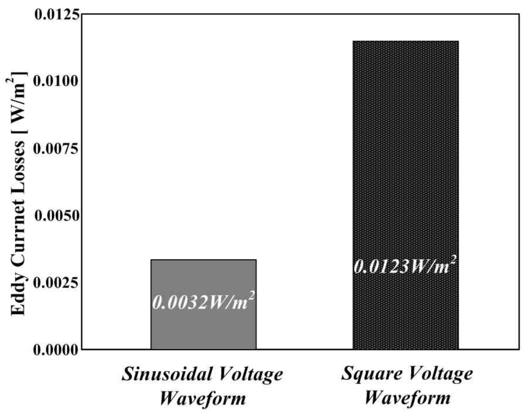

Fig. 5. The comparison of eddy current losses according to non linear-FEM : (a) sinusoidal voltage waveform and (b) square voltage waveform.

LOA according to sinusoidal voltage waveform. And the cylindrical LOA with retaining sleeve can be judged that the eddy current losses are more significant than our LOA because of high electrical conductivity. Therefore, the eddy current losses induced in magnet and sleeve should be predicted, for the case when cylindrical LOA has the retaining sleeve. We will calculate the eddy current losses of cylindrical LOA with retaining sleeve by using analytical method presented in this paper.

V. REFERENCES

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