Compensation Strategy of the Numerical Analysis in Frequency Domain on Induction Motor considering Magnetic Flux Saturation

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Numerical analysis in frequency domain is one of the useful method to analyze the induction motor owing to its relatively short computational time compared to that of conventional time-domain analysis. Parameters are assumed to have sinusoidal condition for correct frequency analysis. However, flux density at the core is distorted to have non-sinusoidal value on account of the nonlinear material property. Therefore, result of the numerical analysis in frequency domain has an error to the one in time-domain. In this paper compensation strategy is proposed to reduce the error of frequency domain analysis. Comparison between the results of numerical analysis in both time and frequency domain is conducted to verify the error. Then analyzed flux density at the core using frequency analysis is modified to use spatial periodicity of the induction motor. Re-calculation on the result of numerical analysis in frequency domain has conducted with proposed compensation strategy and the result is compared to the one in time-domain analysis for validation.

Index Terms—**Finite element analysis, Frequency-domain analysis, Induction motor, Nonlinear magnetics**

I. Introduction

Methods that are used to analyze the performance characteristics of the motor are normally categorized into two; Equivalent Circuit Method(ECM) and Numerical Analysis Method. It is easy to understand the mechanism of the motor and to calculate performance characteristics, such as torque, using ECM. On the other hand, it is possible to consider partial magnetic flux saturation and nonlinear characteristics of the material using numerical analysis method, while massive calculation time is required for accurate analysis. Commonly, ECM is used at conceptual design stage when decide such thing as motor size and power. Numerical analysis is utilized to consider specific performance of the motor as torque ripple, losses and radial forces[1][2]. Recently, computational speed is rapidly improved so that numerical analysis is used more often. However, it is still difficult to use numerical analysis on designing induction motor since it requires even more computation time due to its transient characteristics.

Useful method to utilize numerical analysis in designing induction motor is conducting it on frequency-domain. Frequency analysis is a similar method to a phasor diagram in circuit theory. All rotating or alternating parameters are transformed in to the frequency domain which makes calculation a lot simpler. The value of rotating frequency should be identical to transform the parameters into the frequency domain, and the parameters, such as flux and current, are assumed to be in sinusoidal condition. Electric motor should satisfy the condition to produce constant average torque as calculated in (2) according to (1) [3]. Induction motor meets its condition since the sum of the rotating mechanical speed and the induced current frequency is equal to the value of synchronous frequency.

$$\begin{aligned}T = \frac{i_s i_r L_{sr}}{4} \{ &\sin[(\omega_m + (\omega_s + \omega_r))t) + \alpha + \beta_0] \\ &+ \sin[(\omega_m - (\omega_s + \omega_r))t) - \alpha + \beta_0] \\ &+ \sin[(\omega_m + (\omega_s - \omega_r))t) - \alpha + \beta_0] \\ &+ \sin[(\omega_m - (\omega_s - \omega_r))t) + \alpha + \beta_0] \end{aligned} \tag{1}$$

$$\omega_s = \omega_r \pm \omega_m \tag{2}$$

Where, ω_s is the synchronous frequency, ω_m is the rotational mechanical speed and ω_r is the frequency of the induced current in the rotor bar.

This is the same condition as the synchronous frequency and the slip-frequency having same value when rotor is restrained. Therefore, parameters can be transformed into the frequency domain on account of the slip-frequency. This method enables reduction of computation time takes to analyze on single slip-frequency, so that torque profile according to the slip-frequency can be obtained with extremely reduced computation time compared to that of time-domain.

Nevertheless, flux wave form is distorted to have non-sinusoidal condition due to the nonlinearity of the electric steel sheet, which violates the assumption of frequency analysis. This causes the error in numerical analysis on frequency domain. In this paper, cause of the error in frequency analysis is investigated and the compensation strategy is proposed. All analysis is carried out based on finite element method.

II. Comparison of the Calculation in Time-Domain and Frequency-Domain

To clarify the phenomenon, the result of numerical analysis fed by current source in time-domain and frequency-domain are compared. The specification of induction motor used in comparison is shown in Table I.

TABLE I
SPECIFICATION OF COMPARED MODEL

Contents	Value
Motor Output Power	100 kW
Outer Diameter	220 mm
No. of Stator Slots	24
No. of Rotor Slot	42
Electric Steel Sheet	35PN230
Rotor Bar Conductor	Aluminum

First, numerical analysis is conducted in frequency-domain. Then, numerical analysis in time-domain is conducted under identical slip-frequencies. The results of comparison are shown in Fig. 1. When slip-frequency is constant, relative value between mechanical speed of rotor and synthesized magnetic field rotating speed remains constant. Therefore, produced torque by electromagnetic field is a constant value when slip-frequency is a single value, theoretically. Since rotating speed is not related to torque, numerical analysis in time-domain is conducted in rotor restrained condition, when slip is 1 and slip-frequency has equal value of synchronous frequency.

