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Metaheuristic Design and Optimization of Fuzzy-Based SRM Speed Controller using Ant Colony Algorithm

[1]Mohamed Yaich and [2]Moez Ghariani
[1]National Engineering School, Sfax University, Sfax, Tunisia
[2]National School of Electronic and Telecommunications, Sfax University, Sfax, Tunisia

Abstract: For electrical drives good dynamic performance is mandatory so as to respond to the changes in command speed and torques. Thus various speed control techniques are being used for real time application. The speed of Switched Reluctance Motor (SRM) can be adjusted to a great extend so as to provide relatively easy control and high performance. There are several conventional and numeric types of controllers intended for controlling the SRM speed and executing various tasks, PID controller, Fuzzy Logic Controller (FLC) or the combination between them, fuzzy-swarm, fuzzy-neural networks, fuzzy-genetic algorithm, fuzzy-ants colony, fuzzy-particle swarm optimization. We would like to clarify in this study the use of Ant Colony Optimization Algorithm (ACO) to optimize the scaling factors of fuzzy logic controller for speed regulation of SRM. The obtained results were simulated on MATLAB/Simulink environment. Excellent flexibility and adaptability as well as high precision and good robustness are obtained by the proposed strategy. The simulations results demonstrate that the proposed ACO-FLC speed controller realize a good dynamic behavior of SRM compared with conventional FLC controller.

Key words: Switched Reluctance Motor (SRM), Fuzzy Logic Controller (FLC), Ant Colony Optimization (ACO), speed control, flexibility, precision

INTRODUCTION

Switched Reluctance Motor (SRM) is appropriate for many variable speed and servo-type applications and interest towards SRM is the easing day by day in the motor drive industry. The characteristic of SRM is nonlinear because the torque developed in the SRM is always nonlinear function of position of rotor and phase current. The advent of modern control technology and power electronics have enabled SRM drive to become increasingly popular. Because of its non-linear characteristics the conventional PID controller is not the better choice. Thus, it is interesting to use for this kind of systems, non-conventional control techniques, such as fuzzy logic in order to achieve high performances and robustness. Fuzzy Logic Controller (FLC) one of the intelligent control technique is utilized in this work. FLC uses humain problem solving methodology to control the speed of non linear system and the performance of FL is also good. FLC provides a proper approach for representing, influencing and executing a human's heuristic knowledge about how to control a system (Selvaganesan *et al*., 2006). The fuzzy logic controller is one of the most important control schemes used for plants having difficulties in deriving mathematical models or having performance limitations with conventional linear control schemes (Hsu *et al*., 2001). However, in spite of high dynamic response and best disturbance rejection (Hsu *et al*., 2001; Ibrahim and Levi, 2000), the major drawback is that such fuzzy controllers are optimized for a correct action only around a fixed steady-state condition. The dominating question at hand is how we can modify the control action when the operating conditions change and/or the plant model is time-varying (Hayachi *et al*., 2001; Romeral *et al*., 2000). Hence, the controller needs to be retuned to achieve good performance and robustness.

The FLC contains a set of parameters that can be altered on-line in order to improve its performance and robustness. These include the scaling factors for each controller variable, the membership function of the linguistic variable and the rules (Mokrani and Abdessemend, 2003; Hayachi *et al*., 2001; Romeral *et al*., 2002; Balestrino *et al*., 2002). The present study investigates an intelligent FL speed controller uses the ACO algorithm to optimize the scaling factors instead of the traditional trial and error method. The drive system plays an important role to meet the other requirement. It should enable the drive to follow any reference speed tracking into account the effects of load impact, saturation and parameter variation. MATLAB/Simulink Software packages are utilized to simulate each part of the system

Corresponding Author: Mohamed Yaich, National Engineering School, Sfax University, Sfax, Tunisia

under study. The simulation of the overall system is composed of these simulated components when they are properly interconnected.

MATERIALS AND METHODS

SRM modeling: The reluctance motor is a type of synchronous machine. It has wound field coils of a DC motor for its stator windings and has no coils or magnets on its rotor, Fig. 1 shows its typical structure. It can be seen that both the stator and rotor have salient poles, hence, the machine is a doubly salient machine. SRM have different stator and rotor pole combination 6/4, 8/6, etc., the 6/4 topology is taken for discussion in this study is shown in Fig. 1. The rotor of SRM does not have permanent magnet or winding and doesn't have cage winding, either. Rotor is fabricated with a number of salient pole laminations.

The inductance of a phase winding is a non linear function of current (i) and rotor position (Θ). The inductance pattern of a phase is repeated for every 90° for 6/4 SRM. In one rotor rotation, an SRM with NS stator poles and NR rotor poles makes a certain number of angular steps. An angular step is defined as equal to the difference between the rotor pole pitch and the stator pole pitch (Davis, 1988). Because of its mode of operation, the angular period is equal to the rotor pitch and one period contains a number of steps equal to the machine number of phases.

