Magnetic Equivalent Circuit Modeling of an Axial-Field Magnetic Gear

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This paper presents a two-dimensional (2D) magnetic equivalent circuit (MEC) model to investigate the magnetic field distribution in the air-gap of an axial-field magnetic gear. The MEC model is configured as a meshed reluctance network with permanent magnet magnetomotive-force sources. The MEC model based on reluctance networks (RN) is considered as a good compromise between accuracy and computational effort. This is a new model that will allow a faster analysis and design for the axial-field magnetic gears (AFMG). Flux density in the air-gap is calculated with the proposed model and verified by finite element simulations.

***Index Terms*— Finite element method, magnetic equivalent circuit, magnetic gears, reluctance network.**

I. Introduction

MAGNETIC GEARS (MGs) are increasingly studied as potentially useful tools for an efficient mechanical power transmission without the issues associated to conventional mechanical gears. MGs hold important advantages over their mechanical counterparts. They can realize speed change and torque transmission between input and output shafts by a contactless mechanism with quiet operation and overload protection. The most studied MGs technology is focused on radial-field topology. However, for the application of contactless coupling, the axial-field magnetic gears (AFMG) is thought to be more practical due to its simpler mechanical structure and can be designed compactly [1]. Mezani et al, [2], investigated one of the early AFMG topologies. Lubin developed a two-dimensional (2D) analytical model for the original design of the AFMG [3]. The analysis of the magnetic field distribution in the air-gap is of main importance for predicting and optimizing the performance of MGs; hence, the modeling method is very important in their design process. The magnetostatic finite element method (FEM) and the analytical methods are mainly used to carry out the massive calculation to evaluate the magnetic field distribution in the air-gap. However, although these methods have high-level accuracy and can yield excellent results, their attractive use is reduced due to its high computational cost [4]. The magnetic equivalent circuit (MEC) based on reluctance networks (RN) offers an alternative modeling method. This method is a mesh-based circuit representation. With this configuration, more details can be taken into consideration and satisfactory accuracy can be achieved compared to FEM but with only a fraction of computational time. The MEC method can support steady-state and dynamic simulations; it has been proposed as the basis for design optimization [5]. Steady-state characteristics can reveal the main transmitting capability of the MGs. There are only a few published works on MEC modeling applied to MGs [6]-[7]. However, these works consider the radial-field topology. This paper presents a steady-state modeling of an AFMG employing a 2D MEC based on RN, using a mesh-flux formulation.

II. The Axial-Field Magnetic Gear Topology

Fig. 1a shows the selected AFMG topology. This topology consists of three main structures: two rotors with axially oriented permanent magnets (PMs) on their surfaces and a modulator with stationary ferromagnetic pole-pieces between the two rotors. The low-speed rotor includes a back iron disk and p_l PMs pole pairs; the high-speed rotor includes a back iron and p_h PMs pole pairs. The number of the pole-pieces of the modulator is n_s, which is given by the sum of the pole pairs of the rotors. The two rotors on both sides of the air-gap interact by the magnetic flux axially across the ferromagnetic pole-pieces. We have considered two configurations. The first configuration considers p_l = 7 and p_h = 2, hence, n_s = 9 as in [3]. The second configuration considers p_l = 23 and p_h = 4, hence, n_s = 27, as in [2].

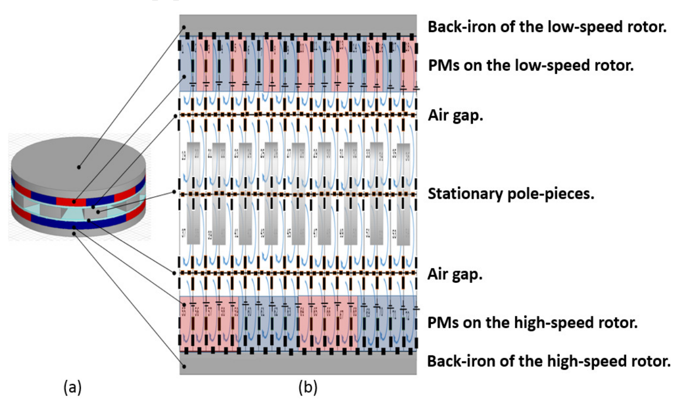

Fig. 1. Topology of the axial-field magnetic gear: (a) Structure; (b) 2D MEC.

III. 2D Magnetic Equivalent Circuit

Fig 1b shows the 2D MEC for the configuration p_l = 7 and p_h = 2. A similar 2D MEC was constructed for the configuration p_l = 23 and p_h = 4. For both configurations, the AFMG is divided into seven layers in the axial direction to take into account the different materials. The minimum repetitive unit in that direction, i.e. the number of steel pole pieces, determines the number of divisions in the circumferential direction.