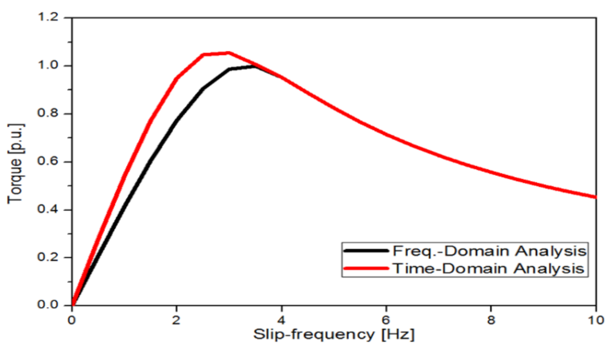
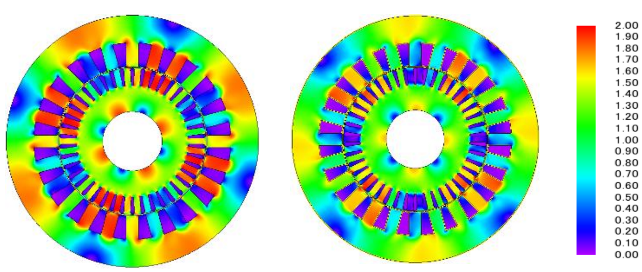


Fig. 1. Comparative analysis result in time-domain and frequency-domain.

As shown in Fig. 1, the results of numerical analysis in time-domain does not match with the one in frequency-domain when slip-frequency is small. Induction motor has highly saturated distribution of magnetic flux density when slip-frequency is small as shown in Fig. 2. Consequently, the error occurs due to the magnetic flux saturation, which is caused by nonlinear characteristic of electric steel sheet.



(a) (b)

Fig. 2. Magnetic Flux Density Distribution at (a) SF=1Hz, (b) SF= 8Hz

Frequency analysis premise sinusoidal condition of flux and current. However, nonlinear characteristic gives rise to magnetic saturation and the flux wave form is distorted because of it. Flux density of single element at the middle of the teeth when motor is magnetically saturated is obtained in Fig. 3. In case of frequency analysis, the peak value of the wave form is considered as the peak value of sinusoidal wave form. Thus, flux wave form is estimated as the smaller value than its actual value. Accordingly, for proper prediction of motor performance, such as torque, the result of the frequency analysis should be compensated as much as the fundamental amplitude of original wave form calculated in time-domain.

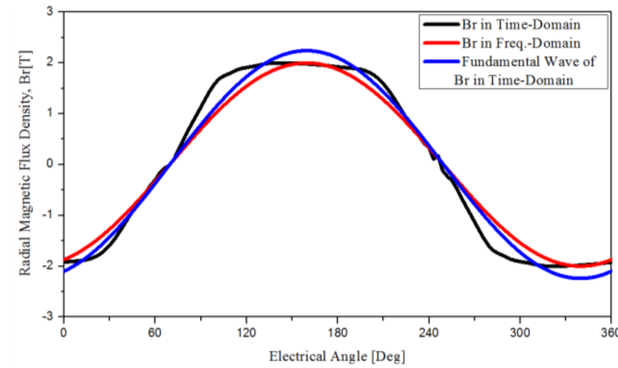
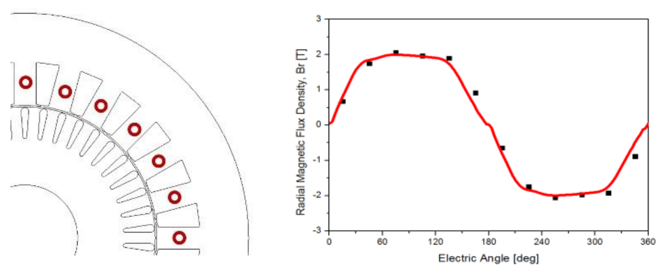


Fig. 3. Flux wave form comparison of the numerical analysis

III. COMPARISON STRATEGY OF THE NUMERICAL ANALYSIS IN FREQUENCY DOMAIN

The most accurate method to compensate is conducting numerical analysis on every slip-frequency where the result in time-domain and frequency-domain do not match. Since it is time consuming process, flux data is compensated using periodicity of the rotating machine [4] as shown in Fig.4. In Fig. 4-(b), black dot is the obtained flux density by numerical analysis in frequency domain and red line is the one from single element in time-domain.



(a) Data obtaining point (b) Wave form compensation

Fig. 4. Flux wave form compensation using periodicity

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