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Published in:
Proceedings of the International Conference on Electrical Machines, ICEM 2020

DOI:
[10.1109/ICEM49940.2020.9270726](https://doi.org/10.1109/ICEM49940.2020.9270726)

Published: 23/08/2020

Document Version
Peer reviewed version

Please cite the original version:
Andriushchenko, E. A., Kallaste, A., Belahcen, A., Heidari, H., Vaimann, T., & Rassõlkin, A. (2020). Design optimization of permanent magnet clutch. In *Proceedings of the International Conference on Electrical Machines, ICEM 2020* (pp. 436-440). [9270726] (Proceedings (International Conference on Electrical Machines)). IEEE. <https://doi.org/10.1109/ICEM49940.2020.9270726>

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Design Optimization of Permanent Magnet Clutch

E. A. Andriushchenko, A. Kallaste, A. Belahcen, H. Heidari, T. Vaimann, A. Rassõlkin

Abstract – Design optimization of permanent magnet clutches can be an effective solution for minimization of the volume at a given torque output. This study proposes an optimization method for permanent magnet clutch, which allows obtaining a complex and detailed design. Design and optimization model of the clutch, optimization method and algorithm are comprehensively discussed. Optimization using 2D finite element analysis, combined with a genetic algorithm is demonstrated. The obtained optimal shapes reduced the volume of clutch discs by 31% while the maximum integral attraction force met the limit.

Index Terms – electromagnetic coupling, design optimization, genetic algorithms.

I. INTRODUCTION

PERMANENT MAGNET (PM) clutches have been widely applied for torque transition between two shafts without mechanical contact. The lack of mechanical contact denotes the air-gap between driving and driven member. This design feature brings several advantages to PM clutches over mechanical clutches [1], [2]. Firstly, the lack of friction reduces the risk of mechanical failures, reduces vibration and proposes easier maintenance. Additionally, the isolation of the driving and driven members is desired for a list of applications [3]–[5]. For instance, they are highly suitable for usage in a damaging, corrosive environment. Additionally, biological and food processing equipment such as mixers or agitators often requires torque to be transmitted through a separator.

One of the key requirements for clutches is a minimum volume of magnetic and non-magnetic materials with the desired torque output. These requirements can be satisfied by means of design optimization of PM clutches. So far, a considerable amount of literature has been published on design optimization of electromagnetic devices [6]–[8]. Besides, several studies have optimized design of PM clutch with different approaches [9], [10]. Up to now, most researchers have carried out optimizations using only linear dimensions as decision variables, for instance, diameters of discs or thickness of magnets [5]. However, it may be beneficial to exploit the designs that are more precise by defining optimal shapes instead of dimensions, since modern

manufacturing techniques allow obtaining highly complex structures. For instance, additive manufacturing provides a wide range of opportunities to more sophisticated design production. Therefore, this paper is focused on the optimization of a PM clutch shapes with the aim of obtaining the lowest weight while keeping the torque above the defined limits. As a first approximation, only shapes of the iron disks are considered in this study.

This paper begins by formulating the operation principle of the clutch and defining the design and optimization models. Later on, Section II. continues with the optimization method and algorithm description. Towards the end, results of the optimization are reported and discussed.

II. DESIGN OPTIMIZATION

A. Design model

The first step in any optimization is to create a design model. In this study, the design model of the clutch was made in program Finite Element Method Magnetics (FEMM). Fig. 1 illustrates the initial design of the clutch (a) and the model of the clutch (b), where magnets are highlighted in beige colour. In principle, the clutch consists of driving and driven member. The driving member possesses PM teeth placed on the disc made from printed steel. The magnets are magnetized as it is shown in Fig. 1. On the other hand, the driven member is fully made from printed steel. Working principle of PM clutch is based on attraction force between magnetic and steel teeth. The attraction force is a vector that includes two components: axial attraction force F_z and tangential attraction force F_t . The axial attraction force allows two members to couple and move synchronously. The angle between the members and subsequent tangential attraction force are responsible for transmitted torque. This is due to the fact that the tangential attraction force arises between the members when one member spins relative to the other one. When this force reaches the maximum value, the driven member shifts to another stable position, where its teeth are aligned with the magnetic teeth of the driving member. However, if the torque on the driving member exceeds the maximum value that clutch can handle, the driven member slips. Consequently, the maximum value of the tangential attraction force defines the torque that the clutch is able to transmit [4], [11]. Therefore, the considered clutch was optimized with respect to the transmitted torque.