This is an integer number. Hence, the accuracy of the results is proportional to the number of pole divisions. The model is based on flux mesh equations rather than nodal equations. Under non-linear operating conditions, the computational performance of the mesh-based MEC formulation is superior to that of the nodal-based formulation [8].

The mesh-based RN is the basis for the MEC formulation. The base geometry form for each reluctance element is a sector layer, where for a 2D modeling, only the axial and circumferential components are considered. Linear reluctance elements are defined only by their geometries. They represent the permanent magnets (PMs), the air-gaps and the slots between the pole pieces. Non-linear reluctance elements depend on both the geometry and the magnetic non-linearity of the curve B-H, corresponding to the ferromagnetic material. They represent the rotors yokes and the ferromagnetic pole-pieces. The sources are represented by the PMs, modeled by magnetomotive force sources functions, (MMF). The overall system is defined in the following form:

$$[\mathcal{R}(\varphi)]\bar{\varphi} = \bar{F}(\theta) \quad (1)$$

The solution of (1) is obtained using Newton-Raphson method:

$$\bar{\phi}_{m_{i+1}} = \bar{\phi}_{m_i} + \left[[\mathcal{R}] + \frac{\partial[\mathcal{R}(\phi_{m_i},\varphi)]}{\partial \phi_{m_i}}\right]^{-1} \{F(\theta) - [\mathcal{R}]\bar{\phi}_{m_i}\} \quad (2)$$

where ϕ is the loop flux vector, φ is the branch flux vector, $\mathcal{R}$ is the reluctance element matrix and $F(\theta)$ is the MMF sources which are functions of the rotor position, θ.

IV. Preliminary Results and Validation

In order to compare the results of the MEC modeling, a 3D FEA model was created in the ANSYS Maxwell finite element simulation software package. Figs. 2 and 3 respectively illustrate the calculated variation of the axial component of the flux density in the middle of the high-rotor air-gap for p_l = 7 and p_h = 2 configuration and p_l = 23 and p_h = 4 configuration. In both plots, it can be found that the modulation of the ferromagnetic pole-pieces on the magnetic field distribution in the air-gap determined in the MEC exhibits a close tendency to that presented by the 3D-FEM model. Currently, we are working with the optimization stage of the MEC model.

V. Conclusion

The MEC modeling allows us to easily parameterize the reluctance network to represent different topologies of magnetic gears. In this paper, a new model for the axial-type magnetic gear is presented using a MEC based on RN. Magnetic flux density has been calculated and compared to a 3D FEM model. The results in both models show a close agreement. This demonstrates that a MEC model can predict the complicated distribution of the magnetic field density in the air gap when the parameterization of this model is compatible with FEM model.

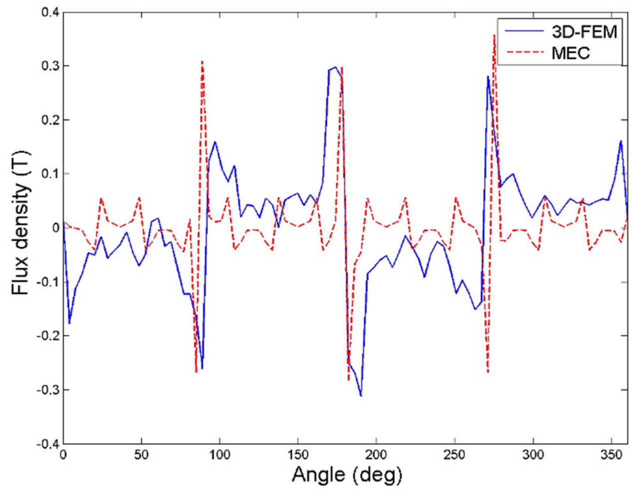

Fig. 2. Axial flux density in the high-speed rotor air-gap: p_l = 7 and p_h = 2.

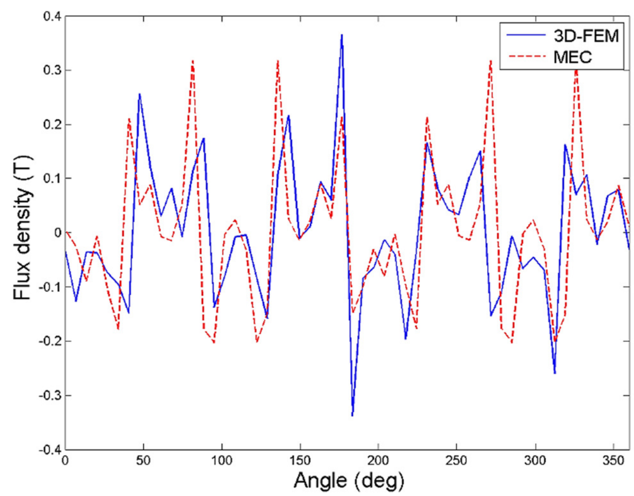

Fig. 3. Axial flux density in the high-speed rotor air-gap: p_l = 23 and p_h = 4.

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