Optimum Performances for Non-Linear Finite Elements Model of 8/6 Switched Reluctance Motor Based on Intelligent Routing Algorithms

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Abstract. *This paper presents torque ripple reduction with speed control of 8/6 Switched Reluctance Motor (SRM) by the determination of the optimal parameters of the turn on, turn off angles (Θ_{on}, Θ_{off}), and the supply voltage using Particle Swarm Optimization (PSO) algorithm and steady state Genetic Algorithm (ssGA). With SRM model, there is difficulty in the control relapsed into highly non-linear static characteristics. For this, the Finite Elements Method (FEM) has been used because it is a powerful tool to get a model closer to reality. The mechanism used in this kind of machine control consists of a speed controller in order to determine current reference which must be produced to get the desired speed, hence, hysteresis controller is used to compare current reference with current measured up to achieve switching signals needed in the inverter. Depending on this control, the intelligent routing algorithms get the fitness equation from torque ripple and speed response so as to give the optimal parameters for better results. Obtained results from the proposed strategy based on metaheuristic methods are compared with the basic case without considering the adjustment of specific parameters. Optimized results found clearly confirmed the ability and the efficiency of the proposed strategy based on metaheuristic methods in improving the performances of the SRM control considering different torque loads.*

Keywords

Finite elements method, parameters optimization, particle swarm optimization, steady state genetic algorithm, switched reluctance motor, torque ripple reduction.

1. Introduction

The switched reluctance machine has attracted great attention of many researches due to several advantages such as simple structure, low cost, simplicity of the power converter, fault tolerance, and capability to use in high temperature environments [1] and [2]. However, it has some disadvantages as the higher torque ripples compared to conventional machine, also, a significant acoustic noise as well as speed oscillations [3], [4] and [5]. The doubly salient structure and magnetic saturation created the inherent non-linearity in SRM, this is the main reason for the existence of the mentioned defects. Furthermore, it makes a difficulty in analysis, modelling, and control. Therefore, the use of Finite Elements Method (FEM) is considered an effective method to analyze and treatment the non-linear model of SRM [5], [6], [7] and [8].

Many researchers have proposed different strategies to improve the performance of SRM in various ways, such as control and design [4], [5], [6] and [7]. The modern control techniques have a significant contribution to improving the torque ripples and the speed response. However, such control is complex due to the inherent non-linearity and power converter properties. Several researches in [8], [9], [10] and [11] have been presented the importance of selecting the control parameters in SRM, which showed a significant impact on the quality of results. The selected parameters by manual selection or other analytical techniques have yielded acceptable results, but they are not sufficient. Therefore, the intelligent algorithms developed have been considered as an alternative solution to improve the parameters in SRM. In general, the optimization based on maximizing or minimizing a real function to get the best solution by using a special algorithm, thus, it allows to select the best input values according with output values by computing the value of the objective function. These algorithms have been used in many research areas, in particular for solving practical problems related to power system planning, operation and control, such as to solve the practical economic dispatch problem [12], and to minimize the power loss in distribution networks [13].

Various intelligent methods have been proposed to improve the performances of the SRM for the design optimization [5], [14] and [15], sensorless speed control [16], a second order sliding mode control [17], and the problem of determining the optimal control parameters [11]. This latter used non-dominated sorting genetic algorithm to find optimal values of Proportional-Integral (PI) regulator and the turn on and turn off angles (Θ_{on}, Θ_{off}) was successfully applied to reduce the problems of integral squared error of speed and torque ripple. On the other hand, it was based on a linear model, which makes the results so far to the real and practical cases.

The standard particle swarm optimization is one of algorithms based on swarm intelligence, introduced by Kennedy and Eberhart in 1995 [18]. This algorithm inspired by the collective behaviour of animals in nature such as flocking behaviour of birds and schooling behaviour in fish. The original PSO algorithms and a large number of variants and various hybrid algorithms based PSO have been applied successfully to solve many real-world problems addressing non-linear and non-continuous constraints. This algorithm, gives good solutions in a short time.

In this work, control system depends on speed control and current control for a non-linear model of 8/6 SRM based on different characteristics determined by the use of FEM. Furthermore, the PSO and ssGA algorithms have been applied to find optimal values of specified parameters of SRM such as the turn on, turn off angles (Θ_{on}, Θ_{off}) and the supply voltage.

In order to evaluate the efficiency of the proposed metaheuristic methods to reduce the torque ripple, the obtained results are compared with the results of the basic case without adjusting the standard parameters of the SRM.

2. The Switched Reluctance Motor Drive Model

The SRM is one of the machines with a simple structure. On the other hand, the inherent non-linear makes it difficult to study and to model. To overcome these difficulties, the static characteristics will be identified by the FEM, which are used in the dynamic model.The electrical equation for each phase of dynamic model of the SRM is given by:

$$V = R_s i + \frac{\mathrm{d}\phi(\Theta, i)}{\mathrm{d}t}, \tag{1}$$

where R_s is the resistance per phase and the flux linkage per phase ϕ, which is given by:

$$\phi(\Theta, i) = L(\Theta, i) i, \tag{2}$$

where $L(\Theta, i)$ is the inductance dependent on the rotor position and the phase current.