Following these geometric definitions, the relationship between the Number of Stator/Rotor poles (NS/NR), for 3 phases SRM can be written as:

$$N_R = \frac{2}{3} N_S \quad (1)$$

This expression (Eq. 1) shows that, the number of stator pole NS is a multiple of three in this particular case. Three phases SRM configurations are recommended for EV and HEV applications in order to reduce the inverter cost.

MATALB/Simulink is used to study the performance of switched reluctance motor (Yaich *et al*., 2017). The entire simulation work is carried out with the corresponding block diagram, special functions of MATLAB and parameters. Accurate modeling of the drive system is required to design the controller for fast acceleration or regulation of speed. Such a system is designed with the assumption that the phases are independent electrically and decoupled magnetically.

The mathematical modeling explaining the dynamics of 6/4 SRM consists of electrical equation for each phase and the equation governing the mechanical systems (Le-Huy and Brunelle, 2005). Stator phase voltage is the input to SRM model. The electrical circuit for each phase

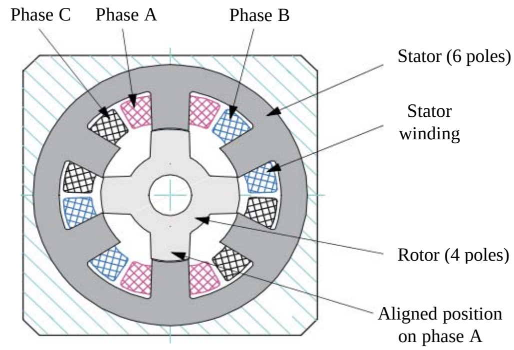

Fig. 1: 3-phase 6/4 SRM

is connected to the electronic power converter (e.g., an asymmetrical DC-DC converter) and is associated with nonlinear inductance due to the saliency present in stator and rotor. Mutual coupling between the stator phases is assumed to be negligible.

The linkage flux in the stator winding is associated with the instantaneous voltage across the SRM phase terminal (Martin *et al*., 2016) by using Faradays law:

$$V_i = R_i I_i + \frac{\partial \psi_i (0, I_i)}{\partial t} \quad (2)$$

Where:

V = Voltage across the terminals
I = Phase current
Ψ = Flux linkage in the winding
i = Phase (i = 1, 2, 3)

As the SRM is having salient poles in stator and rotor and is having magnetic saturation effect, the flux linkage in SRM phase varies as a function of Θ (rotor postion) and the Eq. 2 can be rewritten as follows:

$$V = RI + \frac{\partial \Psi}{\partial I}\frac{dI}{dt} + \frac{\partial \Psi}{\partial \theta}\frac{d\theta}{dt} \quad (3)$$

Where:

$\partial\Psi/\partial I$ = It defined as L(O, I), the instantaneous inductance
$\partial\Psi/\partial\theta \; d\theta/dt$ = The instantaneous back emf

The parameters of studied system used in simulation are as shown:

SRM parameters:

- Phase number 3
- Number of stator poles 6
- 30° pole arc
- Number of rotor pole 4
- Pole arc 30°
- Maximum inductance 60 mH (unsaturated)
- Minimum inductance 8 mH

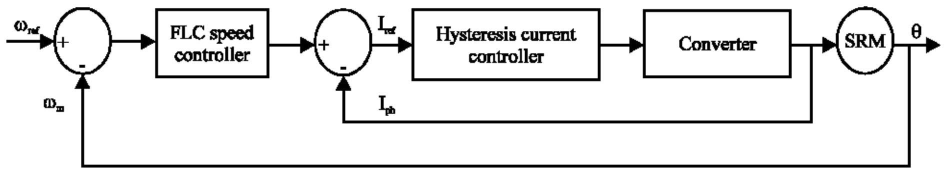

Fig. 2: Bloc diagram of the SRM drive

- Phase resistance R = 1.30 Ω
- Moment of inertia J = 0.0013 kg/m^2
- Friction F = 0.0183 Nm/sec
- Inverter voltage V = 150 V

ACO parameters:
- Number of nodes n = 10
- Number of ants m = 5
- Maximum iteration t_{max} = 5
- Maximum distance for each ant's tour d_{max}= 49
- Parameter which determines the relative importance of pheromone versus distance β = 0.2
- Heuristically defined coefficient ρ = 0.6
- pheromone decay parameter α = 0.1
- Parameter of the algorithm q_a = 0.6
- Initial pheromone level τ_0 = 0.1

Design of fuzzy logic controller: In this study a three-phase 6/4 SRM with two switches per phase bridge converter topology with FLC speed controller is chosen. A control block diagram of this drive system is best illustrated in Fig. 2. The controller has an inner current control loop and an outer speed control loop. The speed controller generates a current command based on the error between the reference speed and the motor speed. The current in the designed phase is regulated at the reference level by hysteresis control.

