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Teeth Shape Design of a Switched Reluctance Motor for High Torque Using Genetic Algorithms

Mouellef Sihem, Bentounsi Amar, Benalla Hocine

Abstract— This paper describes a procedure for optimizing the stator and rotor pole arc of a double saliency switched reluctance motor type SRM 6/4 to maximize the electromagnetic torque using genetic algorithms. To reduce the computation time in the nonlinear regime, the code optimization is advantageously coupled to a semi-numerical model of the studied motor. The various simulations in MATLAB were used to optimize the teeth angles, thus improving the average torque.

Index Terms— Genetic algorithms, MATLAB, optimization, switched reluctance motor, teeth angles.

1 Introduction

After a period of stagnation, the switched reluctance machines (SRM) in recent years have seen a remarkablegrowth thanks to their simplicity and robustness, which reduces manufacturing costs and maintenance, and also their various applications [1-3].

Presently, many studies are conducted to improve their performance along different axes: *(i)* geometry optimization; *(ii)* control strategies; *(iii)* use of new materials with interesting magnetic properties [4-9].

Considering the aspect multi-physics of the electrical machines, the optimization process of several interdependent parameters is a very complex problem [10]. Based on the different optimization methods to local or global search [11-13], ones finally selected for this study a meta-heuristic approach using genetic algorithms, a widely used method for solving optimization problems in many application areas.

The objective of this work is to improve the average torque via an optimization of the pole arcs of the stator, β_s, and the rotor, β_r, which are flexible parameters for the SRM design and that directly influence the electromagnetic torque [14-16]. Hence the choice of these two geometrical parameters for this first performance optimization work that we hope to continue in other directions, in particular on the level of the magnetic characteristics of materials.

2 Modeling The SRM

The machine topology studied is a double saliency three-phase SRM 6/4 with Ns = 6 stator teeth and Nr = 4 rotor teeth as represented "Fig. 1". Its operating principle, similar to the stepper motor, has long been known: by exciting successively the three stator phases, the rotor teeth are positioned to maximize the inductance of the power phase, under the rule of '*maximum flux*' (aligned position); by turning off the power, the motor will continue its movement until it reaches a position corresponding to the minimum value of inductance or flux (unaligned position). On the linked flux (λ)-current (*i*) characteristics, the area between the previous two extreme positions represents the electrical energy converted into mechanical energy per cycle, $W=W_a-W_u$, as shown in "Fig. 2".

As described in [17], to determine analytically the relations flux-At from only seven characteristics equal-flux lines traced by the finite element method "Fig. 3" and corresponding to seven magnetic equivalent circuits, we implemented a program in MATLAB package software for the iterative calculation of the saturated aligned and unaligned inductances, respectively L_a and L_u, and the corresponding energies, W_a and W_u, from which one can deduce the average torque "Fig. 4":

$$T_{av} = \frac{qN_r\left(W_a - W_u\right)}{2\pi} \tag{1}$$

$$W_a = \left(\lambda_1 + \lambda_2 + \ldots\ldots\ldots + \frac{1}{2}\lambda_n\right) * \delta i \tag{2}$$

$$W_u = \frac{1}{2}\lambda_u I_p \tag{3}$$

$$\delta_i = \frac{I_p}{n} \tag{4}$$

The integration step δ_i is the ratio of the peak value of current I_p on the number of intervals n.

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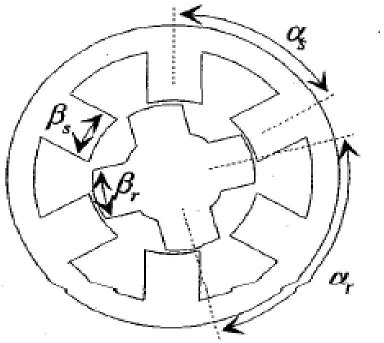


Fig. 1. Cross-section of studied SRM 6/4

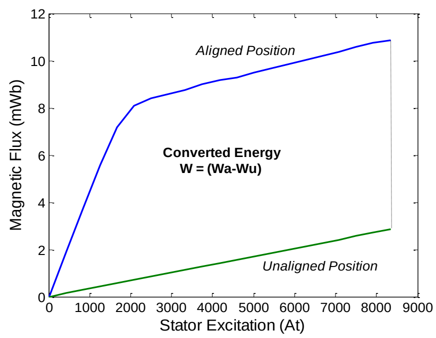
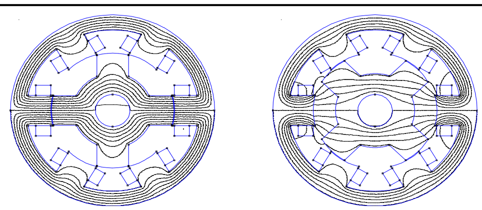