Here, we note that, it is sufficient to use the inductance rather than flux linkage in order to get the SRM model. The mechanical equation is as follows:

$$J\frac{\mathrm{d}\omega}{\mathrm{d}t} = T_e(\Theta, i) - B\omega - T_L, \tag{3}$$

and:

$$T_e(\Theta, i) = \sum_{j=1}^{4} T_{ej}(\Theta, i), \tag{4}$$

where J is the moment of inertia, B the friction coefficient, ω the rotor speed, T_L the torque load, T_e the total electromagnetic torque and T_{ej} refers to the static torque generated by the j^{th} phase ($j = 1, 2, 3, 4$).

Hence we must define the static characteristics of the inductance and the static torque that will depend on the FEM which has been effective in SRM modelling [7], [8] and [10]. In this way, the effect of magnetic saturation and air gap variation can be taken into account. By solving the non-linear Poisson equation using the two-dimensional (2D) FEM, we obtain the value of the magnetic vector potential $\vec{A}$ which allows to identify the characteristics of the magnetic distribution. Poisson's equation is given as follows:

$$\text{Curl}\,\left(\nu\ \text{Curl}\,\vec{A}\right) = \vec{J}. \tag{5}$$

In Cartesian coordinates (x, y), Eq. (5) takes the following form:

$$\frac{\partial}{\partial x}\left(\nu\frac{\partial A_Z(x,y)}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu\frac{\partial A_Z(x,y)}{\partial y}\right) = \\ = -J_Z(x,y), \tag{6}$$

where ν is the magnetic reluctivity, and J_Z the source current density.

Depending on the result of the magnetic vector potential, it is possible to calculate the value of the flux linkage for one phase in SRM:

$$\phi = \frac{1}{i} \int_V \vec{J}\vec{A} \mathrm{d}V. \tag{7}$$

The inductance and magnetic co-energy depending on the flux linkage are calculated according to the next equations:

$$L(\Theta, i) = \frac{\phi(\Theta, i)}{i}, \tag{8}$$

$$W'_{em} = \int_0^i \phi(\Theta, i)\partial i \Big|_{\Theta=\mathrm{const}}. \tag{9}$$

The static torque can be calculated by differentiating magnetic co-energy with respect to angular position of the rotor for single phase excitation as follows:

$$T(\Theta, i) = \frac{\partial W'_{em}}{\partial \Theta}\Big|_{i=\mathrm{const}}. \tag{10}$$

The non-linear FEM of 8/6 SRM has been implemented and analyzed by using ANSYS Parametric Design Language (APDL) because of its compatibility and ability to achieve the model with all the requirements and to reach the needed characteristics.

To get the SRM characteristics, non-linear FEM must be analysed from an unaligned position to an aligned position for various excitation current ($i = 2$ A to 16 A). The analysis for one phase is sufficient to identify all the characteristics of the other phases because the SRM is homogeneous and symmetrical in physical characteristics.

The simulation results depend on solving Eq. (6) by FEM in order to obtain the magnetic vector potential, then the magnetic flux density and the magnetic field intensity until access to the flux linkage, the static torque and the inductance. After the modelling and the analysis by the non-linear FEM, the simulation results can be displayed for many positions and for different excitation currents. Hence, the magnetic vector potential and the magnetic flux density for the basic geometry of 8/6 SRM at aligned and unaligned position and at excitation current ($i = 4$ A) are shown in Fig. 1 and Fig. 2, respectively.

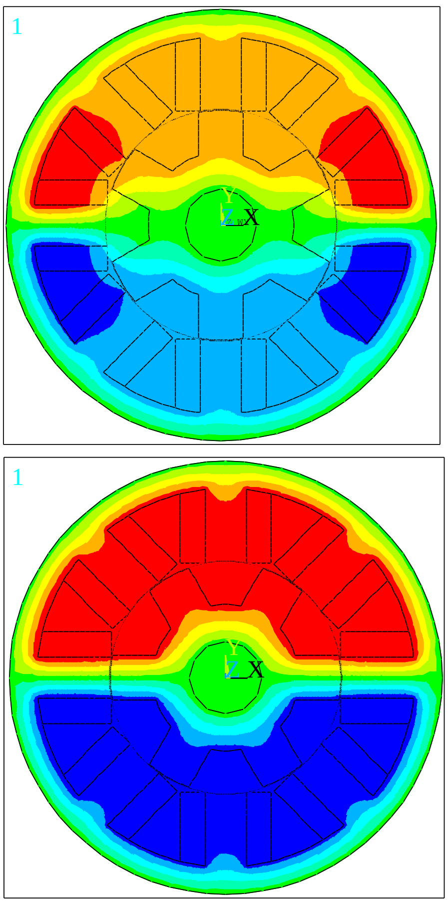

Fig. 1: Magnetic vector potential distribution at aligned and unaligned position and at excitation current ($i = 4$ A).