For a given system, the dimensions of the initial design are reported in Table I. As a first approximation, the volume of the clutch was reduced by means of the reduction of the volume of discs, particularly, by optimizing the discs

This research work has been supported by Estonian Ministry of Education and Research (Project PSG137).

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shapes.

The flux distribution in discs in the radial direction was not changing significantly. Therefore, it was acceptable to optimize only a cross-section of a circle type (A-A) and use an obtained optimal geometry along the radial direction. In order to simplify the model for making 2D analysis, the cross-section was considered with straightened air gap. To simulate the geometrical continuity of each disk, periodic boundary conditions were implemented on the sides of each disk. They are shown as red and green lines in Fig. 1. The clutch was placed in the air box. The length of the disks L was calculated as the length of the circle with a diameter of D_m . Consequently, the shift in this design model represented the angular deflection between clutch halves. Particularly, the used shift value was equal to 5 mm and denoted the position when the attraction force between the halves of the clutch was maximum. The members of the clutch were separated by the air gap equal to 1 mm.

B. Materials

As it was mentioned before, the driving part teeth were permanent magnets, while the material of the driven member was printed steel [12]. Fig. 2 illustrates B-H magnetization curve, which characterises the magnetic properties of the utilized material. Particularly, the properties were obtained from the sample made from the gas-atomized pre-alloyed powder of Fe-Si by selective laser melting printing.

Sintered Nd-Fe-B (N52) magnets were utilized in the optimized clutch since these magnets are the strongest permanent magnets available in today's market [13]–[15].

C. Optimization model

The first step in optimization is to constitute an optimization model. An optimization model includes objective functions, constraints and decision variables [16]–[18].

In order to obtain optimal shapes of the discs, the points on the discs' end faces were chosen as decision variables (see Fig. 3). Particularly, by changing the position of each point in z and z' -direction, different complex shapes could

Fig. 1. Initial design (a) and model (b) of the clutch.

TABLE I
MAIN DATA OF THE CLUTCH UNDER OPTIMIZATION

Dimension	Symbol / formula	Value
Outer diameter	D	65 mm
Diameter in the middle of magnets	D_m	44.6 mm
Clutch length in developed view	$L = \pi \cdot D_m$	140 mm
Magnet length	L_m	20 mm
Magnet height	H_m	5 mm
Magnet width	W_m	10 mm
Space between magnets	W_s	7.5 mm
Discs height	H_d	4 mm

be formed. Only six points on each disc were satisfactory ($p_i, i=1...12$), for the reason that flux lines were symmetric with respect to the axes of clutch's teeth (t_{11}, t_{21}). The variation limits of decision variables p_{1-6} in z -direction and p_{7-12} in z' -direction were $[0, 3.5]$.

The objective function of the optimization model was the volume of the discs. The integral tangential attraction force F_t was used as a constraint. During the optimization, the force was kept above 95% of the initial value with a maximum reduction of the volume. The values of objective and constraint were calculated in FEMM. The initial values of objective and constraint are reported in Table II.

D. Optimization method and algorithm

Optimization method can be described as a strategy or procedure within which an optimization model is optimized. Optimization method applied in this problem is called a direct optimization method since it uses design model accompanying by optimization algorithm [16], [19].

Fig. 2. B-H magnetization curve for printed steel.

Fig. 3. Decision variables mapped on design model.

The considered optimization model had a high number of decision variables – twelve. Generally, it is rather difficult to optimize this kind of a model [16], [20]. Therefore, in order to prevent the overloading of the applied algorithm and reduce execution time, the optimization was made in two steps. More specifically, the shapes of the driving and driven disc were optimized one after another.

The optimization models were as follows:

$$\begin{aligned} \min: & V_1(p_1, \dots, p_6); \\ \text{s.t.} & F_{t_1}(p_1, \dots, p_6) \geq [F_{t_1}], \quad [F_{t_1}] = 119 \text{ N}; \end{aligned} \quad (1)$$

$$\begin{aligned} \min: & V_2(p_7, \dots, p_{12}); \\ \text{s.t.} & F_{t_2}(p_7, \dots, p_{12}) \geq [F_{t_2}], \quad [F_{t_2}] = 117 \text{ N}. \end{aligned} \quad (2)$$

Fig. 4 shows the applied optimization method in detail and provides the settings of the algorithm. The objective and constraint were calculated in the design model and optimization algorithm was proposing decision variables.

