Improvement of Convergence Behavior for Steady-State Analysis of Permanent Magnet Synchronous Motor

H. Katagiri, Y. Kawase and T. Yamaguchi
Department of Information Science, Gifu University
1-1, Yanagido, Gifu, 501-1193, Japan
E-mail khiro@fem.info.gifu-u.ac.jp

***Abstract*— The usefulness of the novel simplified Time Periodic-Explicit Error Correction method, which can improve the convergence behavior for the steady-state analysis of electromagnetic equipments including DC magnetic field, for the practical permanent magnet synchronous motor (PMSM) is clarified quantitatively. Moreover, it is found that the convergence behavior for the steady-state analysis of a PMSM can be improved by using not the periodicity of the exciting current but the periodicity of the eddy current in the permanent magnet.**

***Index Terms*— DC magnetic field, permanent magnet synchronous motor, simplified time periodic-explicit error correction, steady-state analysis.**

I. Introduction

In order to improve the convergence behavior for the steady-state analysis of the magnetic field including the eddy current, Dr. Tokumasu *et al*. developed the simplified time periodic-explicit error correction (simplified TP-EEC) method [1], and reported the improved convergence behavior of the steady-state analysis of the C-shaped core with the aluminum plate excited by the sinusoidal current.

However, the simplified TP-EEC method can not be applied to the magnetic field analyses including the DC magnetic field because the method needs the ordinary cycle periodicity of the magnetic vector potential like the complex approximation method.

In order to improve the convergence behavior of the magnetic field analyses including the DC magnetic field, we proposed a novel simplified TP-EEC method (hereinafter called “simplified TP-EEC-DC method”), and the usefulness of the method is clarified thought the steady-state analysis of the C-shaped core with the aluminum plate excited by the sinusoidal current including the DC current [2].

In this paper, the usefulness of the method for the practical permanent magnet synchronous motor (PMSM) is clarified quantitatively through the steady-state analysis of a interior permanent magnet synchronous motor (IPMSM).

Moreover, it is found that the convergence behavior for the steady-state analysis of a PMSM can be improved by using not the periodicity of the exciting current but the periodicity of the eddy current in the permanent magnet.

II. Analysis Method

A. Fundamental Equations of Magnetic Field

The fundamental equations of the magnetic field discretized by the back Euler method with step-by-step can be written using the magnetic vector potential $\boldsymbol{A}^i$ at time step i as follows:

$$\mathrm{curl}(\nu\,\mathrm{curl}\,\boldsymbol{A}^i) = \boldsymbol{J}_0{}^i + \boldsymbol{J}_e{}^i + \nu_0\,\mathrm{curl}\,\boldsymbol{M} \quad (1)$$

$$\boldsymbol{J}_e{}^i = -\sigma\frac{\boldsymbol{A}^i - \boldsymbol{A}^{i-1}}{\Delta t} \quad (2)$$

where ν is the reluctivity, $\boldsymbol{J}_0{}^i$ is the exciting current density, $\boldsymbol{J}_e{}^i$ is the eddy current density, ν_0 is the reluctivity of the vacuum, $\boldsymbol{M}$ is the magnetization of the permanent magnet, σ is the conductivity, and Δt is the time interval.

B. Simplified TP-EEC-DC method with ordinary cycle periodicity [2]

The conventional simplified TP-EEC method with ordinary cycle periodicity needs the ordinary cycle periodicity of $\boldsymbol{A}$ like the complex approximation method. Therefore, the method can not be applied to the magnetic field analyses including the DC magnetic field.

On the other hand, in the simplified TP-EEC-DC method with ordinary cycle periodicity, the ordinary cycle periodicity of $\boldsymbol{J}_e$ is employed.

$\boldsymbol{J}_e$ does not include the DC component even if the time-periodic $\boldsymbol{A}$ includes the DC component. Thus, $\boldsymbol{J}_e$ satisfies the ordinary cycle periodicity because it does not include the DC component.

$$\sum_{j=0}^{m-1}\boldsymbol{J}_e{}^{i-j} = 0 \quad \left(\because \int_t^{t-T}\boldsymbol{J}_e(\tau)d\tau = 0\right) \quad (3)$$

(at steady state)

where T is the time period, and m is the number of time steps for the time period.

By using the ordinary cycle periodicity of $\boldsymbol{J}_e$, $\boldsymbol{J}_e$ can be corrected like $\boldsymbol{A}$ corrected in the conventional simplified TP-EEC method with the ordinary cycle periodicity as follows:

$$\tilde{\boldsymbol{J}}_e{}^i = \boldsymbol{J}_e{}^i + \boldsymbol{p}, \quad \boldsymbol{p} = -\frac{1}{m}\sum_{j=0}^{m-1}\boldsymbol{J}_e{}^{i-j} \quad (4)$$

where $\widetilde{J}_e^{\,i}$ is the corrected eddy current density, and $\boldsymbol{p}$ is the correction vector by which the error of J_e^i is approximated. $\boldsymbol{p}$ becomes zero at the steady state because (3) is satisfied.

The corrected magnetic vector potential $\widetilde{A}^i$ can be obtained by solving (1) with $\widetilde{J}_e$ instead of (2) as follows:

$$\mathrm{curl}(\nu\,\mathrm{curl}\widetilde{\boldsymbol{A}}^i) = \boldsymbol{J}_0^{\,i} + \widetilde{\boldsymbol{J}}_e^{\,i} + \nu_0 \mathrm{curl}\boldsymbol{M} \qquad (5)$$

This method can be applied to the steady-state analysis of the nonlinear magnetic field analysis.