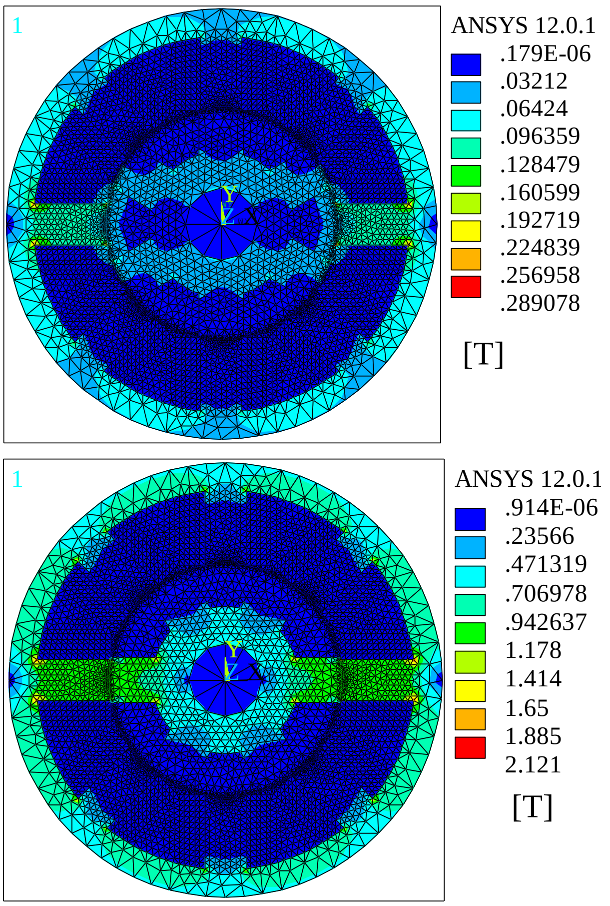

Fig. 2: Flux density distribution at aligned and unaligned position and at excitation current ($i = 4$ A).

The previous relations (see Eq. (7), Eq. (8) and Eq. (10)) give the characteristics of the SRM based on results of the non-linear FEM, hence the results of inductance and static torque can be given as a function of rotor position and current, which are presented in Fig. 3 and Fig. 4, respectively.

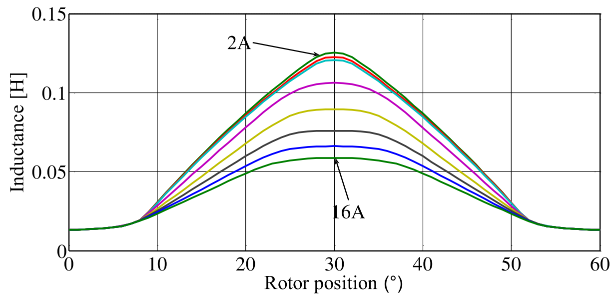

Fig. 3: Inductance characteristics as a function of the rotor position for different current values.

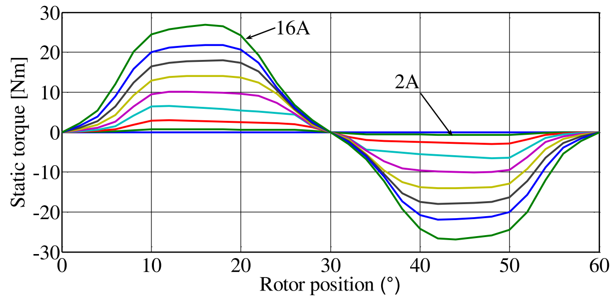

Fig. 4: Static torque characteristics as a function of the rotor position for different current values.

From these results the effect of magnetic saturation and air gap variation can be seen. In Fig. 3, the inductance values change with variation of rotor position and current values. Also, in Fig. 4, it can be seen that static torque is always proportional to the derivative of self-inductance. The dynamic model of an 8/6, four phases SRM is developed using the above characteristics with electrical and mechanical equations, for more details see [10].

3. Control Strategy and Optimization

The strategy of control (as shown in Fig. 5) consists of tow regulators; the first regulator is a PI speed regulator, followed by a hysteresis current regulator.

The speed regulator gives the current reference which processed by the hysteresis controller in order to obtain the electromagnetic torque necessary to achieve the desired speed. On the other hand, the hysteresis controller output depends on a comparison between the measured and desired current in order to give a signal to switch control signal generator, which in turn determines the commutation angles with regard the beginning and the end angles (Θ_{on}, Θ_{off}) for the asymmetric converter. The use of this method allows maintaining the desired speed based on the given hysteresis controller for the current of each phase. However, the torque ripple defect remains undesirable in the SRM. On the other hand, we can reduce this defect by finding the most appropriate parameters to use in the control system.