The fuzzy logic proportional-derivative controller consist mainly a reference to a fuzzy logic inference system. The inference system has three linguistic variables which are the two inputs (error signal and error derivative) and the output (control signal). The fuzzy logic inference system for the fuzzy proportional-derivative controller contains a set of fuzzy logic rules that define the behavior of the system in relation between the error signal, error derivative signal and the control signal of the controller (Karuppanan and Mahapatra, 2012). The first input to the fuzzy logic inference system is the error signal which is the difference between the desired speed wref and the actual speed wm of the SRM. The error derivative signal is achieved by differentiating the error signal before passing it to the fuzzy logic controller block. Since, the fuzzy logic controller block expects two inputs, a multiplexer is used to combine the error signal and the error derivative signals as input into block

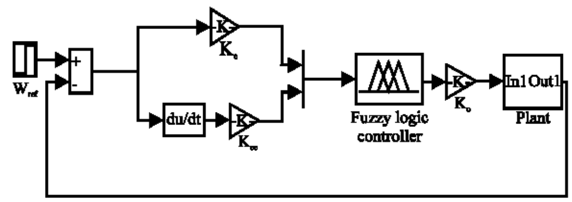

Fig. 3: Simulink model for fuzzy logic controller

Table 1: Fuzzy inference rule

	Derivative error						
U(t)	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Fig. 3. The tuning of fuzzy logic controller can be achieved by either; most importantly adjusting the range of the universe variables are defined as {NB, NM, NS, ZE, PS, PM, PB} meaning negative big, negative medium, negative small, zero, positive small, positive medium and positive big respectively, adjusting the input and output scaling gains of the controller or adjusting the number, type and positions of the member functions used (Fig. 3). The membership functions of the conventional fuzzy logic controller are shown in Fig. 4. The type of fuzzy inference engine used in this study is Mamdani. Fuzzy rules are best summarized in Table 1.

Fuzzy controller lacks the tuning of parameters (number of membership functions and its type, rules number and formulating rules). The tuning of scaling factors for this parameter is done interactively by trial and error or human expert (Dubey, 2007).

Optimal fuzzy: Logic controller based on ACO algorithm the tuning of FLC parameters are necessitated to an effective method for tuning. Now a days, several new intelligent optimization techniques have been emerged, such as Genetic Algorithms (GA), exploiting the idea of Darwinian evolution, Simulated Annealing (SA), Particle Swarm Optimization (PSO) algorithm and Bacteria Foraging Optimization (BFO) among these nature-inspired strategies the Ant Colony Optimization (ACO) algorithm

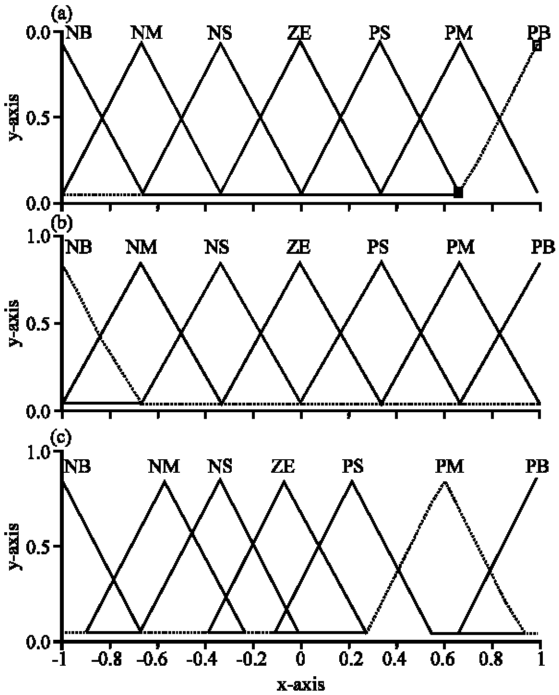

Fig. 4: Membership functions for: a) Speed error; b) Change in speed error; c) Change in output

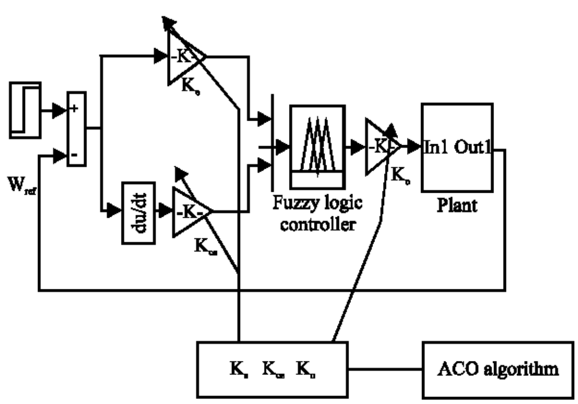

Fig. 5: Ant colony optimization for scaling factors selection in fuzzy logic controller

is relatively novel (Dorigo and Caro, 1999), ACO has received great attention in a control system such as the search of optimal PID controller (Omar *et al.*, 2013; Najeeb *et al.*, 2017). The most important considerations in designing any fuzzy system are:

