Electric Power Systems Research 108 (2014) 282–292

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Design optimization of double-sided permanent-magnet radial-flux eddy-current couplers

S. Mohammadi [a,*], M. Mirsalim [a,b]

[a] Electrical Machines and Transformers Research Laboratory, Department of Electrical Engineering, Amirkabir University of Technology, Tehran 15916, Iran
[b] Department of Electrical Engineering, St. Mary's University, San Antonio, TX 78228, USA

ARTICLE INFO

Article history:
Received 22 April 2013
Received in revised form 23 September 2013
Accepted 16 November 2013
Available online 20 December 2013

Keywords:
Design optimization
Eddy-current couplers
Finite-element method (FEM)
Genetic algorithm

ABSTRACT

It is essential for engineers to improve overall performance of electromagnetic devices. In this paper, single/multi-objective design optimization of double-sided permanent-magnet radial-flux eddy-current couplers is carried out. To this end, an analytical model of such devices is developed by combining conventional magnetic equivalent circuit techniques with Faraday's and Ampere's laws. The model is capable of easily dealing with complex geometries and material properties such as iron saturation and the PM characteristics as well as the associated design constraints so that the designs that are more realistic can be achieved. A genetic algorithm that enjoys a flexible objective function is finally adopted to find the optimal machine parameters. Finite-element method is also employed to verify the results.

1. Introduction

Electromagnetic devices are widely employed in nowadays industry, which makes their optimization quite necessary to achieve a satisfactory overall efficiency. Eddy-current couplers offer many advantages such as transferring a torque without any mechanical contact, soft starting, isolating the moving bodies, absorbing or damping the shocks and vibrations, and needless from precise alignment techniques [1–3].

There is a growing interest in population-based design optimization (PBDO) of electromagnetic devices [4–11], such as genetic algorithms (GA), wherein the objective function is not required to be differentiable. These methods are also able to efficiently exploring through a large discontinuous search-space to find the global optimal solution [12]. However, analytical expressions for the performance indices of the device are necessary, whereby fast and relatively accurate solutions can be provided, while on the other hand, numerical approaches such as finite-element method are very time-consuming and usually good for verification of the results.

Analytical modeling and fuzzy-genetic optimization of eddy-current couplers based on the solution of Laplace's and Poison's equations have been presented in [1,2,4] wherein, in addition to complication and to account for design constraints, significant problems may appear in complex geometries in which no symmetries may exist. In addition, the mentioned model assumes that the relative recoil permeability of the PMs to be unity (only remanence of PMs is accounted for) and also, iron saturation is ignored and its permeability is considered to be infinity., all of which besides the inaccuracy problems, does not allow for effectively accounting for material properties that finally results in limiting the practical design space. Analytical modeling of PM-assisted machines based on the mentioned procedure has also been developed in [13–15], and together with how to adopt PM materials in [16,17], and simple calculations without considering the reaction fields have been set forth in [18]. Magnetic equivalent circuit (MEC) techniques have recently become popular in the analysis and optimization of such devices by providing a flexible solution, along with easily considering the design constraints and material properties [19–29].

The main contribution of this paper is single/multi-objective optimizations and the study of the design aspects of radial-flux double-sided permanent-magnet (DSPM) eddy-current couplers. In order to achieve this goal, a simple yet accurate analytical model of such devices is established, wherein Faraday's and Ampere's laws are combined with the MEC techniques. Hence, the reaction field is taken into account as well. The implemented model accurately accounts for the PM characteristics, i.e., both the remanence and the coercivity, as well as saturation characteristic of the utilized steel material, all of which provides a better practical design framework. It is worth noting that this approach can only be applied to the devices wherein the induction part is a solid conductive-sheet such as eddy-current couplers and brakes, and linear induction

* Corresponding author. Tel.: +98 2164543536; fax: +98 2166406469.
E-mail address: sajad.mohammadi@aut.ac.ir (S. Mohammadi).

0378-7796/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsr.2013.11.014

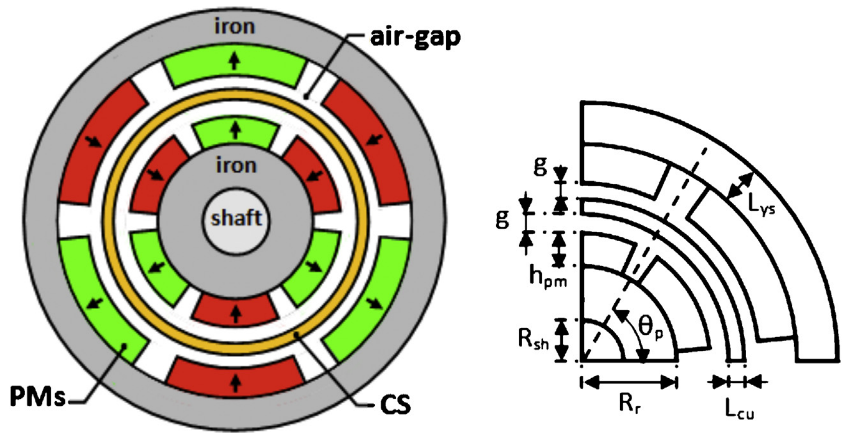

Fig. 1. The schematic view of the studied eddy-current coupler.