Fig. 2. Extremes magnetic characteristics flux vs. excitation mmf



(a) (b)

Fig. 3. Flux plot by FEM at fully (a) aligned and (b) unaligned positions

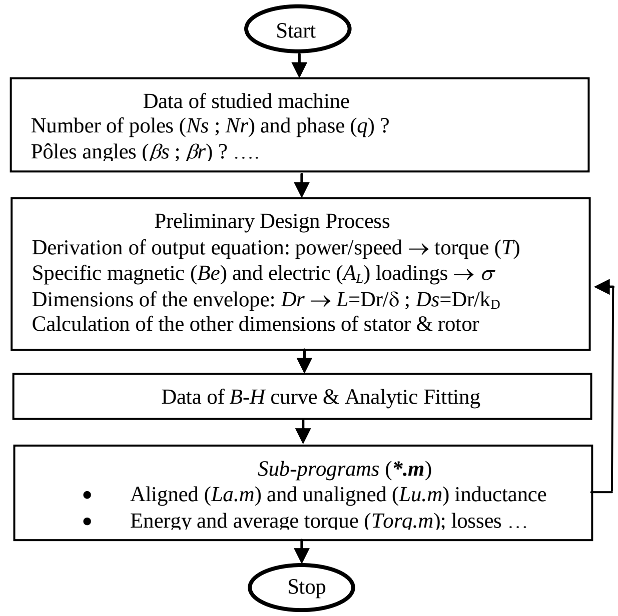


Fig. 4. Flowchart of the simulation main program

3 Optimization Design of SRM

3.1 Genetic algorithm design process

Genetic algorithms (GA) are stochastic optimization methods defined by J. Holland [11]. They are based on the mathematical translation of natural phenomena that are natural selection (that determines which members of a population survive and reproduce) and reproduction (which ensures mixing and recombination of parental genes to form down to potential new ones). This translation is used for solving problems involving the modeling of all the steps that form the process of genetic algorithms and optimization of a function or system depends on several parameters which need to be calculated for well-defined criteria (maximization, minimization).

The steps for implementing a genetic algorithm can be summarized as following:

- *Coding*: with the basic genetic algorithm, as founded by Holland, the first question to ask is: "how to describe a individual?". i.e, how the parameters can be coded? In an GA, we do not work directly with the data of the problem but with a representation of them called coding. The encoded form of a solution of the objective function is a chromosome consisting of a set of genes and fully describes an individual "Fig. 5 ". A gene that corresponds to a parameter and consisting of 0 and 1. In this case, each real value is encoded by its equivalent in binary. The set of individuals is called population.

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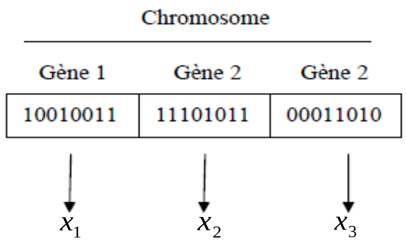

Fig. 5. Illustration of the optimization coding variables

- *Initial population*: the initialization is used to form the initial population. This step should not be overlooked because if the population is not evenly distributed at the beginning, the evolution is likely to focus on a local optimum from which it can be difficult to escape. So we try to create an initial population as diverse as possible. Classically, for each individual in the population, the initialization mechanism is to randomly draw each bit in a string. for example, in the case of a binary representation, the draw is from the set {0, 1} [14].

- *Evaluation*: individuals of the same generation will be compared and evaluated so to determine among them which ones are well suited to the given problem. This evaluation is based on a test of individuals according to a function called adaptation, evaluation or fitness function.

- *Selection*: the selection operator is usually based on Darwin's theory [18]. So the best individuals are more likely to survive and reproduce. Individuals best suited are selected while the less well adapted are excluded without being able to have offspring.

- *Crossover*: The crossover operator is used to introduce a small change in the solution or change the direction of research (enrich the diversity of the population). Typically, the crossings are made by choosing two random individuals (parents) to be "crossed" with a certain probability of crossover P_c means that when both parents are applying for reproduction, we get a real x random according to a uniform [0,1], if x less than P_c, then we meet the parents in order to generate two new individuals (children) "Fig. 6 ". The children replace their parents and form a new intermediate population.

