Journal of Magnetism and Magnetic Materials 417 (2016) 389–396

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Analytical model and design of spoke-type permanent-magnet machines accounting for saturation and nonlinearity of magnetic bridges

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ARTICLE INFO

Article history:
Received 16 April 2016
Received in revised form
14 May 2016
Accepted 31 May 2016
Available online 2 June 2016

Keywords:
Spoke-type permanent-magnet machines
Analytical model
Lumped parameter magnetic circuit model
Magnetic material
Magnetic bridge
Magnetic field distribution

ABSTRACT

Based on subdomain model, this paper presents an analytical method for predicting the no-load magnetic field distribution, back-EMF and torque in general spoke-type motors with magnetic bridges. Taking into account the saturation and nonlinearity of magnetic material, the magnetic bridges are equivalent to fan-shaped saturation regions. For getting standard boundary conditions, a lumped parameter magnetic circuit model and iterative method are employed to calculate the permeability. The final field domain is divided into five types of simple subdomains. Based on the method of separation of variables, the analytical expression of each subdomain is derived. The analytical results of the magnetic field distribution, Back-EMF and torque are verified by finite element method, which confirms the validity of the proposed model for facilitating the motor design and optimization.

1. Introduction

Benefiting from magnetic materials, the permanent-magnet (PM) motors obtain the advantages of compact structure, high power/torque density and high efficiency, as well as some operational advantages such as wider constant-power speed range and higher torque output [1–5]. As a typical topology of PM motors, the spoke-type motor offers a more superior performance for the reduction of consumed PM and the manufacturing cost owing to the concentrated flux from rotor PMs [6–8].

The no-load air-gap magnetic field distribution (MFD) is the foundation of the performance indices for spoke-type motor design, i.e., steady state and transient dynamic performance, back electromotive force (EMF), and torque-speed characteristics, etc. For a design purpose, finite element method (FEM) and analytical model are often used to predict the MFD. Various researches on the design of these machines with FEM have been successfully investigated in the past [9], e.g., a novel model of 2-D FEM in [10] is proposed to investigate PM overhang structure. The FEM considers magnetic energy, and is useful to the design and analysis of PM motor with PM overhang. In [11], considering skewing and sinusoidal permanent magnet configurations, the FEM is adopted to minimize torque pulsations, including cogging torque and electromagnetic torque ripple for a spoke-type motor. However, FEM is too time-consuming and theory-lacking to provide a physical insight to the motors, especially for the parametric analysis at the first stages of the design process. Benefiting from the logical exploration of the whole search space of solutions, analytical models can effectively reduce the predesign stages duration and provide analytical understanding. From the point of view of engineer and research, analytical models are often preferred [12].

There are two common type analytical models: the lumped parameter magnetic circuit model and analytical model based on the Poisson's and Laplace's equations in constant permeability regions. The former mainly calculate the average of the magnetic field rather than the detailed distribution in a region [13,14]. The drawback of the method is that the calculation accuracy is greatly affected by the way how to build the analytical models, which weakens the contributions to the design and optimization.

The analytical model based on the Poisson's and Laplace's equations help to overcome aforementioned problem. In [15] and [16], the MFD of a spoke-type motor is calculated by a subdomain model based on the assumption of nonmagnetic bridges. Although this method is qualified for the motor design, the neglect of magnetic bridges limits the application.

In fact, the spoke-type motor with magnetic bridges is widely used in EVs. As the saturation and nonlinearity of magnetic bridges complicate the boundary conditions making no solution

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http://dx.doi.org/10.1016/j.jmmm.2016.05.106
0304-8853/

of the Poisson's and Laplace's equations, to the author's knowledge, there is no study on these machines that designs this motor with analytical models. This paper presents a new analytical model to predict the no-load MFD of spoke-type motors considering saturation and nonlinearity of magnetic materials. Based on the method, the performance is calculated, e.g., back-EMF, torque. The finite element (FE) results verify the validity of the analytical model.

2. Analytical model

The advantages of the proposed approaches are highlighted by a 16-pole/18-slot spoke-type motor. Fig. 1 shows the initial model with magnetic bridges and fan-shaped magnets, where g_i is the angular position of the ith magnet, α is the width angle of magnets, R_f, R_{mi}, R_{mo}, R_r and R_s are the radii of the shaft, magnet inner surface, magnet outer surface, rotor outer surface and stator bore, respectively.

2.1. Simplification of magnetic bridges

The proposed analytical method is based on the subdomain model including fan-shaped regions with radial sides. For the standard boundary conditions, the first step is to simplify magnetic bridges.

The magnetic bridges, which protect the permanent magnets from flying away from the rotor, provide a path for the permanent-magnet leakage flux. As the leakage fluxes pass the magnetic bridges causing saturation, the permeability is different in the rotor, especially the magnetic bridges whose permeability is much smaller. To prove this, FEM is adopted to simulate the distribution of magnetic flux density and relative permeability in the rotor (shown in Fig. 2). From the figure, it's worth noting that the magnetic flux density is about 2 T in the bridge and less than 1.5 T in other region. According to the material B–H profile of rotor (shown in Fig. 3), the region is non-saturation when the magnetic flux density less than 1.6 T. Hence, the rotor can be divided into two pieces: fan-shaped saturation regions and non-saturation region. As Fig. 2 shows, the range of saturation is bigger than α, and the permeability of saturation region is almost the same. In the magnetic bridge regions, the permeability can be assumed as a constant, which satisfies the solution of Poisson's and Laplace's equations.