Table 1
The specifications of the case-study coupler.

Parameter	Value (mm)	Parameter	Value
Shaft radius, R_{sh}	22	Axial length, L	30 mm
Rotor radius, R_r	100	PM parameters	N42
PM height, h_{pm}	4	Number of PMs, p	6
Air-gap length, g	0.5	PM ratio, α_m	0.7
CS thickness, L_{cs}	1	Conductive material	Cu
Outer-yoke length, L_{yo}	23	Steel grade	M19-29-G

Table 2
The characteristics of available Nd–Fe–B PMs and CS materials.

Type	B_r (T)	H_c (kA/m)	Type	B_r (T)	H_c (kA/m)
Permanent magnet materials					
N27	≈1.05	≈800	N40	≈1.27	≈928
N30	≈1.10	≈800	N42	≈1.30	≈928
N33	≈1.15	≈840	N45	≈1.35	≈870
N35	≈1.19	≈872	N48	≈1.40	≈840
N38	≈1.23	≈904	N50	≈1.42	≈840
Conductive materials					
Material	σ (Ms)	ρ (g/cm^3)	Material	σ (Ms)	ρ (g/cm^3)
Copper, Cu	58	8.94	Aluminum (Al)	38	2.7

machines, and for example cannot directly be applied to squirrel cage machines. Moment of inertia of the inner rotating part, i.e., the conductive-sheet (CS) is very low in this structure that provides a better dynamic behavior in comparison to single-sided PM structures. The research is then followed by analytical calculations for several design considerations to be placed on the optimization procedure, so that designs that are more realistic can be achieved. Finally, GA is employed to maximize the developed torque while an attempt is made to reduce the PM volume and moment of inertia of the CS. Results are additionally confirmed through FEM.

2. Studied topology and implemented model

2.1. Coupler geometry

Fig. 1 illustrates the schematic view and geometrical parameters of a radial-flux DSPM eddy-current coupler, for which the design optimizations have been carried out. It can be observed that radially-polarized PMs alternating in the direction of magnetization are placed on the air-gap side of inner and outer parts, and CS rotates between them, i.e., one part is attached to a load and the other part to the prime-mover. Therefore, as the load torque increases the relative speed between the two rotating parts of the device goes up and hence, more current is induced in the CS from which a magnetic field is also produced that interacts with the primary magnetic field to develop an electromagnetic torque. Parameters of the studied coupler are listed in Table 1. Properties of PMs and CS materials must be adopted among available ones [16,17] summarized in Table 2.

2.2. Implemented model

The block diagram shown in Fig. 2 illustrates how the implemented model operates. PMs produce a primary magnetic flux density in the air-gap that is determined through MEC. Induced currents in the CS due to the relative speed between the two rotating parts are then calculated through Faraday's law. Then, the effect of the reaction field produced by these induced currents is accounted for using Ampere's law.

2.2.1. Magnetic equivalent circuit

Flux paths and magnetic equivalent circuit corresponding to one flux loop of the electromagnetic system are depicted in Fig. 3. Since PMs are radially magnetized with a constant flux over a variable area, the achieved remanence varies with radius [26] and hence, mean radius of a PM is employed to determine the equivalent flux source of the inner and outer PMs as follows:

$$\varphi_{ri} = \alpha_m \theta_p \left(R_r + \frac{h_{pm}}{2} \right) L B_r \tag{1}$$

$$\varphi_{ro} = \alpha_m \theta_p \left(R_r + 2g + L_{cs} + \frac{3h_{pm}}{2} \right) L B_r \tag{2}$$

where, $\theta_p = 2\pi/p$ is the pole-pitch angle, and the other parameters have been depicted in the figures and Tables. Although a mean radius may be used to calculate all reluctances [20,24] by linear expansion of the structure, but to obtain a higher accuracy especially in the presence of a nonmagnetic CS, they are determined based on the original circular configuration. As mentioned, in the implemented MEC-based model through the exact value of relative recoil permeability of PMs i.e., $\mu_r = -B_r/\mu_0 H_c$, contrary to the subdomain models, both PM characteristics, i.e., remanent B_r and

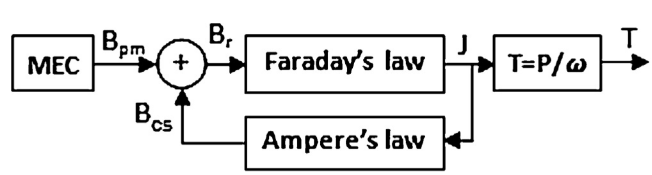

Fig. 2. The functional block diagram of the implemented model.