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Optimal Design of Switched Reluctance Motor Using PSO Based FEM-EMC Modeling

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Article Info	ABSTRACT

This paper aims to optimize the design of a prototype of a 6/4 Switched Reluctance Motor (SRM) using the Particle Swarm Optimization (PSO) algorithm. The geometrical parameters to optimize are the widths of the stator and rotor teeth due to their significant effects on the prototype design and the performances in terms of increased average torque and reduced torque ripple. The studied 3kW SRM is modeled using a numerical-analytical approach based on a coupled Finite Element Method with Equivalent Magnetic Circuit (FEM-EMC). The simulations are performed under MATLAB environment with user-friendly software. The optimal results found are discussed, compared against those obtained by the Genetic Algorithms (GA) and showed a significant improvement in average torque.

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1.   INTRODUCTION

To meet challenging requirements, new design and more efficient structures of electrical machines are investigated by manufacturers and researchers. In this context, Permanent Magnet Synchronous Motor (PMSM), Brushless dc motor (BLDC), Linear Switched Reluctance Motor (LSRM) and rotary Switched Reluctance Motors (SRMs) have been explored in the literature as they are an attractive alternative to induction and synchronous machines [1-4]. Due to their robustness, reliability, high performance and reduced cost, the SRM found numerous applications at high speed drive or low speed generator (electrical vehicles, air-conditioners, extractors, centrifuges, flywheel energy storage, shipbuilding, aeronautics, and gearless wind generator) [5-7].

Metaheuristic methods are general optimizing algorithms applicable to a wide variety of problems. They appeared in the 1980s, with a common ambition: to solve efficiently the difficult optimization problems, for which there is no known most effective classical method [8], [9]. New techniques inspired by artificial intelligence have emerged and developed to offer as potential alternative techniques to improve the quality of the solution, namely Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and so on.

The PSO is a still relatively unknown and relatively young technique in the field of design [10], [11]. It is analogous to GA in the sense that the system is initialized with a random population of solutions; it is compared to all its neighbors by maintaining each time the best result [12]. Unlike the GA and other metaheuristic algorithms, PSO has the flexibility to control the balance between global and local exploration of the search space [13], [14]. The PSO has achieved rapid development following advantages [15-17]: simple concept, easy implementation, robustness and computational efficiency. In [18], the torque production is improved using PSO algorithm to optimize the stator and rotor angles of a 8/6 SRM. In [19], the PSO is applied to the rotor pole arc of a 4/2 SRM to minimize the torque ripple.

One aspect of the contribution of this work lies with the application of the Particle Swarm Optimization method (PSO) for optimizing the average torque of a 6/4 SRM through various geometric parameters. The other aspect is the comparative study of the performance of PSO and GA algorithms applied to the machine GA [20]. The results show that the PSO-based approach gives the best performance in terms of solution quality, accuracy and convergence time. The main contribution of this work is related to the numerical-analytical approach used to model the studied SRM using a user-friendly program carried out under MATLAB.

The paper is organized as follows: Section 2 describes the FEM-EMC approach modeling of the studied SRM. In Section 3 the PSO algorithm is presented with the formulation of the problem. The results obtained are discussed in Section 4. The paper concludes in Section 5.

2. FEM-EMC MODELING OF THE SRM

Modeling of electric machines can be classified into three categories: analytical models, finite element analysis (FEA) and equivalent magnetic circuits (EMC), which can be considered as a semi-analytical method [21]. Modeling using EMC has been chosen for further investigation because it seemed a good technique with great speed and acceptable accuracy. The model produced will be used later in an optimization process that aims to find the best system parameters.

The machine topology studied is a double saliency three-phase 6/4 SRM with Ns=6 stator teeth and Nr=4 rotor teeth as represented "Figure 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 "Figure 2".

