This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TEC.2016.2623566, IEEE Transactions on Energy Conversion

Unbalanced Magnetic Force Analysis in Eccentric Surface Permanent-Magnet Motors Using an Improved Conformal Mapping Method

Farhad Rezaee-Alam, Behrooz Rezaeealam, and Jawad Faiz, *Senior Member, IEEE*

***Abstract*-- This paper introduces an improved conformal mapping (ICM) method for the calculation and analysis of unbalanced magnetic force (UMF) in eccentric surface-mounted permanent-magnet (SMPM) motors considering the static, dynamic and mixed rotor eccentricities. Having the on-load air gap field components obtained through ICM, and by using the Maxwell Stress Tensor (MST) method, the ICM method accurately predicts the on-load components of magnetic local traction and UMF due to PMs, the armature reaction, and the mutual interaction between both fields under the rotor eccentricity. The other purpose of this paper is to illustrate the difference between the influences of static, dynamic, and mixed rotor eccentricities on the UMF using the ICM method. The influence of initial eccentricity angle and the magnitude of eccentricity on the UMF are also investigated under the static, dynamic, and mixed rotor eccentricities. The predicted results obtained through ICM are verified by comparing with the corresponding results obtained through Finite Element Method (FEM) and the Frozen Permeability Method (FPM). The ICM method is also validated by the experiment.**

***Index Terms*-- Dynamic eccentricity (DE), improved conformal mapping (ICM), magnetic field, magnetic saturation, mixed eccentricity (ME), permanent magnet (PM), static eccentricity (SE).**

I. Introduction

ECCENTRICITY fault changes the air gap magnetic field and hence produces the vibration, the noise, and the unbalanced magnetic force (UMF), which actually bends the shaft and magnifies the magnetic force. A precise model is necessary to predict the air gap flux density distribution for calculation the UMF. So far, different techniques have been used to calculate the UMF in the electrical machines under the rotor eccentricity fault. The finite element method (FEM) can precisely model the impact of the rotor eccentricity fault on the performance of electrical machines [1]. However, FEM is a time-consuming method and is usually used in final stage in order to verify the developed analytical model. The magnetic equivalent circuit (MEC) method [2-3], the winding function theory (WFT) [4-5], and the field reconstruction method (FRM) [6] are not also appropriate methods for modeling the rotor eccentricity fault. The main defect of the MEC is that it is not able to model the air gap of electrical machine precisely. At this end, the MEC and the conformal mapping (CM) methods was combined in [7]. The accuracy of WFT depends on the precision of the modeling of the air-gap and the magnetic saturation. FRM also acts based on the law of superposition and it is quite FEM-dependent.

There are also different analytical models for eccentricity fault analysis. One is based on the exact subdomain model and the perturbation method [8-10]. The perturbation method is very accurate but very complicated. The perturbation analysis appears reasonable only for low severity of eccentricity fault. However, as the ratio of rotor eccentricity fault to air gap length increases, the analytical results based on the perturbation method leads to error. Other examples of analytical models are the Atallah model [11], the Zhu model [12], and the Bianchi model [13].

In [14-15], Dorrell has presented a simple analytical model to analyze the UMF in cage induction machine based on the air gap permeance approach, while considering the stator and rotor MMF harmonics. He then has improved the model introduced in [14] by taking into account the tooth saturation effect [16]. As reported in [17], the core saturation strongly changes the magnitude of UMF in electrically excited machines. These unsaturated [14] and saturated [16] analytical models were used to analyze the UMF in cage induction motors with axial-varying rotor eccentricity [18]. Dorrell has also compared the UMF produced in fractional-slot PM motors with surface-magnet and consequent-pole rotors under centered and rotor eccentricity conditions [19]. In [14-20], the one dimensional (1-D) models have been used for the UMF analysis. The two dimensional (2-D) slotless analytical models have been used under load [21] and no-load conditions [8] for magnetic field and UMF analysis. The CM method has not been so far used accurately for magnetic field analysis in electrical machines with rotor eccentricity fault [22].

In this paper, an ICM method presented in [23] with a new technique for modeling the magnetic saturation is used for the UMF analysis in one typical SMPM motor with 12 slots and 4 poles under the SE, DE, and ME faults. This paper is organized as follows: Section II presents a new technique to include the magnetic saturation in ICM method. Section III states the importance of separation and calculation of the air gap field components at on-load. The simulation results of local traction and UMF and their comparison with

F. Rezaee-Alam and J. Faiz are with the Department of Electrical and Computer Engineering, University of Tehran, Tehran 14395, Iran. (e-mail: farhad.rezaee.alam@gmail.com) .
B. Rezaeealam is with the Departement of Electrical Engineering, Lorestan University, Daneshgah Street, 71234-98653, Khorramabad, Lorestan, Iran

corresponding FEM and FPM results are given and discussed in sections IV-V. An experimental verification is presented in section VI. Section VII concludes the paper.

II. SATURATION EFFECT MODELING

The ICM method for eccentricity fault analysis has been presented in [23]. In [23], the saturated complex air gap permeance was calculated for step (n+1)th by using the calculated magnetic field in step (n)th while neglecting the magnetic saturation for the first step of simulation. In the present paper, modeling approach for magnetic saturation has been improved compared to [23]. The simulation algorithm includes two loops, one internal loop and one external loop. The internal loop is used to take into account the magnetic saturation, and the external loop is used to calculate the air gap magnetic field, the flux-linkage, the back-EMF, the phase currents, the UMF, and so on.