The values of the turn on, turn off angles (Θ_{on}, Θ_{off}) and the supply voltage have a significant impact on the performances of SRM. For this pertinent reason, we relied on the parameter optimization strategy based metaheuristic techniques, as their efficiency in reducing

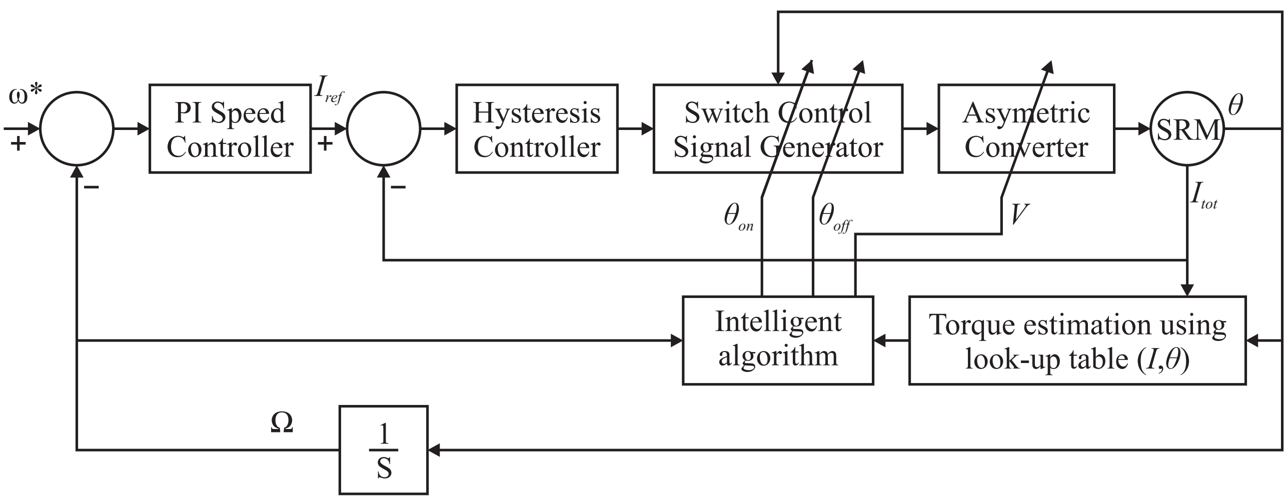

Fig. 5: Block diagram of control system for SRM drive with PSO.

the torque ripple will be demonstrated in the simulation results.

The static torque characteristics transferred to the control system to determine the instantaneous torque by using the look-up table in Matlab Simulink. Furthermore, the proposed intelligent algorithms are adapted and applied to optimize specified parameters of SRM in order to reduce the torque ripple.

3.1. Model Based on the PSO Algorithm

In previous works [8], [9] and [19], authors introduced ways to find optimal parameter for SRM. This has been a successful research but can be better accessed using intelligent algorithms. In this work, a proposed strategy contains speed control by current control, where the PSO will play an essential role in determining the optimal parameters of the turn on, turn off angles (Θ_{on}, Θ_{off}), and the supply voltage in order to obtain torque ripple reduction with speed control. PSO algorithm will be used in off line mode because it helps to address each value separately, but it takes a long time in processing. The proposed method for coordination of PSO with the control system is described in the flowchart as shown in Fig. 6.

PSO is a robust stochastic optimization technique based on velocity update and position update. During each generation, each particle adjusts its position according to the particles previous best position and the global best position. Each particle also has memory and hence, can remember the best position in search space it has ever visited in order to calculat a new velocity (v^{k+1}), value by its current velocity (v^k), the distance from its previous best position (P_{best}), and the distance from the global best the position (G_{best}). Then the velocity and position are calculated according to the following formulas:

$$x^{k+1} = x^k + v^{k+1}, \tag{11}$$

$$\begin{aligned} v^{k+1} = w \cdot v^k + c_1 \cdot \mathrm{rand}_1 \cdot (P_{best} - x^k) + \\ + c_2 \cdot \mathrm{rand}_2 \cdot (G_{best} - x^k), \end{aligned} \tag{12}$$

where x^k is the current searching point, x^{k+1} is modified searching point, w is the inertia weight, c_1 and c_2 are acceleration coefficients, and k is the iteration time. Besides, rand_1 and rand_2 are random numbers in the interval $[0-1]$.

The inertia weight in this study is not fixed but varies according to the following formula [20]:

$$w(k) = w_{\max} + \left(\frac{w_{\max} - w_{\min}}{k_{\max}}\right) \cdot k. \tag{13}$$