The algorithm used here was a single-objective genetic algorithm (GA) [21], [22]. Nowadays, GAs are widely applied due to the high number of advantages such as [23]:

- 1) ability to find a global minimum,
- 2) ability to handle non-analytic problem definition,
- 3) possibility to be adjusted to a particular problem,
- 4) robustness to noisy evaluation functions.

GA includes several operators that justify the flexibility of the algorithm as long as can be easily adjusted to a particular problem. To name, crossover, mutation, selection

TABLE II
INITIAL SPECIFICATIONS OF THE CLUTCH

Specification	Symbol/formula	Value
The maximum integral tangential attraction force	F_t	124 N
Driving disc volume	V_1	11200 mm ³
Driven disc volume	V_2	11200 mm ³

Fig. 4. Scheme of applied optimization method.

and fitness scaling are the operators. Fitness scaling is used to calculate the performance of each individual (decision variables set). The function of selection is to choose the best individuals. Further, the selected individuals constitute a new generation together with crossover fraction, which is generated by the operator crossover. This operator is applied to two individuals in order to create a new one. Finally, the operator that provides diversity and broadens the search space is mutation. It is important to mention that GA can be directly applied only to unconstrained optimization. Therefore, it is necessary to use additional techniques, such as constraint- handling methods, that can keep solutions in the feasible region [24], [25]. It is worth mentioning that algorithm settings, i.e. operators' functions, have a direct effect on optimality of the results. Therefore, for a defined problem, algorithm settings were chosen according to the common settings used in electrical devices optimization [26]–[28].

As it is shown in Fig. 4, the augmented Lagrangian was applied to handle the constraint. This method combines the objective function with constraint function using the Lagrangian [29]. Consequently, the final formulation of the problem was as follows:

$$V_i - \lambda_i \cdot s_i \cdot \log(s_i - [F_{t_i}] + F_{t_i}), \quad (3)$$

where the elements $\lambda_i > 0$ are known as Lagrange multiplier estimates and the components $s_i > 0$ are known as shifts and $s_i = \mu \cdot \lambda_i$, $\mu > 0$.

The number of individuals was 300 ($=30 \cdot 5 \cdot 2$), where 30 is the size of each generation and 5 is the number of generations. Consequently, it required 300 evaluations of the optimization model that resulted in 4 hours of calculations.

III. RESULTS

Fig. 5 shows the optimal geometry of the clutch and presents the optimal values of decision variables. Overall, the volume of the driving disc was reduced significantly by 36%, while the maximum value of the integral tangential attraction force met the limit $F_t=119$ N. The second step of optimization demonstrated considerable changes in the driven disc volume as well (25%). Overall, there was a significant difference (31%) between initial and optimal design volumes. What is interesting about the results is that there were no changes in the attraction force after the driven disc optimization. Therefore, it may be assumed that the geometry of the driving disc had a stronger effect on the attraction force.

In addition, the dependence of the integral attraction force on the increase in the shift was built (see Fig. 6). In Fig. 6, blue line illustrates the attraction force in initial design configuration, red line demonstrates the force after the driving disc optimization, and black line denotes the final optimized design configuration. As it was noticed before, the maximum integral attraction force did not experience radical changes after optimization. This effect remained the same way during changing of the shift.

IV. CONCLUSION

The purpose of the current study was to optimize PM clutch shapes in order to obtain the lowest weight while keeping the torque above the defined limits.

The problem had a single-objective optimization model, where the volume of clutch's discs was the objective and the tangential attraction force was considered as a constraint. The applied method was based on the interaction between the design model and the genetic algorithm. The optimization was made in two steps, i.e. the driving and driven disc were optimized separately. It allowed preventing the overloading of the applied algorithm and reducing execution time.

Fig. 5. Optimized geometry and optimal values of parameters.

Fig. 6. Optimization results. Blue: the initial design. Red: the driving disc optimization. Black: the final optimized design.

The result of this optimization was the significant reduction in the volume of the discs (31%), while the tangential attraction force experienced a small change from the initial value.

The present study lays the groundwork for future research into PM clutches optimization. Specifically, a natural progression of this work is to obtain optimal shapes of the permanent magnets, teeth, and discs in 3D.

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