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Optimal Design of an Axial-Flux Eddy-Current Magnetic Coupling

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Abstract—This paper presents a design optimization of an axial-field eddy-current magnetic coupling. The design procedure is based on a torque formula derived from a 3-D analytical model and a genetic algorithm method. The torque formula is very accurate in terms of precision and computational time, and is valid for all the slip speed values. The main objective of this paper is to determine the best design in terms of magnets volume in order to transmit a torque between two movers while ensuring a low slip speed and then a good efficiency.

Index Terms—Eddy-current; Magnetic coupling; Optimal design.

I. INTRODUCTION

As shown in Fig.1, an axial-field eddy-current magnetic coupling consists of two opposing discs. One disc is equipped with rare-earth permanent magnets magnetized in the axial direction and regularly distributed to obtain alternately north and south poles. The other disc is composed of a conducting plate, generally made of copper, screwed to the back-iron [1], [2], [3]. The transmitted torque of such a device is due to the interaction of magnets field and induced currents in the conducting plate which depend on the slip speed between the two discs. From its working principle, eddy-current coupling presents Joule losses which are directly related to the slip speed. The normal working range area of such device corresponds to low slip values where the Joule losses are limited. The efficiency is given by $\eta = 1 - s$ where s is the slip ($s = (\Omega_1 - \Omega_2)/\Omega_1$).

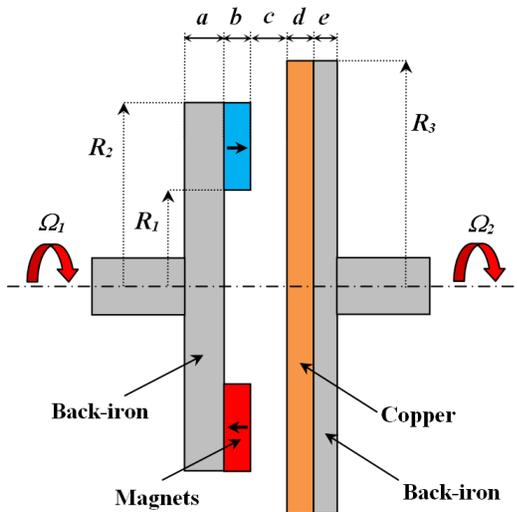


Fig. 1. Axial-field eddy-current magnetic coupling with its geometrical parameters.

The geometrical parameters of the studied coupler are given in Fig.1: R_1 is the inner radius of the magnets, R_2 the outer radius of the magnets, R_3 the outer radius of the copper

plate, a is the thickness of the back-iron (magnets side), b the magnets thickness, c the air-gap length, d the thickness of the copper plate, e the thickness of the back-iron (copper side). The pole-arc to pole-pitch ratio of magnets is α , and p is the pole-pairs number. The mean radius of the torque coupler is defined as $R_m = (R_1 + R_2)/2$. The main objective of this paper is to determine the best design in terms of magnets volume in order to transmit a torque between two movers while ensuring a good efficiency.

II. ANALYTIC FORMULAS

A torque formula (1) has been obtained from a 3D analytical model under the mean radius development assumption. The mathematical developments are given in [1]. This formula depends directly on the physical and geometrical parameters of the coupler:

$$T_e = \frac{1}{2} \mu_0 p^2 \tau R_3 \Re \left[\sum_{n=1}^N \sum_{k=1}^K j k \frac{M_{nk}^2}{\alpha_{nk}} r \sinh(\alpha_{nk} b) \right] \quad (1)$$

with:

$$M_{nk} = \frac{16 B_r}{\pi^2 \mu_0 n k} \sin\left(k \alpha \frac{\pi}{2}\right) \sin\left(n \frac{\pi}{2} \frac{R_2 - R_1}{R_3}\right); \quad \tau = \frac{\pi}{p} R_m$$

and:

$$r = \frac{-(\cosh(\alpha_{nk} c) \sinh(\gamma_{nk} d) + \frac{\alpha_{nk}}{\gamma_{nk}} \sinh(\alpha_{nk} c) \cosh(\gamma_{nk} d))}{\cosh(\alpha_{nk} (b+c)) \sinh(\gamma_{nk} d) + \frac{\alpha_{nk}}{\gamma_{nk}} \sinh(\alpha_{nk} (b+c)) \cosh(\gamma_{nk} d)}$$

$$\alpha_{nk} = \sqrt{\left(\frac{n\pi}{R_3}\right)^2 + \left(\frac{k\pi}{\tau}\right)^2}$$

$$\gamma_{nk} = \sqrt{\left(\frac{n\pi}{R_3}\right)^2 + \left(\frac{k\pi}{\tau}\right)^2 + j \sigma \mu_0 \Omega R_m \frac{k\pi}{\tau}}$$

where n and k are odd integers, \Re denotes the real part of a complex number, $j = \sqrt{-1}$, σ is the electrical conductivity of the copper, B_r the remanence of the permanent magnets, and Ω is the slip speed ($\text{rad}\cdot\text{s}^{-1}$).