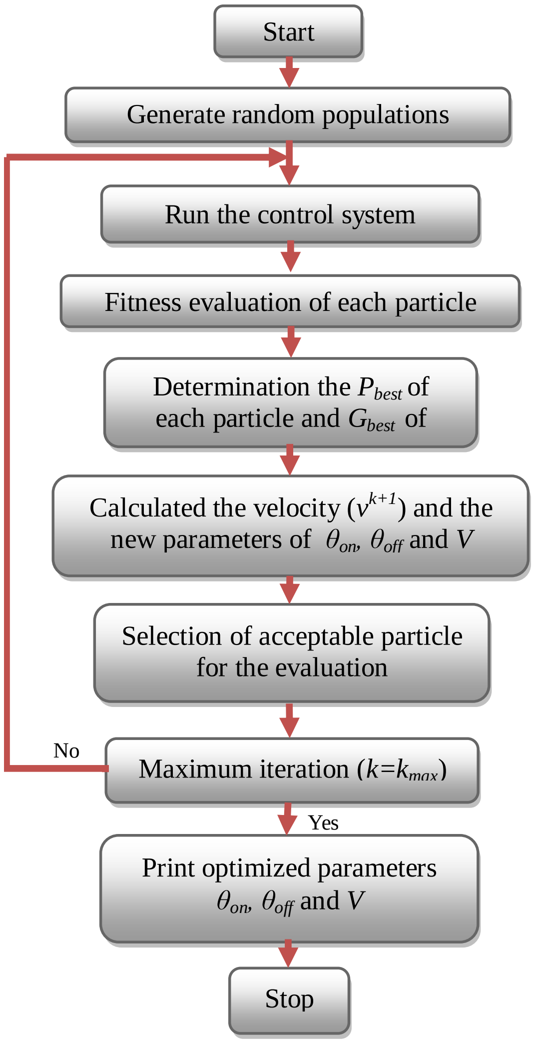

Fig. 6: Flowchart of the PSO for the control system.

The parameters $k_{\max}$ and k are the maximum number of iterations and the current number of iteration, respectively. Also, $w_{\min}$ and $w_{\max}$ denote the maximum and the minimum inertia weight, respectively.

The coefficients in Eq. (12) are constants: $C_1 = C_2 = 2$. The number of maximum iteration is equal to 100 and the inertia weight values are: $w_{\min} = 0.4$ and $w_{\max} = 0.9$.

The PSO program has been developed using MATLAB language, for its ability to be associated with the control system in Simulink.

3.2. Steady State Genetic Algorithm

Genetic Algorithms (GA) are a common and useful tool for numerical optimization algorithms used in several applications. Here they will be applied to the control system to determine the possibility of improving the parameters.

In the application of genetic algorithm, we will rely on binary encodings because it is the most common encodings, effective and easy to deal with, where each bit in the chromosome takes two possibilities: either 1 or 0 [21].

In order to reach the solution of the problem, following steps were used:

- **Generation of the initial population**: The initial population is generated chromosome randomly with taking into account the domain specific. The size of a population is equal to 10.

- **Evaluation**: Each chromosome is decoded to real number and evaluated by fitness function until selection of parents.

- **Selection**: The technique used in the selection of parents is survival of the fittest mechanism, also called steady state [22] and [23]. It is characterized by the preservation of suitable chromosome, which distinguishes the ssGA algorithm from other variant of genetic algorithms.

- **Crossover**: The types of crossover operators used N-point crossover in order to be more diverse in the offspring. A long tail section must be used for the chromosome, because it consists of three parameters (Θ_{on}, Θ_{off}, V).

- **Mutation**: Is used here, for each generation, a certain percentage by random manner in order to get a new optimized chromosome with different characteristics.

After the previous steps have been achieved, a new generation will be reproduced until a convergence criterion is reached such as a fixed number of generations. Moreover, the proposed algorithm has been developed using MATLAB language; the maximum number of iteration taken is equal to 100.

3.3. The Fitness Function

The determination of the fitness equation correctly allows an assessment of the elements in an effective manner. It helps to reach the optimal solution. We note that the experience factor in the specialty plays an important role in determining the most appropriate equation.

The control system of SRM gives the results of speed and torque which will be relied upon in the fitness equation, the value of torque estimated using look-up table (I, Θ) [8].

By detailing the instantaneous torque can be calculated the torque ripple as follows:

$$T_r = \frac{T_{\max} - T_{\min}}{T_{\text{mean}}}. \tag{14}$$

To complete the fitness equation, the static error of speed must be considered. Otherwise there would be no reason to reduce the torque ripple without speed control:

$$\text{SE} = \max\left(|\omega_{ref} - \omega|\right). \tag{15}$$

With regard to Static Error (SE) of speed, it is only important when it is less than a certain value (SE $< \epsilon$), meaning that the SE has an impact on the fitness equation just if its value unacceptable physically (large error). Hence, from Eq. (14) and Eq. (15), we can identify the fitness equation as follows:

$$f = \frac{1}{\dfrac{1}{T_r} - \dfrac{\text{SE}}{n}}, \tag{16}$$

where n is a natural number. In this study it was taken equal to 3.

The elements of the population generated within the search space are defined by two values for each parameter as given in the following:
$\Theta_{\text{on}} \in [0\ ^\circ\ (0 \text{ rad}) - 10\ ^\circ\ (0.1745 \text{ rad})]$,
$\Theta_{\text{off}} \in [15\ ^\circ\ (0.2618 \text{ rad}) - 25\ ^\circ\ (0.4363 \text{ rad})]$,
$V \in [200 - 400]$ V.

4. Simulation Results and Discussion

To confirm the effectiveness of the proposed smart algorithms, various simulations are carried out. In the first scenario, the performances of the 8/6 SRM in term of ripple torque, and speed response are analysed considering the standard parameters. In the second scenario, the two proposed algorithms ssGA and PSO are adapted and applied to optimize specified parameters related to the 8/6 SRM such as Θ_{on}, Θ_{off} and voltage supply to improve the performances of the 8/6 SRM in particular ripple torque reduction at different loading conditions. Finally, a comparative study is given to clarify the importance of applying intelligent algorithms to find the optimized parameters to improve the performances of the 8/6 SRM at various loading conditions.