As described in [22], to determine analytically the relations flux-At from only seven characteristics equal-flux lines traced by the finite element method (FEM) and corresponding to seven magnetic equivalent circuits (EMC), 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 as depicted in "Figure 3":

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

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

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

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

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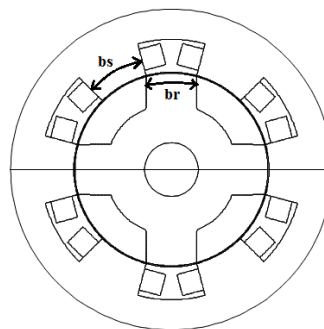

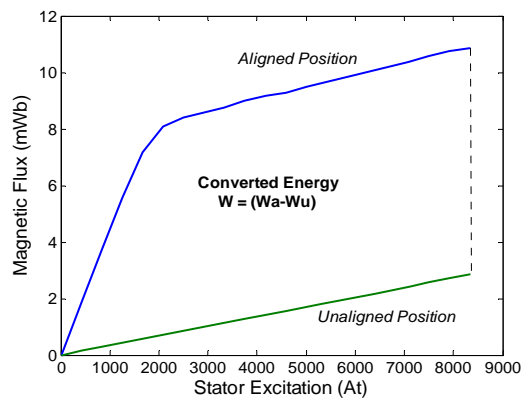Figure 1. Cross-section of the studied 6/4 SRM

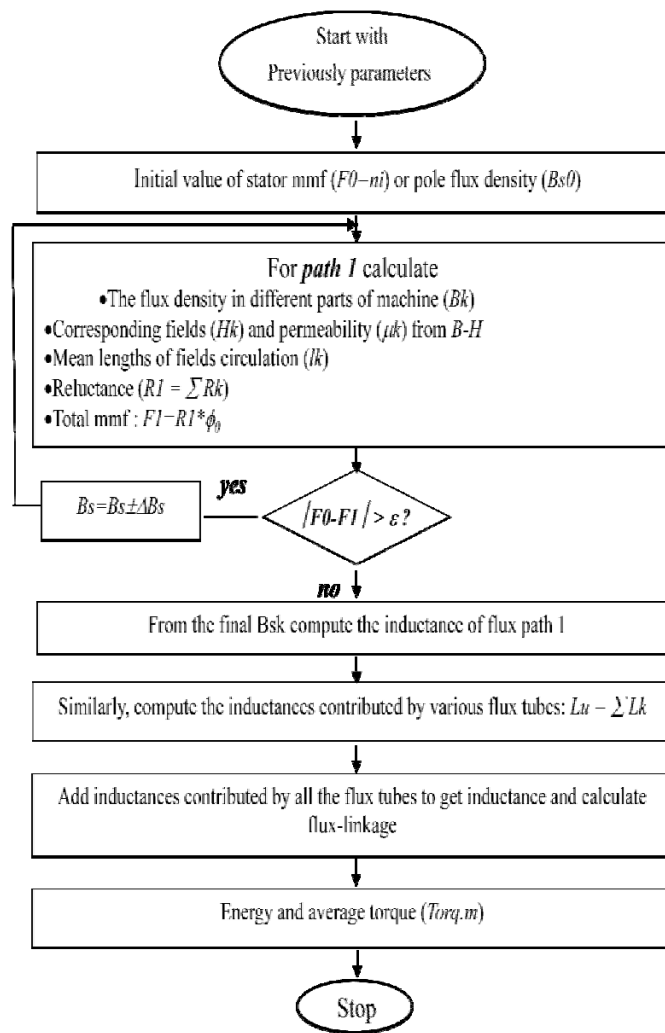Figure 2. Extremes magnetic characteristics flux vs. excitation mmf

Figure 3. Flowchart of main program of simulation under MATLAB

3.   PARTICLE SWARM OPTIMIZATION ALGORITHM

3.1. Basic Concepts of PSO

The Particle Swarm Optimization method (PSO) is a relatively recent heuristic proposed by Eberhart and Kennedy for the first time in the early 90s [23], based on a stochastic population candidates solutions to develop an optimal solution to the problem presented. This method is particularly suitable for non-linear systems; it does not require the calculation of the first and second derivative, unlike the gradient type methods. Its basic idea is inspired from the actions of animal groups (swarms) in their search for the best subsistence areas. Thus, each individual in the population has the memory of its previous experience and the information provided by the group on the most promising regions. This contribution to the overall experience, in addition to personal experience is one of the features of PSO which ensure it success in global searches.