By using (4) and (5) every one period of the time-periodic eddy current, the convergence behaviors of steady-state analyses can be improved.

III. STEADY-STATE ANALYSIS OF IPM MOTOR

Fig. 1 shows the analyzed model of an IPM motor based on that in [3]. In order to make the effects of the simplified TP-EEC-DC method understandable, the size is larger than that in [3] and the rotation speed is higher than that in [3]. The analysis region is 1/2 of the whole region because of the symmetry. The three-phase AC current flows in the coil.

Fig. 2 shows the eddy current density waveform in element A in permanent magnet as shown Fig.1 at the steady state. The eddy current waveform satisfies the ordinary cycle periodicity not only in one period of the exciting current, but also one period of the slot harmonics, which is 120 degrees of the electrical angle. Therefore, it seems that the simplified TP-EEC-DC method can be used not only every one period of the excited current but also every one period of the slot harmonics.

Fig. 3 shows the errors of the instantaneous eddy current loss in the permanent magnet, which are normalized by the eddy current loss at the steady state. The error means the difference between the instantaneous value and the value at the steady state. The corrections by the simplified TP-EEC-DC method are repeated until 720 degrees of the electrical angle. By using the simplified TP-EEC-DC method, the convergence behaviors become better after the correction. The corrections every one period of the slot harmonics decrease the error more rapidly than that every one period of the excited current.

The convergence behavior for the steady-state analysis of the IPMSM can be improved by using not the periodicity of the exciting current but the periodicity of the eddy current in the permanent magnet.

Table I shows the discretization data and CPU time. The time step calculations are repeated until the error of the instantaneous eddy current loss becomes less than 1%. The CPU time using the simplified TP-EEC-DC method using the periodicity of the slot harmonics is shortest, and the CPU time is approximately 1/88 of that without the simplified TP-EEC-DC method.

In the full paper, we also describe the theoretical proof of the simplified TP-EEC-DC method using the periodicity of the eddy current in the permanent magnet in detail, and the method is applied to other permanent magnet motors, and the usefulness is clarified.

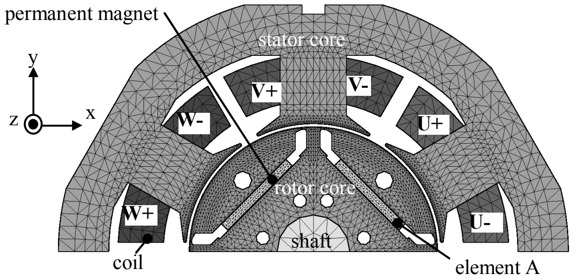

Fig. 1. IPM motor.

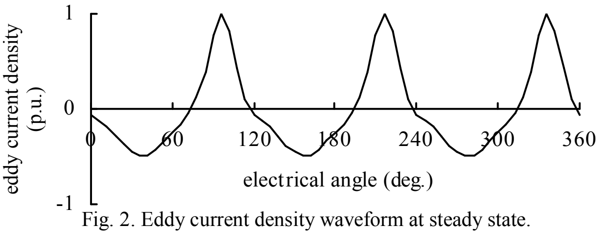

Fig. 2. Eddy current density waveform at steady state.

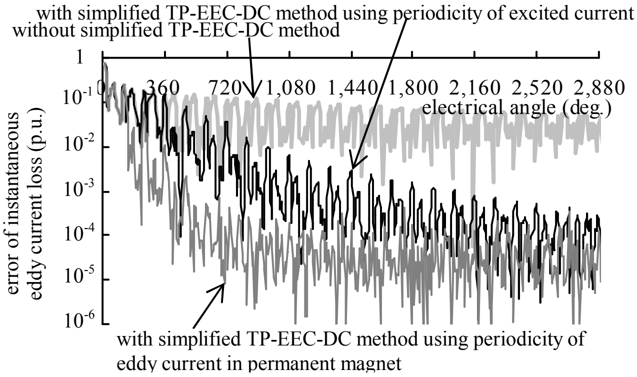

Fig. 3. Errors of instantaneous eddy current loss.

TABLE I
DISCRETIZATION DATA AND CPU TIME.

	without simplified TP-EEC-DC method	with simplified TP-EEC-DC method using periodicity of excited current	with simplified TP-EEC-DC method using periodicity of slot harmonics
Number of elements	30,552		
Number of time steps required for steady states	3,773	123	42
CPU time (min.)	173.8	5.8	2.0

Computer used: Core i7 (3.4GHz) PC

REFERENCES

[1] T. Tokumasu, M. Fujita, and T. Ueda, "Problems Remained in Practical Usage of 2 Dimensional Electromagnetic Analyses (5)", *Papers of Joint Technical Meeting on Static Apparatus and Rotating Machinery*, SA-09-57/RM-09-63 (2009) (in Japanese).

[2] H. Katagiri, Y. Kawase, T. Yamaguchi "Novel Simplified Time Periodic-Explicit Error Correction Method for Steady State Analysis of AC Magnetic Field Including DC Component", *IEEJ Trans. PE*, vol. 133, no. 3, 2013 (to be published).

[3] Y. Kawase, T. Yamaguchi, T. Yano, M. Igata, K. Ida, Y. Kataoka, A, Yamagiwa, "Three-Dimensional Finite Element Analysis of an Interior Permanent Magnet Motor Considering Carrier Harmonics," *Papers of Joint Technical Meeting on Static Apparatus and Rotating Machinery*, SA-05-96/RM-05-103, 2005 (in Japanese).