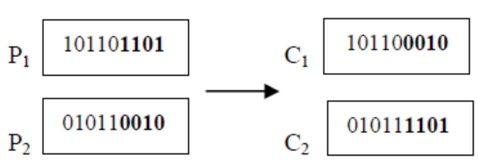

Fig. 6. Crossover operation

- *Mutation*: the mutation, which is a unary operation, represents the frequency with which genes of a given chromosome are muted. For example, a widely used mutation is to randomly draw a single gene in the chromosome and replace it with a random value with a probability of mutation P_m to expand the space of explored solutions "Fig. 7 ".

Fig. 7. Mutation process

Sometimes, important information stored in genes may disappear during the intersection operations. The essential role of the mutation is to remedy this type of degeneration [12]. On the other hand, the mutation operator's role is to prevent the algorithm to stagnate, if the population converges to a local optimum, the mutation operator operates with a high rate, that is to say a high probability Pm, which can disperse a significant portion of the population of the search space [18]. However, the choice of the value of P_m is critical as it introduces a significant impact on the performance of the genetic algorithm. In the specialized literature, it is suggested a very low probability of mutation to ensure the asymptotic convergence of the method in the exploration space [19].

3.2 Problem position

The design problem is formulated as a constrained, nonlinear and multi-variable problem; for this reason, the program was written in a MATLAB environment. The design variables are the stator and the rotor pole arc angles. So the search region of these two parameters must satisfy certain conditions chosen according to the rules of feasible triangle “Fig. 8”. These rules are used to define the lower and higher limits of each variable so to define the search region, namely [20]:

$$\beta_s \le \beta_r \tag{5}$$

$$\beta_s \ge \frac{2\pi}{qNr} = \beta_{sm} \tag{6}$$

$$(\beta_s + \beta_r) \prec \alpha_r = \left({2\pi}/{N_r} \right) = 90^\circ \tag{7}$$

$$\beta_{sm} = \left(\frac{2\pi}{qN_r} \right) = 30^\circ \le \beta_s \le 45^\circ = \left(\frac{\pi}{N_r} \right) \tag{8}$$

$$\beta_{rm} = 30^\circ \le \beta_r \le 60^\circ = (\alpha_r - \beta_{sm}) \tag{9}$$

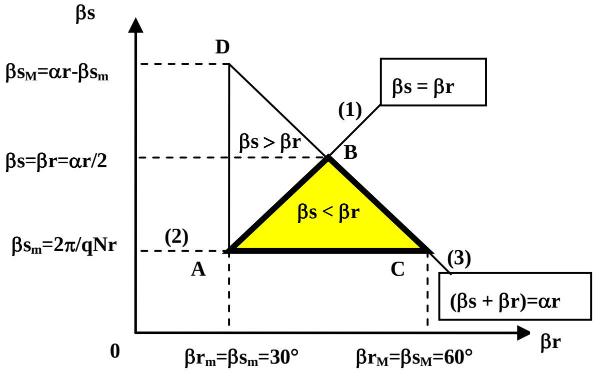

Fig. 8. Feasible triangle

To find the optimal sizes of the pole arc angle of stator and rotor (*Br* and *Bs*), to have the maximum average torque, the model was coupled with our semi-analytical calculation tool GA. In this application, the rotor and stator pole arcs are the two parameters (genes) to optimize. For each pair (βs, βr) generated by the genetic algorithm, the first step is the determination of the inductances and the second step is the calculation of the average torque developed by the combination (βs, βr).

The flowchart given in Figure 9 illustrates the design optimization process.

The genetic algorithm parameters used for the design optimization problem are fixed by the following values:

- Population: 20 machines.
- Probability of crossover: 70%.
- Probability of mutation: 9%.
- Number of generations: 100.

4 Optimization Results

The procedure described above was then realized and desired outcomes were identified by the genetic algorithm. The results are interpreted by the graphs "Fig. 10, 11, 12". The results of the optimal design are presented in Table 1. The design of the motor with a stator pole arc β_s = 40° and a rotor pole arc β_r = 50 ° shows an improvement of about 40% of the average torque compared with the initial construction. Figure 10 shows the change of the best average torque obtained in each generation. The optimal solution is obtained at the 26th generation.

The results in Figures 11 and 12 show the variations of β_s and β_r around their optimal values.

Figure 13 shows the magnetic flux according to the ampere-turns deduced from the analytical model for the initial construction and optimized. Holding constant the magneto motive force, a high electromagnetic energy is possible by optimizing the average torque.