A swarm of particles, which are potential solutions to the optimization problem, "flies" the search space, in the search for the global optimum. The movement of a particle is influenced by three components [24]:
1.   A component of inertia: the particle tends to follow its current travel direction;
2.   A cognitive component: the particle tends to rely on its own experience, and thus to move towards the best site in which it has already passed;
3.   A social component: the particle tends to rely on the experience of its congeners, and thus to move towards the best sites already reached collectively by the swarm.

3.2. Basic Principle of PSO

In a search space of dimension D, the algorithm starts with a random initialization of the particle swarm. Particle i of the swarm is modeled by its position vector $\vec{x}_i = \left(x_{i1}, x_{i2}, ..., x_{iD}\right)$ and the velocity vector $\vec{v}_i = \left(v_{i1}, v_{i2}, ..., v_{iD}\right)$.

The quality of its position is determined by the value of the objective function at that point. This particle remembers the best position in which it has already passed, which is noted $\vec{P}best_i = \left(pbest_{i1}, pbest_{i2}, ..., pbest_{iD}\right)$. The best position achieved by its neighboring particles is noted $\vec{G}best = \left(gbest_1, gbest_2, ..., gbest_D\right)$.

Indeed, at iteration t +1, the velocity vector and the position vector are calculated from the equation (5) and equation (6), respectively.

$$v_{i,j}^{t+1} = w v_{i,j}^{t} + c_1 r_{1,j}^{t}\left[pbest_{i,j}^{t} - x_{i,j}^{t}\right] + c_2 r_{2,j}^{t}\left[gbest_j^{t} - x_{i,j}^{t}\right] \tag{5}$$

$$x_{i,j}^{t+1} = x_{i,j}^{t} + v_{i,j}^{t+1}, j \in \left\{1,2,....,D\right\} \tag{6}$$

where : $v_{i,j}^{t+1}, v_{i,j}^{t}$: Are the speed of the particle to t and t +1 iterations. $Pbest$: Is the best position of the particle. $Gbest$: Is the best position of a neighbor at iteration t. $x_{i,j}^{t}$: Is the position of the particle at iteration t. w : Is generally called a constant factor of inertia, it keeps a balance between exploration and exploitation. c_1 and c_2 : are two constants called acceleration coefficients, they keep the balance between individual and social behavior of the particle when they are equal [25]. r_1 and r_2 : are two randomly generated numbers with a range of [0,1], for each iteration and for each dimension j.

3.3. Problem Formulation

The objective function $f(x,u)$ used to formulate the SRM problem represents a maximizing average torque. In the case of an optimization problem where the objective is to be maximized, the function is considered with the opposite sign $-f(x,u)$; the equality constraints expressed by the function $g(x,u)$ are represented by the equations of the maximum and minimum inductances L_a and L_u as well as W_a and W_u energies of the two extreme positions of which the average torque and inequality constraints will be deduced which reflect the lower and upper dental openings which are given by equations limits [26]:

$$\beta_{sm} = \left(2\pi \big/ qN_r \right) = 30° \le \beta_s \le 45° = \left(\pi \big/ N_r \right) \tag{9}$$

$$\beta_{rm} = \beta_{sm} = 30° \le \beta_r \le 60° = \left(\alpha_r - \beta_{sm} \right) \tag{10}$$

$$\left(\beta_s + \beta_r \right) < a_r = \left(2\pi \big/ N_r \right) = 90° \tag{11}$$

Therefore, the proposed solutions must take the constraints of construction into account. These constraints are taken into account by penalizing proportionally the objective function for constraint violations. In the context of taking into account the constraints, it is to degrade the performance of infeasible individuals in function of their proximity to the feasible area of the search space. For each element of the search space, its proximity to the feasible region can be measured through the level of violation of each constraint. Using this measure of infeasibility of the individual x from each constraint, the penalty function in the general form can be introduced:

$$Min \quad F_{obj} = -f(x) + F_{penalty}$$

$$x_i^1 \le x_i \le x_i^u, i = 1,......, n \tag{12}$$

4. SIMULATION RESULTS AND DISCUSSION

A comparative study with Genetic Algorithms (GA) has been made to verify the performance of the proposed algorithm.