The standard parameters are given as follows:
$\Theta_{\text{on}} = 0\ ^\circ(0 \text{ rad})$, $\Theta_{\text{off}} = 23\ ^\circ(0.4014 \text{ rad})$, $V = 350$ V.

Figure 7 shows the total dynamic torque and speed response in case of standard parameters. Figure 8 presents the phase currents.

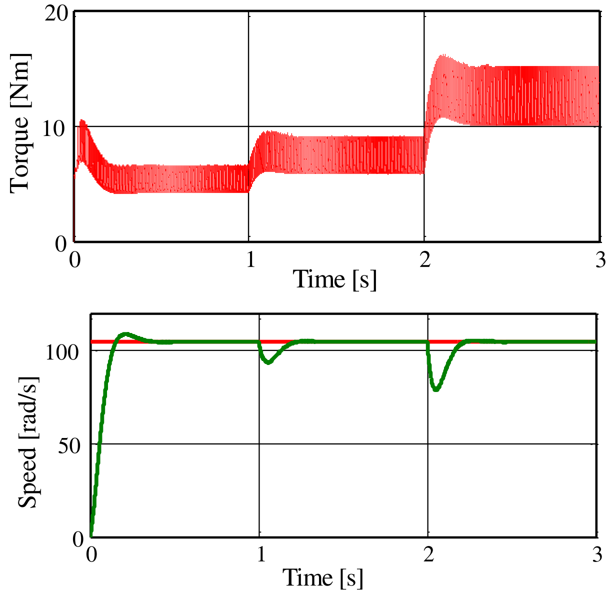

Fig. 7: The total dynamic torque and speed response by using the standard parameters.

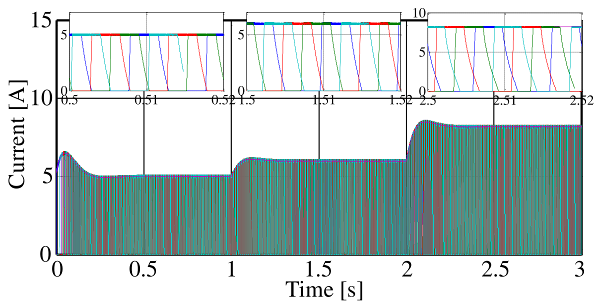

Fig. 8: The current controlled by hysteresis controller of the SRM phases for standard parameters.

After applying the control strategy based on PSO and ssGA algorithms, the convergence curves of the fitness function of each algorithm are shown in Fig. 9 and Fig. 10. Each algorithm has been addressing the problem of the ripple torque for three torque loads where it has given different results.

From the convergence curves of the fitness function it can be observed that the results achieved using PSO

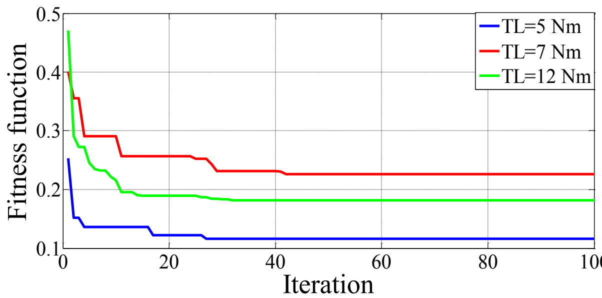

Fig. 9: Convergence curves of the fitness function for PSO optimization with different loads.

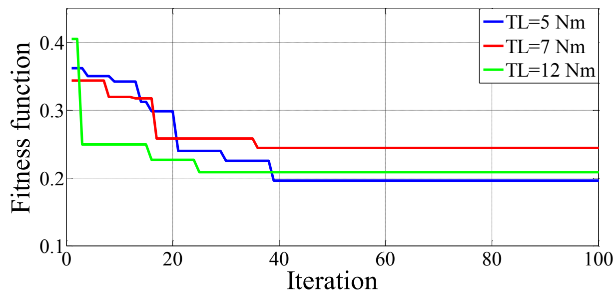

Fig. 10: Convergence curves of the fitness function for ssGA with different loads.

at normal and considering loading conditions are better than ssGA. Furthermore, it is important to note that the optimized parameters associated to control system affect greatly the ripple torque.

The optimal values of the turn on, turn off angles (Θ_{on}, Θ_{off}), and the supply voltage using PSO and ssGA have been applied to the control system to see how the effectiveness of these algorithms in the SRM machine affect the performances. After relying on the previous values as reported in Tab. 1, the simulation results of the total dynamic torque and the speed response for PSO and ssGA are shown, respectively, in Fig. 11 and Fig. 13. The current controlled by hysteresis controller is presented in Fig. 12 and Fig. 14. During simulations, the torque load has been changed at 1 s and 2 s.

