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An improved conformal mapping method for magnetic field analysis in surface mounted permanent magnet motors

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Abstract

Purpose – The purpose of this paper is to present an improved conformal mapping (ICM) method that simultaneously considers the influence of relative recoil permeability of PMs, the armature reaction, the stator slotting, and the magnetic saturation on determination of the PM operating point in its different parts.

Design/methodology/approach – The ICM method is a time-effective method that considers the magnetic saturation by suitable increments in air-gap length under each tooth and also the width of slot openings. In this paper, the analytical and numerical conformal mappings such as the Schwarz-Christoffel (SC) mapping are used for magnetic field analysis due to the permanent magnets and the armature reaction in one slotted air gap. The field solution in the slotted air gap is obtained through the modulation of field solution in one slotless air-gap using the complex air-gap permeance.

Findings – The ICM method can consider the magnetic saturation in different electric loadings, and also the variation of PM operating points in its different parts.

Practical implications – The ICM method is applied to one surface mounted permanent magnet (SMPM) motor and is verified by comparing with the corresponding results obtained through finite element method (FEM), and frozen permeability finite element method (FP-FEM).

Originality/value – This paper presents an ICM method with a new technique for saturation effect modeling, which can be used to separate and calculate the on-load components of air-gap field and torque.

Keywords Modelling, Magnetic field, Permanent magnet machine, Magnetic saturation, Improved Conformal Mapping (ICM), Schwarz-Christoffel (SC) mapping

Paper type Research paper

1. Introduction

In-depth knowledge of air-gap magnetic field distribution is necessary for accurate computation of torque, back electromotive force (Back-EMF), winding inductances, noise and vibration. Although the finite element method (FEM) can be used for accurate prediction of magnetic field, the numerical methods are generally more time-consuming than other methods (Ebrahimi *et al.*, 2009).

Alternatively, the analytical and semi-analytical methods are not time-consuming and can be used for initial evaluation of performance and design optimization of electrical machines. Apart from the magnetic equivalent circuit (MEC) method (Naderi, 2016), the analytical and semi-analytical methods are unable to include the saturation effect in the field calculation. However, the main defect of MEC is in the modeling of air gap of electrical machines. For this reason, MEC was combined with conformal mapping (CM) method in Lim *et al.* (2014) and with the analytical models based on the formal solution of Maxwell's equations in Laoubi *et al.* (2015). The winding function theory (Ojaghi and Nasiri, 2014) and

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the field reconstruction method (Torregrossa *et al.*, 2012) are other examples of the semi-analytical methods. The accuracy of winding function theory depends on the modeling precision of the air-gap and the saturation effect. Field reconstruction method also acts based on the law of superposition, and it is quite FEM-dependent. The analytical models can be classified in two general groups, as:

(1) 1-D Analytical Model.

(2) 2-D Analytical Model.

The 1-D analytical model is very convenient for modeling the electrical machines with small air gap, such as the induction motors (Frauman *et al.*, 2007), which mainly predicts the air gap flux density by multiplying the magneto-motive force (MMF) by the air gap permeance distribution. The tangential component of air gap flux density is neglected by the 1-D analytical model, for this reason the use of this model is not suitable for modeling the surface mounted permanent magnet (SMPM) electrical machines. However, the 1-D analytical model was used for the cogging torque prediction in light of its simplicity for physical understanding of the problem (Zhu *et al.*, 2009).

The first group of 2-D analytical models is the subdomain model. The main idea of the subdomain model is to solve the governing equations in all subdomains (air gap, permanent-magnets, slots and, slot openings) and to obtain the final results by applying the boundary conditions on the interfaces between subdomains (Zhu *et al.*, 2010).

Another group of 2-D analytical model is the CM method which is used in this paper. The CM method acts based on the complex analysis. The CM method was initially used to calculate the carter coefficients for considering the slotting effect in electrical machines (Heller and Hamata, 1977). The CM method was then used to derive a 2-D relative permeance function that considers the slotting effect (Zhu and Howe, 1993). However, this 2-D permeance function is unable to predict the tangential component of air-gap magnetic field. The complex permeance model was proposed by Zarko, which was superior to the previous models (Zarko *et al.*, 2006). An infinitely deep slot opening, ignoring the interaction effect between adjacent slots, and neglecting the deformation of magnet shape and circular contour to predict the air gap flux density are the main assumptions of Zarko's model. The numerical Schwarz-Christoffel mapping and the Matlab SC Toolbox were used to relax these assumptions (Driscoll and Trefethen, 2002). In O'Connell and Krein (2009), three CMs, including SC mapping and two logarithmic complex functions, are used to calculate the air gap field in an annular domain (main canonical domain) using Hague's solution (Hague, 1929).

This paper is organized as follows: Section 2 presents the modeling process by ICM. A new technique for considering the magnetic saturation is introduced in Section 3. The simulation results and their comparison with those obtained through FEM and FP-FEM are shown and discussed in Section 4. Section 5 compares different methods in terms of the computation time. Section 6 presents the conclusion.

2. Modeling process by ICM

The simulation algorithm by ICM was explained in Abbaszadeh and Rezaee Alam (2016) for current-input SMPM motors. However, the ICM method presented in this paper is more improved than (Abbaszadeh and Rezaee Alam, 2016) for exact modeling the saturation effect and calculating the on-load cogging torque for voltage-input SMPM motors.