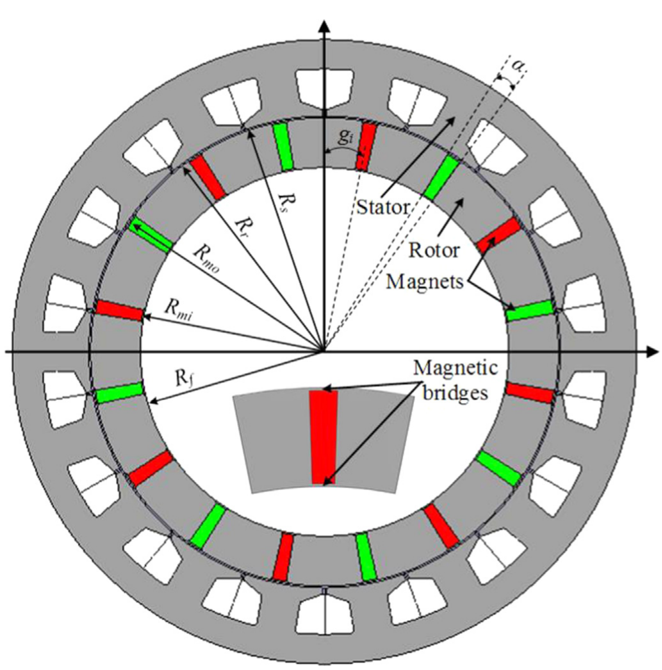

Fig. 1. Initial model of a 16-pole/18-slot spoke-type motor.

Fig. 4 shows the simplified rotor model, where β_1 and β_2 are the width angle of outer and inner simplified magnetic bridges in the saturation region, respectively. β_1 and β_2 are obtained by

$$\beta_1 = \alpha + \frac{2(R_r - R_{mo})}{R_r} \text{ and } \beta_2 = \alpha + \frac{2(R_{mi} - R_f)}{R_f} \tag{1}$$

The fan-shaped saturation regions are parts of the subdomain model which needs the permeability value. Taking into account the saturation and nonlinearity, a lumped parameter magnetic circuit model is employed to analyze the flux paths around the magnets. As shown in Fig. 5, the fluxes produced by magnets pass the magnet, magnetic bridges, and air-gap, where R_{m0} is the reluctance of one magnet, R_g is the reluctance of one-half of the per pole air gap, R_{b1} is the reluctance of the outer magnetic bridge, R_{b2} is the reluctance of the inner magnetic bridge, Φ_r, Φ_0, Φ_g, Φ_{b1}, and Φ_{b2} are the remanent magnet flux, magnet leakage flux, air-gap flux, outer magnetic bridge leakage flux and inner magnetic bridge leakage flux, respectively.

Taking into account the solution of saturation and nonlinearity, the iterative method is effective to calculate the permeability of magnetic bridges. Firstly, the initial flux density of outer simplified magnetic bridge is supposed as B_b. Going forward, based on the material B–H profile and lumped parameter magnetic circuit model, calculate the all reluctances and fluxes. Then, check the error $e(B_b)$ of the calculated remanent magnet flux $\Phi_{r1}(B_b)$ and Φ_r, and adjust the B_b. Eventually, repeat this process until the error is satisfied, and obtain the permeability of outer and inner simplified magnetic bridges. For further clarity, the flow chart of employing the iterative method is summarized in Fig. 6. All the parameters can be expressed as

$$R_m = \frac{\alpha \frac{(R_{mi} + R_{mo})}{2}}{\mu_0 \mu_r (R_{mo} - R_{mi}) L} \tag{2}$$

$$R_g = \frac{R_s - R_r}{\mu_0 \frac{(R_s + R_r)}{2} \frac{2\pi}{4p} L} \tag{3}$$

$$R_{b1} = \frac{\frac{\beta_1 (R_r + R_{mo})}{2}}{\mu_4(B_b) \cdot (R_r - R_{mo}) L} \tag{4}$$

$$R_{b2} = \frac{\frac{\beta_2 (R_f + R_{mi})}{2}}{\mu_2(B_b) \cdot (R_f - R_{mi}) L} \tag{5}$$

$$\phi_r = B_r (R_{mo} - R_{mi}) L \tag{6}$$

$$\phi_{b1} = B_{b1} (R_r - R_{mo}) L \tag{7}$$

$$\phi_{b2} = \frac{\phi_{b1} R_{b1}}{R_{b2}} \tag{8}$$

$$\phi_g = \frac{\phi_{b1} R_{b1}}{2 R_g} \tag{9}$$

$$\phi_0 = \frac{\phi_{b1} R_{b1}}{R_m} \tag{10}$$