There is no internal loop in [23], leading to low accurate model of saturation. Fig. 1 shows the general flowchart for transient analysis of an eccentric SMPM motor, including the external and internal loops. As shown in Fig. 1, the inductance matrix is separately calculated in each time step of simulation while considering the magnetic saturation.

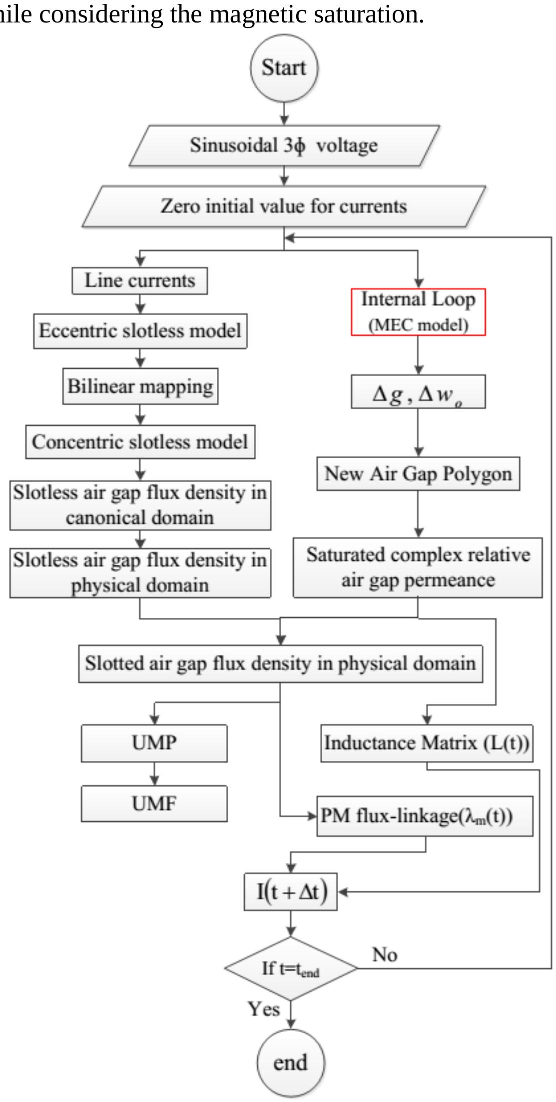

Fig. 1. General flowchart for transient analysis

In the present paper, the increase in the air gap length under each tooth and also the increase in the width of slot openings due to the saturation effect are calculated on-line in each rotor position (in each time step of simulation) by using an internal loop. To calculate these increments in the air gap length and slot opening width in any rotor position, it is necessary to know the value of μ_r before the field solution is obtained. However, it is not known the value of μ_r before obtaining the solution.

For this reason, an internal loop is made. This internal loop includes a nonlinear model of magnetic equivalent circuit (MEC) of the analyzed SMPM motor (12s/4p). Since the B-H curve of the core is nonlinear this MEC model is nonlinear

The node potential equations are assembled in matrix form. This system of algebraic equations is nonlinear and establishing an iterative procedure is necessary. This process is called the method of successive approximation. This method is very simple as such that the normal computational procedure (for linear cases) can be used in an iterative form. The process is as follows:

A. Apply an initial approximation for relative permeability (μ_r) of all element of the stator and rotor core. This initial μ_r is assumed to be equal to the slope of B-H curve in linear region divided by μ_0.

B. Using the approximation to calculate the scalar magnetic potential for all nodes (i.e. the MEC model is solved).

C. The flux density in all core elements can be calculated while having the scalar magnetic potential for all nodes.

D. The new μ_r for each element of the core can then be calculated using (1) while taking into account the B-H curve of the core. The stator and rotor yokes are assumed to be unsaturated.

$$\begin{cases} \emptyset_t \rightarrow \begin{cases} B_{tb} \xrightarrow{BH\ curve} \mu_{r\,tb} = \dfrac{1}{\mu_0}\dfrac{dB}{dH} \\ B_{ts} \xrightarrow{BH\ curve} \mu_{r\,ts} = \dfrac{1}{\mu_0}\dfrac{dB}{dH} \end{cases} \\ \emptyset_{tip} \rightarrow B_{tip} \xrightarrow{BH\ curve} \mu_{r\,tip} = \dfrac{1}{\mu_0}\dfrac{dB}{dH} \end{cases} \quad (1)$$

where '*t*', '*tb*' and '*ts*' are respectively the written abbreviations of 'tooth', 'tooth body', and 'tooth shoe'.

E. Compare the new μ_r with old μ_r (of previous approximation) for each element of the core. If the error criterion indicates that the convergence has not yet been obtained, apply another approximation by using the new μ_r, and go to step B.

Repeat steps B through E until the solution converges.

Having these relative permeabilities (μ_r), the equivalent reluctance can be calculated for each part of the tooth (body, shoe, and tips), as follows:

$$\begin{cases} R_{tb} = \dfrac{l_{tb}}{\mu_0 . \mu_{r\,tb} . A_{tb}} \\ R_{ts} = \dfrac{l_{ts}}{\mu_0 . \mu_{r\,ts} . A_{ts}} \\ R_{tip} = \dfrac{l_{tip}}{\mu_0 . \mu_{r\,tip} . A_{tip}} \end{cases} \quad (2)$$

These equivalent reluctances can be replaced by a proper increase of air-gap length under each tooth (Δg), and by proper decrease of the length of tooth-tips (Δl_{tip}), as follows: