Slip- and High-Frequency Flux Density Separation Method for Rotor Losses Prediction of Induction Motors at Load Conditions

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Abstract: **The fine analysis of different frequency portions of rotor iron losses requires separation of the slip- and high-frequency components of the calculated rotor flux density under load conditions. However, the conventional separation method involves a full slip-cycle finite element simulation of the rotor electromagnetic quantities, which is very expensive in terms of CPU time and memory usage. This paper proposes a time and memory efficient method of slip- and high-frequency separation and rotor loss calculation that needs time-stepping finite element simulation of one or a few supply cycles only. This method finds the magnitudes of slip-frequency flux density by Discrete Fourier Transform (DFT) in space domain. With the fundamentals known, Least Squares Fitting (LST) and DFT are applied to the supply-cycle curves in time domain for the high-frequency harmonics. The calculated harmonics agree well with those by the conventional method. By making good use of the time-varying as well as the spatial information of the rotor flux density, the proposed method achieves a fast and accurate calculation of rotor losses in induction motors.**

Index terms - Induction motors, rotor losses, slip frequency, Discrete Fourier Transform, Finite Element Method

I. Introduction

To calculate the fundamental and harmonic rotor loss by Finite Element Method (FEM), an electromagnetic cycle of the flux density in rotor iron should be calculated completely [1]. Under load condition, a full slip cycle usually has to be simulated in order to extract the high-frequency as well as the slip-frequency components in the rotor flux densities by DFT [2]. However, the CPU time of a slip cycle simulation is generally about 20 to 30 times that of a supply cycle simulation. The simulation of a slip cycle of inverter-fed induction motor is even extremely expensive due to the very small time steps and large consumption of memory.

As to the steady-state analysis of the electrical machines, a parallel time-periodic finite element method (T-P FEM) is presented in [3], which needs more complex mathematical processing. To solve this problem, this paper proposes a method of separating the rotor slip- and high-frequency flux density from one supply cycles of curves simulated by time-stepping finite element method. By utilizing the information from the spatial distribution of the rotor electromagnetic quantities, the method can calculate the slip-frequency magnitude without having to simulate a full slip cycle, and then the high-frequency components can be separated from a supply cycle of harmonic curve which is obtained by curve fitting and subtraction in time domain.

II. CHARACTERISTICS OF ELECTROMAGNETIC QUANTITIES UNDER LOAD CONDITIONS

It is well known that the rotor structure of an induction motor is periodic in space, with respect to a pole pair pitch, as shown in Fig.1 (a). Different positions at the rotor side that have equal radial distance to the center are exposed to the Magnetomotive Force (MMF) wave of equal magnitude. Considering the different reluctances, the rotor flux densities in the above positions still appear respectively in the waveforms with equal magnitude and different time lag depending on the angles between the positions.

This characteristic of rotor electromagnetic quantities is formulated in (1) with the flux density as an example [3].

$$\mathrm{B}(\theta_R,\mathrm{t}) = \vec{M}\cos(np\theta_R + \emptyset + (n(1-s)-1)\omega_1 t)P(\theta_R) \quad (1)$$

Where B is flux density; $\vec{M}$ is the peak of MMF harmonic; $P(\theta_R)$is the permeance harmonics; ω_1 is supply frequency; θ_R is mechanical angle in a stator reference frame; t is time; p is the number of pole pairs; φ is phase angle. In a position that lags $\Delta\theta_R$ in terms of rotor angle, the flux density shows a time shift of Δt whose relation to $\Delta\theta_R$ is given by

$$\Delta\theta_R = \frac{n(1-s)-1}{np}\omega_1\Delta t \quad (2)$$

The characteristic of rotor electromagnetic quantities suggest that the magnitudes of the fundamental time-varying waveforms of flux density at a certain position are approximately equal to those of the fundamental special waveform constituted by a series of flux densities at different sample positions, at a certain moment, as shown in Fig. 1 (b).

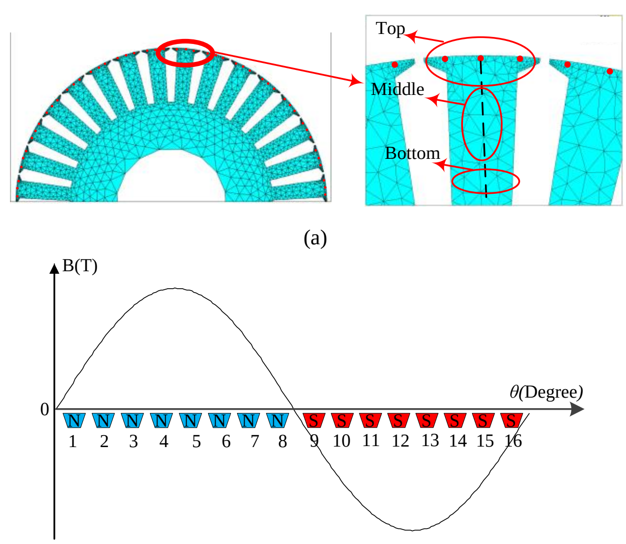

Fig.1 Flux density waveform of Special position. (a) Space symmetrical rotor structure and sampling. (b) Schematic diagram of space waveform

III. SEPARATION METHOD OF SLIP- AND HIGH-FREQUENCY WITH LOAD CONDITIONS

A. *Separation method of slip-frequency component*

Based on the above analysis, we can conclude that the magnitude of the spatial waveform of the flux density in one pole-pair pitch is equal to the magnitude of the time waveform of the flux density in a slip cycle. However, the number of sample points in the rotor core may affect the solution precision of flux density waveform in space. The typical time variations of flux density in rotor teeth, along with the radial and tangential directions, are given in Fig.2 (a) and (b), and the related spatial waveform with different sample points are shown in Fig.2 (c) to (f), it is noted that the flux density is computed by the in-house FEA software. Therefore, the reasonably chosen spatial sample points are the key to the accurate separation of the high frequency components, and the details will be presented in the full paper.