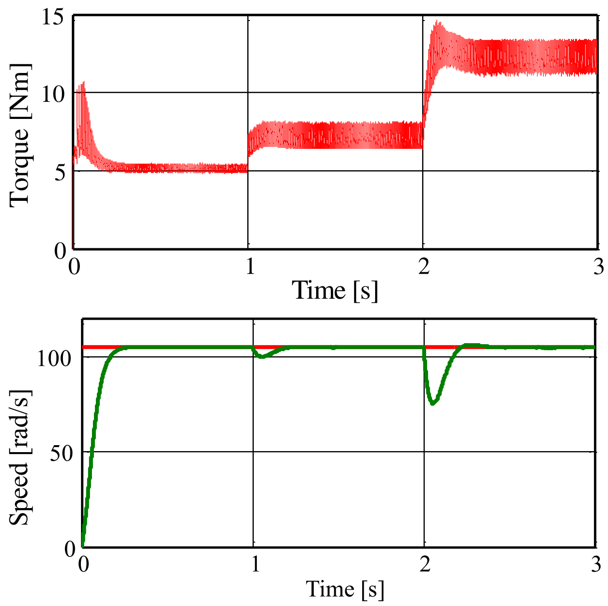

Fig. 11: The total dynamic torque and speed response based on optimal solution given by PSO algorithm.

The performance of the SRM does not have specific law due to the non-linear behaviour. Thus, according to the definition of torque ripple (T_r), at torque load $T_L = 5$ Nm, the performance was better than for oth-

Tab. 1: Optimal solution from the intelligent algorithms for different torque load.

Method	Torque load (Nm)	Parameters			Best value of f	T_r
		Θ_{on} (rad)	Θ_{off} (rad)	V (V)		
PSO	5	0.1398	0.4082	247.15	0.1165	0.1153
	7	0.0129	0.3639	379.59	0.2263	0.2234
	12	0.0700	0.2635	324.12	0.1816	0.1804
ssGA	5	0.1290	0.3934	228.73	0.1963	0.1945
	7	0.0366	0.3637	372.13	0.2446	0.2410
	12	0.1246	0.4136	311.20	0.2086	0.1938

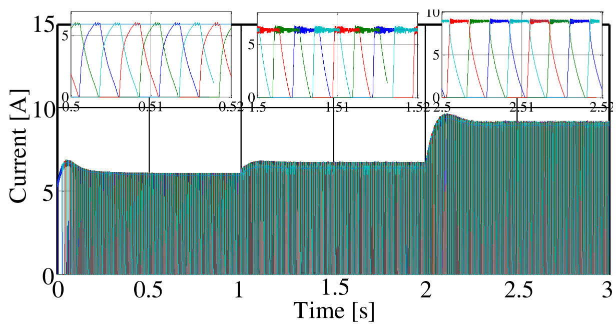

Fig. 12: The current controlled by hysteresis controller of the SRM phases for PSO algorithm.

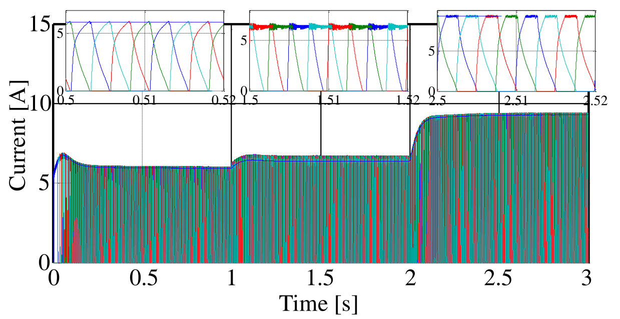

Fig. 14: The current controlled by hysteresis controller of the SRM phases for ssGA algorithm.

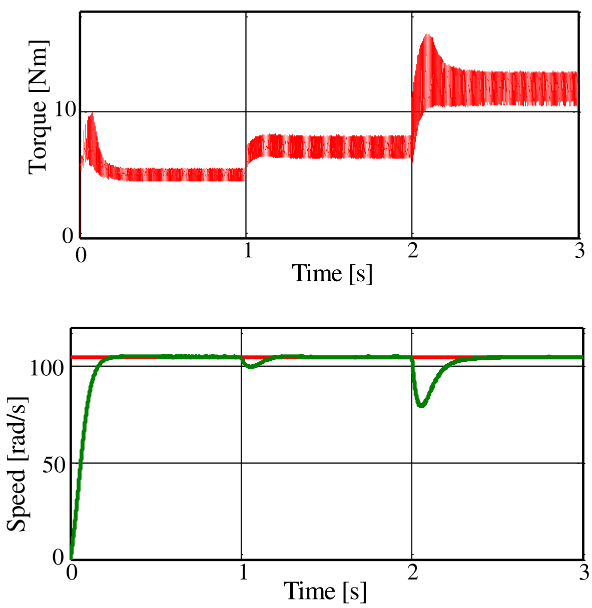

Fig. 13: The total dynamic torque and speed response based on optimal solution by the ssGA algorithm.

ers torque loads. Moreover, at $T_L = 7$ Nm the torque ripple is bigger when compared with $T_L = 12$ Nm. However, if considered the band $(T_{\max} - T_{\min})$ as a reference to determine the performance of the machine, it the performance of $T_L = 7$ Nm was better than $T_L = 12$ Nm.