The thickness of the back-irons (a and e , see Fig.1) should be determined to avoid magnetic saturation. For simplicity, we consider that the mean value of the flux density in the yokes must be under the knee point of the B-H curve (i.e $B < B_s$ with $B_s = 1.5\text{T}$). From the analytical model [1], we derived simple expressions to determine a and e :

$$a \leq 4 \frac{B_r R_m}{B_s \pi p} \sin\left(\alpha \frac{\pi}{2}\right) \left(1 - \frac{\sinh\left(\frac{\pi}{\tau}(c+d)\right)}{\sinh\left(\frac{\pi}{\tau}(b+c+d)\right)}\right) \quad (2)$$

$$e \leq 4 \frac{B_r R_m}{B_s \pi p} \sin\left(\alpha \frac{\pi}{2}\right) \frac{\sinh\left(\frac{\pi}{\tau}(b)\right)}{\sinh\left(\frac{\pi}{\tau}(b+c+d)\right)} \quad (3)$$

It is worth noting that $e < a$.

III. OPTIMAL DESIGN

The analytic model described in the previous section can be easily associated with an optimization algorithm in order to efficiently solve design problems [4]. As a first example, the following problem is considered:

$$(P) \begin{cases} \min_{\mathbf{x} \in D} V_m(\mathbf{x}) \\ \text{with } \mathbf{x} = [R_1, w_m, b, c, d, \alpha, p] \\ \text{s.t. } T_e(\mathbf{x}) \geq 200 \text{ N}\cdot\text{m} \\ R_3(\mathbf{x}) \leq 15 \text{ cm,} \end{cases} \quad (4)$$

where V_m is the total volume of magnets, w_m their width ($w_m = R_2 - R_1$), and R_3 is calculated in order to permit a return path of the induced currents by: $R_3 = R_2 + \frac{\tau}{2}$. The airgap c is fixed to 3 mm. The considered operating point corresponds to a slip speed equal to 150 rpm for a driven speed $\Omega_1 = 3000$ rpm. The load power then equals 59.7 kW transmitted with a 95 % efficiency.

Problem (P) is relatively small: 6 variables (5 real and 1 integer) and 2 inequalities. But it is sufficient to test the validity of our design process. It belongs to the Mixed Integer Non-Linear Program (MINLP) problems class.

Since our model is purely analytic, each evaluation is very fast (less than 1 millisecond). Then the use of a meta-heuristic method with a huge number of evaluations is not a problem. We choose a Particle Swarm Optimization (PSO) algorithm because of its simplicity of implementation [5]. A modified version of classical PSO accounting for integer variables (called MIPSO) had been implemented using free and open-source GNU/Octave software. Bounds constraints are handled by projection, and non-linear constraints by a penalty function. The initial swarm is generated using a latin hypercube sampling.

Since the used method can not assure with certainty the exactness of the solution, 10 different runs had been performed. We use 100 particles, evolving during 1000 iterations. Each run takes about 6 min on a simple laptop (with Core i7 CPU @2.40 GHz). The best one $\tilde{\mathbf{x}}$ is given by Table I.

TABLE I
BEST FOUND SOLUTION $\tilde{\mathbf{x}}$ OF PROBLEM (P)

Variable	Bounds	Unit	Minimum
R_1	[4, 15]	cm	6.91
w_m	[2, 10]	cm	6.33
b	[5, 40]	mm	7.35
d	[5, 20]	mm	5
α	[0.6, 0.9]	-	0.76
p	[[2, 10]]	-	9
Quantity		Unit	Optimal Value
V_m		cm ³	223
T_e		N·m	200
R_3		cm	15

In order to show the effectiveness of our design methodology, we have used a 3D finite element model (FEM) to verify the torque value of $\tilde{\mathbf{x}}$. The authors have developed in [6] a complete 3D steady-state model which takes into account the B-H curve of the iron yokes, and the eddy currents in

both copper and back iron. The yokes thicknesses a and e are calculated by (2) and (3): $a = 6.4$ mm and $e = 4.7$ mm. Fig. 2 shows the geometry of one pole of $\tilde{\mathbf{x}}$ with its corresponding mesh.

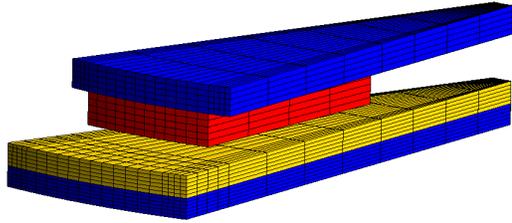


Fig. 2. Geometry and mesh of the optimal solution (one pole)

With this FEM model, the calculated torque is 202 N·m, which proves the accuracy of the analytic model and demonstrates its relevance for an optimal design procedure as presented. In the final paper, other problems of design will be solved.

IV. CONCLUSION

In this paper, we have presented an optimal design of an eddy-current magnetic coupling based on an analytic model. The corresponding MINLP problem is solved thanks to a dedicated particle swarm algorithm. The optimal solution is obtained in 6 min, and fulfills to the specifications. It clearly highlights the relevance of our design procedure.

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