Analysis of the Saturated Electromagnetic Devices under DC Bias Condition by the Modified Harmonic Balance Finite Element Method

¹Xiaojun Zhao, ²Junwei Lu, Senior Member IEEE, ¹Lin Li, ³Zhiguang Cheng, ¹Tiebing Lu

¹School of Electrical and Electronic Engineering, North China Electric Power University

Yonghua North Street, Baoding, 071000, China

158748295@163.com

²Griffith School of Engineering, Griffith University, Brisbane, 4111, Australia j.lu@griffith.edu.au

Abstract— The modified harmonic balance finite element method was applied to investigate the DC biased problem in the saturated electromagnetic devices. The electromagnetic field was solved by the block Gauss-Seidel algorithm combined with the relaxation iterative method. The DC bias effects on magnetizing current and magnetic induction was analyzed by means of harmonic solution in multi-frequency domain. The computation is more efficient than the time-domain FEM and harmonic analysis can be achieved.

L INTRODUCTION

The harmonic balance finite element method (HBFEM) proved to be suitable for solving the harmonic problem [1]. A related method via block decomposition of the system equation was also presented [2]. In the HVDC transmission system, direct current invades the transformer windings and threats the normal operation of electric network. Therefore DC bias effects on power transformers should be investigated by processing the DC component and considering coupled problems in calculation of the DC biased magnetic field.

II. DECOMPOSED HARMONIC BALANCED SYSTEM EQUATION

The vector potential equation can be used to describe the nonlinear magnetic field.

$$\nabla \times (\nu \nabla \times A) = J \tag{1}$$

Since electromagnetic devices are excited simultaneously by direct and alternating current, the steady state variables xare expressed by a triangular series,

$$x(t) = x_0 + \sum_{n=1}^{\infty} (x_{2n-1} \sin n\omega t + x_{2n} \cos n\omega t)$$
(2)

The harmonic finite element system matrix of HBFEM can be obtained by substituting (2) into (1),

$$D_{i,i}A_i + N_iA_i = \sum_{j \neq i}^{\infty} -D_{i,j}A_j + G_i \qquad (i, j = 1, 2, 3...)$$
(3)

 $D_{i,i}$ and N_i represent self reluctivity matrix and harmonic matrix respectively for the *i*-th harmonic solution of magnetic vector potential A_i . $D_{i,i}$ means the mutual reluctivity related to the *i*-th and *j*-th harmonic. G_i is obtained from the spatial distribution of *i*-th harmonic component of current density.

As electromagnetic devices are excited by voltages, the electric potential difference in the coil region can be treated as line integral of electric potential gradient,

$$V_{k,i} = \int_{I_k} (-\nabla \varphi) dl = R_k J_{k,i} S_k + \int_{I_k} (\partial A_i / \partial t) dl$$
(4)

The subscripts k and i indicate circuit number and harmonic number respectively. Combined with finite element method, the corresponding matrix representation can be given,

$$V_{k,i} = M_k J_{k,i} + C_{k,i} A_i$$
(5)

III. MODIFIED HARMONIC BALANCE FINITE ELEMENT METHOD

The harmonic solutions of magnetizing currents and magnetic vector potentials are obtained by solving (3) and (5),

$$\begin{bmatrix} Q_i & G_{k,i} \\ C_{k,i} & M_k \end{bmatrix} \begin{bmatrix} A_i \\ J_{k,i} \end{bmatrix} = \begin{bmatrix} F_i \\ V_{k,i} \end{bmatrix}$$
(6)

$$F_i = \sum_{j \neq i}^{\infty} -D_{i,j} A_j \tag{7}$$

 Q_i is the sum of matrices $D_{i,i}$ and N_i . The term $D_{i,i}$ is diagonally dominant in system matrix in the traditional HBFEM and relatively weak relations exist among all harmonic components of solutions. Therefore, the block Gauss-Seidel algorithm can be used to solve the separated harmonic balance finite element equations. Compared with the traditional HBFEM, the realistic computation by the modified method benefits from the reduced memory requirement, meanwhile the computational time is unaffected.

The modified method is applied to investigate the mechanism of DC biased phenomenon in an Epstein framelike core model and a three-phase power transformer. Magnetizing currents shown in Fig.1 are calculated under different DC bias. The fundamental frequency is 50 Hz.



Fig. 1. Magnetizing currents under different DC bias

IV. REFERENCES

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