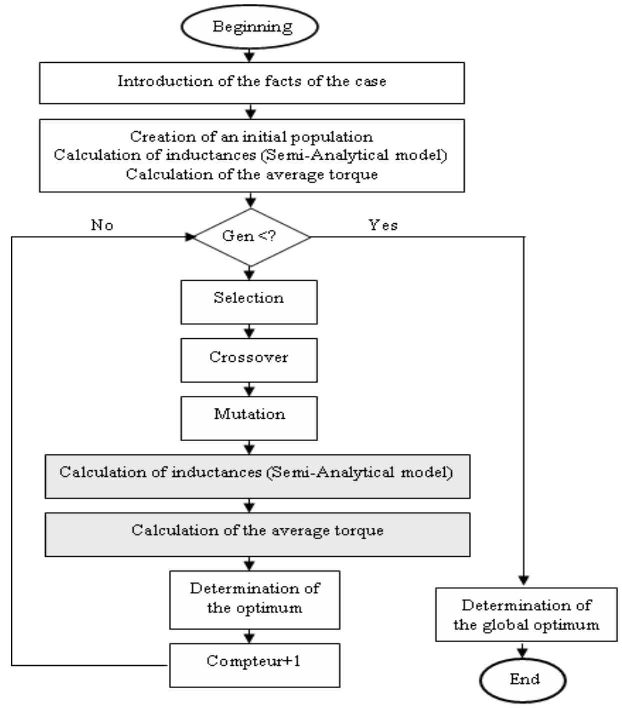

Fig. 9. Design optimization process

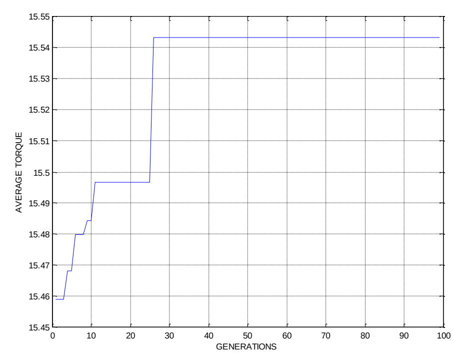

Fig. 10. Average torque over generations

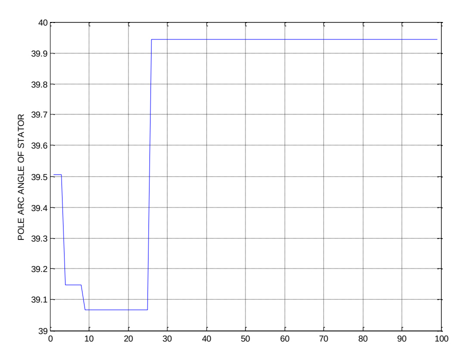

Fig. 11. Change of β_s over generations

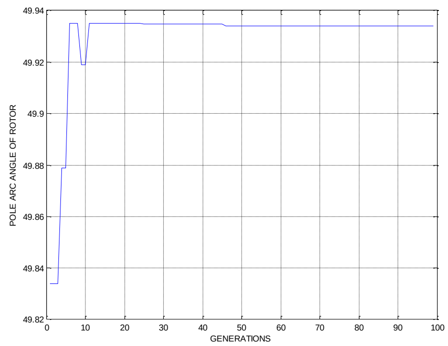

Fig. 12. Change of β_r over generations

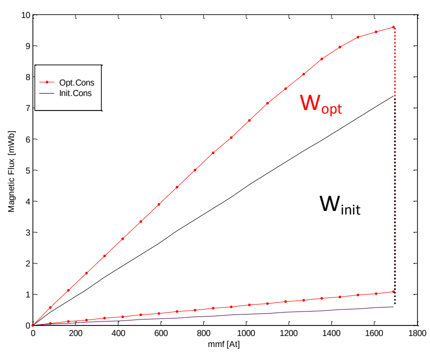

Fig. 13. Extreme characteristics of flux vs. excitation current

TABLE 1
Results of Optimal Design

Parameters	Initial design	Optimal design
Stator pole arc	30 (deg.)	39.9409 (deg.)
Rotor pole arc	30 (deg.)	49.9333 (deg.)
average torque	11.1399 Nm	15.543 Nm

5 Conclusion

In this paper, an original method for optimizing a three-phase SRM 6/4 based on genetic algorithms was presented. The design optimization of stator and rotor pole arc teeth was carried out under MATLAB environment using a user-friendly program based on a semi-numerical approach developed for calculating the extreme values of inductance and corresponding energies. Preliminary results indicate a significant improvement of average torque.

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