

Computationally Efficient Method for Calculating Radial Electromagnetic Force of Induction Motor Using Stepping Time-Harmonic Finite Element Analysis

Ji-Hoon Lee¹, Seung-Hun Lee¹, Yun-Jae Won¹, Byeong-Cheol Bae¹, Moo-Hyun Sung^{1,2}, and Myung-Seop Lim³ *Senior Member, IEEE*

¹Department of Automotive Engineering (Automotive-Computer Convergence), Hanyang University, Seoul 04763, South Korea

²Vehicle Electrification R&D Center, Korea Automotive Technology Institute, Daegu 43011, South Korea

³Department of Automotive Engineering, Hanyang University, Seoul 04763, South Korea, myungseop@hanyang.ac.kr

Transient finite element analysis (FEA), a common method to analyze induction motors, suffers from a long analysis time. As the speed of the induction motor increases and the slip frequency decreases, the analysis time grows exponentially. This paper proposes a computationally efficient method for calculating the radial electromagnetic force in an induction motor using time-harmonic FEA. Unlike conventional time-harmonic FEA, stepping time-harmonic FEA is performed by mechanically and electrically rotating over one cycle during the analysis. The radial and tangential airgap flux densities were compared for different slip frequencies, and the radial electromagnetic force was calculated using Maxwell stress tensor. Furthermore, a spectrum analysis of the radial electromagnetic force was performed using 2-dimensional fast Fourier transform, and the validity and efficiency of the proposed method were confirmed by comparing it with the transient FEA in terms of accuracy and analysis time.

Index Terms—Electromagnetic force, induction motor, time-harmonic finite element analysis

I. INTRODUCTION

TRANSIENT finite element analysis (FEA), a common method to analyze induction motors, suffers from a long analysis time. As the speed of the induction motor increases and the slip frequency decreases, the analysis time grows exponentially. Several studies have employed time-harmonic FEA to shorten the analysis time for induction motors. There have been studies using time-harmonic FEA to extract the parameters of the phase equivalent circuit of an induction motor [1], calculate the forces acting on a linear induction motor [2], and analyze the airgap flux density of a single-phase induction motor [3]. However, the radial electromagnetic forces in induction motors have not yet been analyzed using time-harmonic FEA.

This paper proposes a computationally efficient method for calculating the radial electromagnetic force in an induction motor using time-harmonic FEA. The airgap flux density is calculated through stepping time harmonic FEA by varying the mechanical angle and electrical phase. Maxwell stress tensor (MST) is applied to calculate the radial electromagnetic force. In addition, a spectrum analysis of the radial electromagnetic force was conducted using 2-dimensional fast Fourier transform (2D FFT). The proposed method is validated by comparing the airgap flux density and radial electromagnetic force of transient FEA.

II. STEPPING TIME HARMONIC FEA

The specifications of the induction motor used in this paper are shown in Table 1. The maximum torque at the rated current occurs when the slip frequency is 7Hz. To validate the consistency of the proposed method in terms of airgap flux density and radial electromagnetic force, the proposed method was applied at the slip frequency corresponding to the maximum torque, as well as at a lower frequency of 0.5Hz.

TABLE I
SPECIFICATIONS OF INDUCTION MOTOR

Item	Unit	Value
Number of poles	-	4
Number of stator slots	-	36
Number of rotor bars	-	28
Rated current	Arms	72
Rated speed	rpm	3000

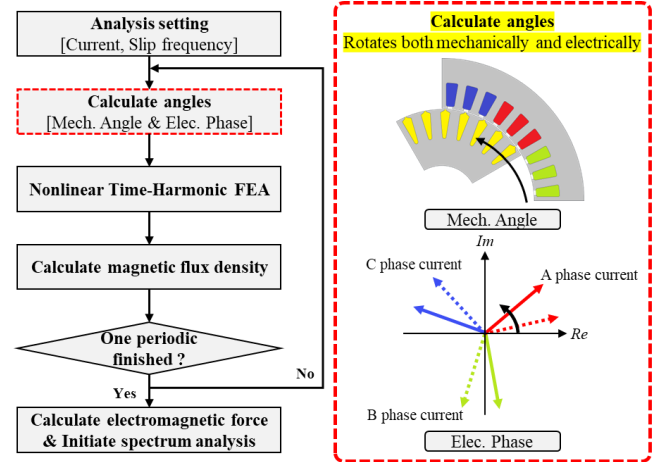


Fig. 1. Flowchart of the stepping time-harmonic FEA.

The process of the stepping time-harmonic FEA proposed in this paper is shown in Fig. 1. First, the magnitude of the current and the slip frequency to be analyzed are applied to the stator. Next, mechanical angles and electrical phases are input to imitate the rotation of the induction motor. A nonlinear time-harmonic FEA is performed, and the flux density at the airgap is calculated. This process is repeated over one cycle of the slip frequency. If the time-harmonic FEA is completed for one cycle, the radial electromagnetic force is calculated using MST as (1):