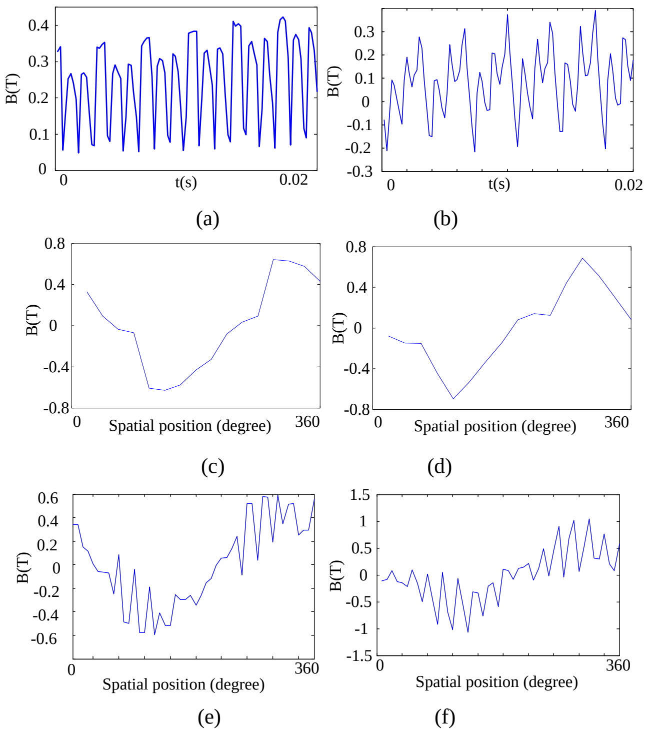

Fig.2 Time and spatial waveform of typical flux density in rotor tooth. (a) Radial flux density in supply cycle. (b) Tangential flux density in supply cycle (c) Spatial Radial flux density with one sample point. (d) Spatial tangential flux density with one sample point. (e) Spatial Radial flux density with three sample points. (f) Spatial tangential flux density with three sample points.

B. Separation method of high-frequency

The high-frequency flux density can be separated by subtracting the slip-frequency components, as shown in Fig.3, and the magnitude of each harmonic can be obtained by DFT.

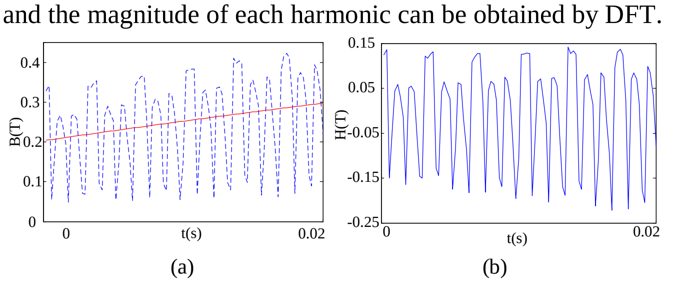

Fig.3 Separation of slip- and high-frequency components. (a) Slip-frequency fitting curve. (b) High-frequency waveform.

C. Magnitude of flux density at special position

With the proposed method, the magnitudes of flux densities at slip- and high- frequency are calculated for the top, middle and bottom positions in the rotor iron core, and the fundamental and the major harmonic components are given in Fig.4, where B_f, B_{1s}, B_{2s} are the magnitude of the fundamental, the first slot harmonic and the second slot harmonic, respectively.

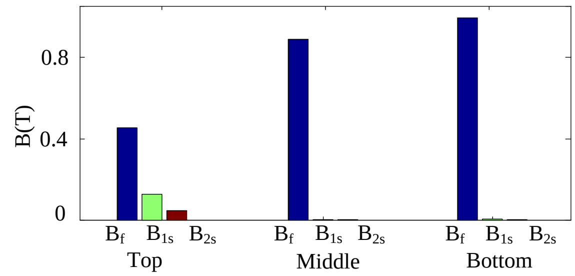

Fig.4 Magnitudes of flux density harmonics in rotor teeth.

IV. Validation of Presented Method

A. Comparison of the in supply cycle and full slip-frequency cycle

The effectiveness of the proposed method is validated by comparing the waveform given by the conventional full slip cycle simulation and that reconstructed by the proposed curve fitting method, as shown in Fig.5. It can be seen that the harmonics obtained by the proposed curve fitting method agree well with those from a full slip cycle of simulation. And the further results of loss prediction and experimental validation will be given in the full paper.

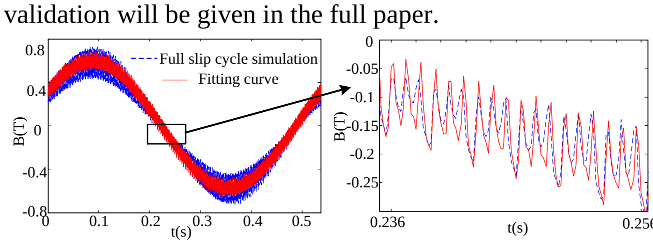

Fig.5. Flux density curve at the top of rotor, by the conventional method and by the proposed curve fitting method.

V. Conclusion

This paper proposes a method of extracting the fundamental harmonics in the rotor flux density of an induction motor under load condition, from one or a few supply cycles of simulated curve. The slip-frequency magnitude of flux density can be extracted by DFT by utilizing the spatial information of these flux densities at a certain moment. The proposed method can significantly reduce the calculation overhead in terms of CPU time and memory usage, for rotor losses of induction motors.

References

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