The PSO and GA parameters used for simulation are summarized in Table 1. For the implementation of PSO, several parameters must be specified, such as acceleration factors (c_1 and c_2), the inertia factor (w), the size of the swarms and the stop criterion. The PSO algorithm has been applied to the objective function according to the flowchart in Figure 4.
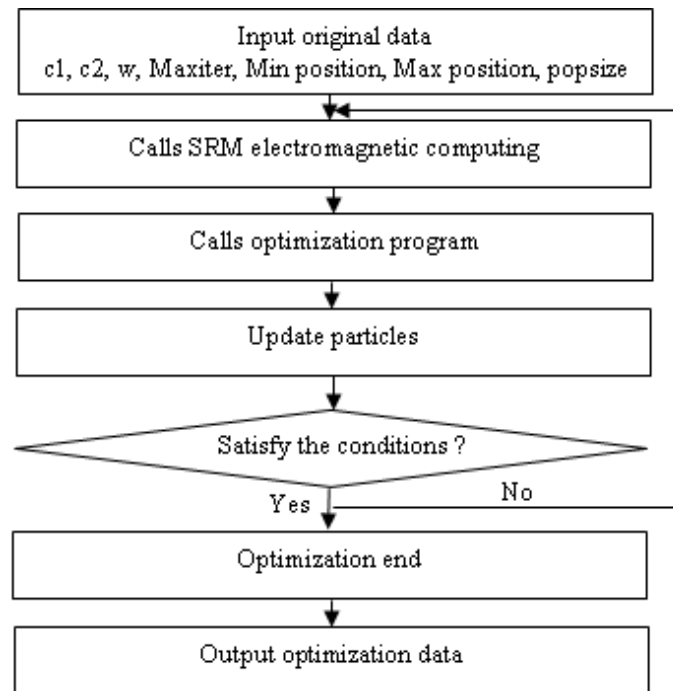

Figure 4. The flowchart of adaptive PSO for SRM

Table 1. Simulation parameters

GA	PSO
Population size:20	Number of Particles:20
Generations:100	Iterations:100
Crossover rate:0.7	$c_1 = c_2 = 2$
Mutation rate:0.09	$W = -0.1$

To confirm the performance of this method, a comparison of its results with the results of genetic algorithms has been made. The comparison is shown in Table 2.

The convergence characteristics of the two methods: PSO and GA for a variable reluctance motor are shown in Figures 5, 6, and 7. According to the results, it can be noticed that the PSO explores a solution superior to the genetic algorithm for the same number of population and generation.

Table 2. Comparison results of PSO and GA for Fa= 1691At

parameters	Prototype	Optimization	
		GA	PSO
Stator pole arc (deg.)	30	39.9409	37.8324
Rotor pole arc (deg.)	30	49.9333	52.1676
average torque (Nm)	11.1399	15.543	15.6178

It can be seen from figure 5, firstly, that the PSO algorithm converges toward the global optimum from the thirty sixth iteration (36), while the convergence of the GA algorithm is reached at iteration (26) with an optimal value lower compared to the PSO algorithm. This proves that the power of convergence to the global optimum in the PSO method exceeds that of the method of genetic algorithms (GA), this will have a direct impact on the time required for convergence of the two methods. Furthermore, the robustness of the PSO algorithm is more remarkable. The difference in average torque between the two optimization methods (15.6178Nm compared with 15.543Nm) is virtually insignificant or negligible (a slight difference of about 0.48%). This will confirm our findings in terms of robustness of the PSO convergence.