It is very important to note that there are some differences in the speed responses but it was stable in all the cases. However, the phase current of the standard parameters was less than the phase current of the optimized parameters because the application time of the supply voltage depending on the values of the turn on and the turn off angles (Θ_{on}, Θ_{off}) was bigger in the standard parameter case.

Figure 15 and Tab. 2 present a graphical and a numerical comparison between the optimal and the standard parameters for the torque ripple, respectively. The obtained results confirm that the intelligent algorithms are effective in improving the performance of the torque ripples by optimization parameters. A ripple re-

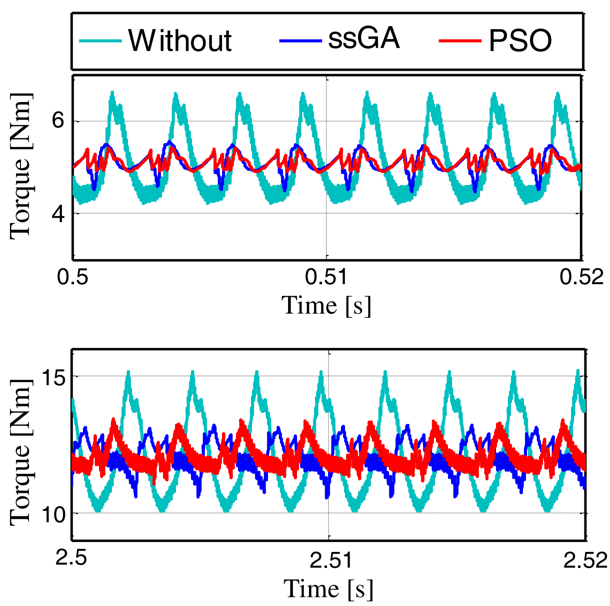

Fig. 15: Comparison of the total dynamic torque given from optimal and standard parameters.

Tab. 2: The torque ripple for the optimal and the standard parameters.

Torque load (Nm)	T_r_PSO	T_r_ssGA	T_r_standard parameters
5	0.1153	0.1945	0.4585
7	0.2234	0.2410	0.4468
12	0.1804	0.1938	0.4094

duction for PSO reaches 74.8 %, 50 %, and 55.9 % for the ssGA algorithm, the reduction reach 57.6 %, 46 % and 52.66 % for TL equal, respectively, to 5, 7 and 12 Nm. Hence, the effect of the intelligent algorithms on the performance of SRM is more significant.

In various real machines, the standard parameters are given for every regime, but the application of intelligent techniques on the control system gives specific parameters for each regime. Hence, in real drive, the optimal parameters can be exploited instead of standard parameters. Therefore, the parameters of SRM should be optimized considering different regimes in particular critical loading conditions to achieve the best performances of the control strategy.

5. Conclusion

In this paper, optimization parameters using particle swarm optimization and steady state genetic algorithm have been proposed and applied to a non-linear physical model of 8/6 switched reluctance motor for torque ripple reduction and speed control.

A non-linear finite elements modelling was adopted for the determination and the analysis of the magnetic characteristic of the switched reluctance motor.

The results of optimal parameters have been presented after explaining the proposed plan for the use of the smart algorithms. The optimal values of the turn on, turn off angles (Θ_{on}, Θ_{off}), and the supply voltage obtained from particle swarm optimization and steady state genetic algorithm was compared with standard parameters in order to prove their validity.

The obtained results, using the proposed intelligent algorithms, were the best in term of torque ripple reduction and flexible speed control.

The fitness function and the parameters determined for the optimization played an important role to reach the best performance.

It is important to conclude that this comparison highlights the effectiveness and the competitiveness of the proposed steady state genetic algorithm and particle swarm optimization algorithms for enhancing the performances of the switched reluctance motor by considering different loading conditions.

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Appendix A

Dimensional model of the machine is given in Tab. 3.

Tab. 3: Dimensions of the 8/6 SRM.

Number of stator poles Ns	8
Number of rotor poles Nr	6
Lamination outer radius (mm)	89.8
Stator yoke inner radius (mm)	78.4
Stator bore radius (mm)	48.18
Rotor outer radius (mm)	47.82
Rotor yoke outer radius (mm)	30.3
Rotor yoke inner radius (mm)	15
The pole arc of stator (Deg)	20.2
The pole arc of rotor (Deg)	22.5
Length of stator laminations (mm)	151
Number of turns per Phase N	176

Tab. 4: The SRM parameters.

Number of phases	4
Stator/rotor poles number	6/8
Speed (rpm)	1500
Power (kW)	4.5
DC link voltage (V)	230–380
Phase resistance (Ω)	1.1
Maximal current (A)	16

Tab. 5: Material property.

Mass density of copper (kg·m^{-3})	8900
Mass density of laminations (kg·m^{-3})	7800