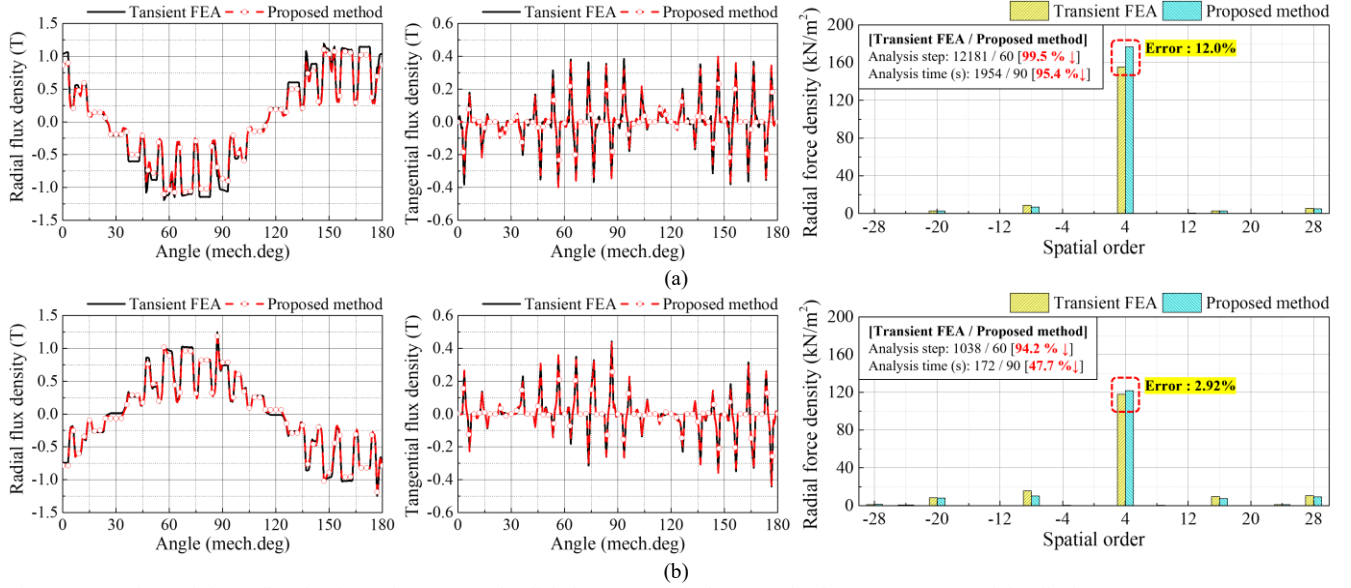


Fig. 2. Comparison of airgap flux density and spectrum of radial electromagnetic force (a) slip frequency 0.5Hz and (b) slip frequency 7Hz.

$$P_r = \frac{B_r^2 - B_t^2}{2\mu_0} \quad (1)$$

where P_r is the radial electromagnetic force density, B_r is the radial magnetic flux density, B_t is the tangential magnetic flux density, and μ_0 is the permeability in vacuum. Unlike the conventional time-harmonic FEA, which performs a single-step analysis, the proposed method considers both mechanical and electrical rotation and analyzes over one cycle. Therefore, it is referred to as stepping time-harmonic FEA.

III. RESULT COMPARISON

The validity of the proposed method was verified by comparing the airgap flux density and the spectrum of radial electromagnetic force with results obtained from transient FEA. The proposed method was applied to the two slip frequencies at the rated current mentioned earlier, while the rotational speed in the transient FEA was maintained at 1000rpm. As shown on the left and middle side of Fig. 2, the radial and tangential airgap flux densities calculated by the proposed method exhibit good agreement with those obtained from transient FEA. A spectrum analysis of radial electromagnetic force was conducted using 2D FFT, and the right side of Fig. 2 illustrates the spatial order with respect to the second-order harmonic in time. Although there are some errors depending on the slip frequency, the dominant orders of the radial electromagnetic force are identical in both methods. Unlike transient FEA, where the number of analysis steps varies with slip frequency, the proposed method has the advantage of maintaining a constant number of analysis steps regardless of the slip frequency. In Fig. 2, the required number of analysis steps decreases, resulting in a reduction in computation time. Fig. 3 shows the experimental setup for testing vibration. In the full paper, the displacement due to the radial electromagnetic force calculated using the proposed method will be compared with the displacement measured through experiments.

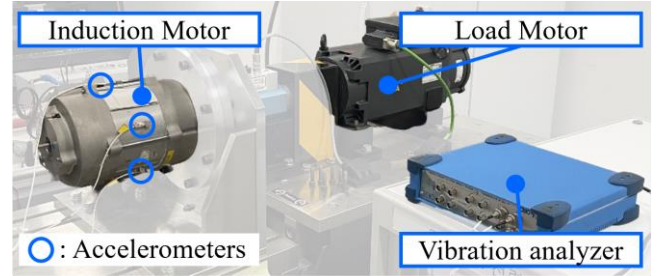


Fig. 3. Vibration test setup.

IV. CONCLUSION

This paper proposes a novel time-harmonic FEA method for calculating the radial electromagnetic force in induction motors. Unlike conventional time-harmonic FEA, stepping time-harmonic FEA is performed by mechanically and electrically rotating over one cycle during the analysis. The radial and tangential airgap flux densities were compared for different slip frequencies, and the radial electromagnetic force was calculated using MST. Furthermore, a spectrum analysis of the radial electromagnetic force was performed using 2D FFT, and the validity and efficiency of the proposed method were confirmed by comparing it with the transient FEA in terms of accuracy and analysis time.

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