The results presented in Figures 6 and 7 show variations of β_s and β_r around their optimum values. The safety constraints are also checked for these two angles. These are qualified in their ranges.
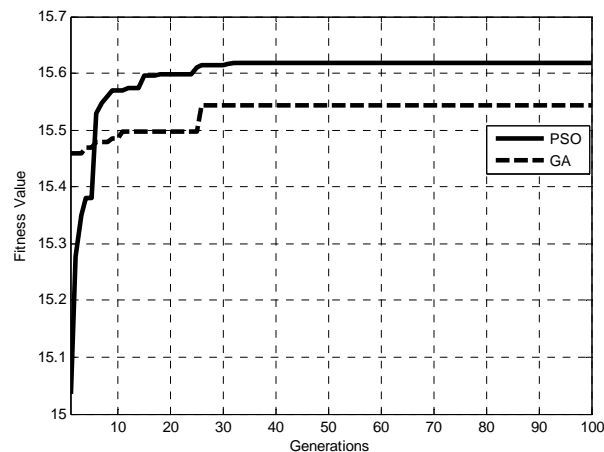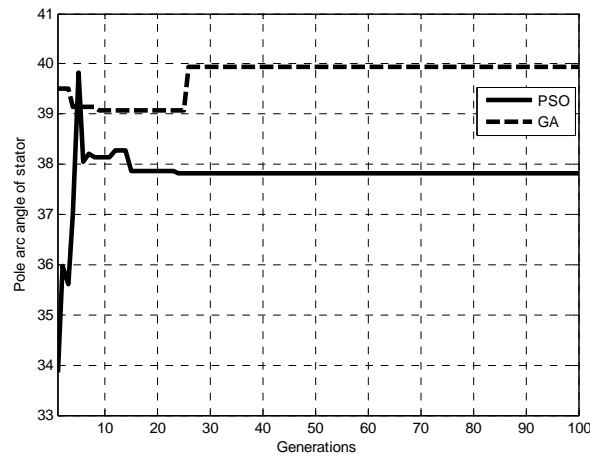

Figure 5. Objective function
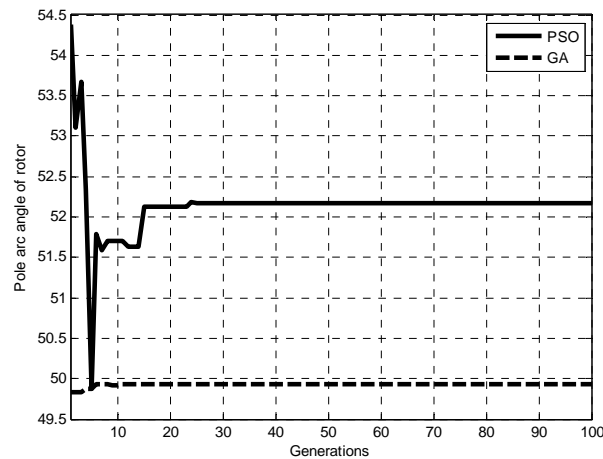
Figure 6. Change of β_s around the optimal value

Figure 7. Change of β_r around the optimal value

5. CONCLUSION

The paper proposes a permeance network modeling and presents a direct coupling between the finite element method (FEM) and the equivalent magnetic circuit method (EMC) to model the switched reluctance machine. The modeling tool presented is designed to be integrated into an optimization process that modifies the geometry of the engine.

The optimization method chosen is the particle swarm optimization (PSO), the stochastic nature, metaheuristics, allows the application to difficult and non-linear problems. The principle of the method is explained as well as the different coefficients of the algorithm and the influence they have on the evolution of the algorithm. The optimization procedure of the design of SRM using PSO is presented with the aim of maximizing the average torque for an efficient solution all by acting on the tooth geometry which has a great influence on motor performance. The difference in the average torque estimated by the two algorithms, PSO and GA, is negligible suggesting the simultaneous convergence to the same quasi-optimal solution.

From the simulation results, it can be found that the PSO can lead to optimal feasible solution, and that is the relative ease of implementation and ability to provide reasonably good solutions for many combinatorial problems.

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