- Generation of fuzzy rules which are generated by experts in the area especially for control problem
- Selecting and adjusting the membership functions
- Selecting the scaling factors

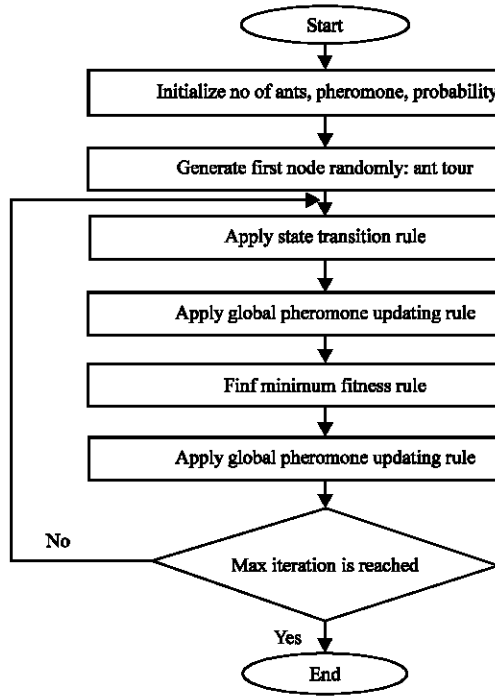

Fig. 6: Flow chart for ant colony optimization algorithm

Number one of the designing steps is determined by experts but step two as shown in Fig. 3, the membership function is determined by two values the start point X1 and the end point X2. These points can be adjusted manually by trial and error (Letting *et al.*, 2010) or by using optimizing algorithm such as the applied technique (ACO). Also, in step three the scaling factors for fuzzy controllers are determined either by trail and error or by ACO. The concept of the speed control and implementation of ACO job are shown in Fig. 5.

The optimal choice of the scaling factors K_e, K_{ce} and K_0 of Fuzzy speed controller, minimization of Integral Squared Error (ISE) of speed ripple which computed from the outer loop can be considered as an objective for both conventional and AI tuning technique. Accordingly, this objective function expression (ISE) is given by:

$$FF = ISE_{speed} = \int_0^{\infty} \left(w_{ref} - w_m\right)^2 dt \quad (4)$$

where e = $w_{reference}$ -w_{actual}. Based on this ISE_{speed} optimization problem can be stated as : minimize ISE_{speed} subjected to: $K_e^{min} \leq K \leq K_e^{max}$, $K^{min}_{ce} \leq K_{ce} \leq K_{ce}^{max}$, $K_a^{min} \leq K_a \leq K^{max}$.

This study focuses on optimal tuning of fuzzy controller for speed tracking of SRM using two methods which are the conventional method trial and error and the intelligence methods such as the ACO method. Ranges of scaling factors for fuzzy speed controller are K_e (0.009-0.01), K_{ce} (0.050- 0.052) and K_0 (75-78) (Fig. 6).

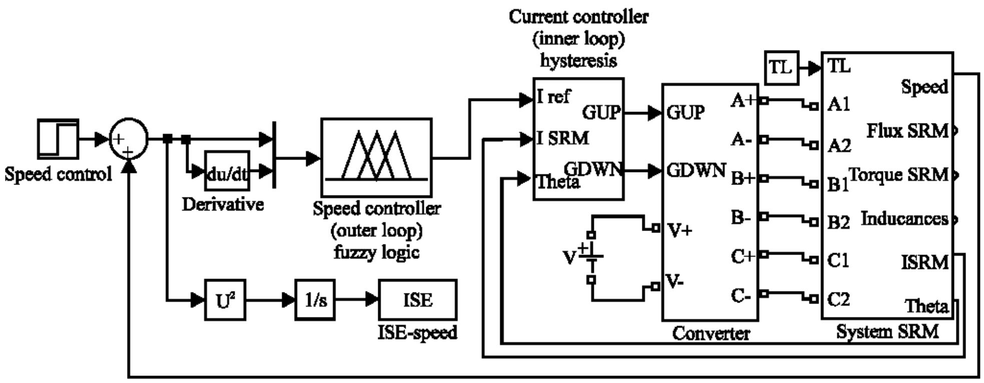

Fig. 7: MATLAB/Simulink for SRM drive system

The aim of the optimization process is to search for the optimum controller parameters setting that would minimize the difference between reference speed and actual one, otherwise would not enhance minimize the fitness function FF. The ACO algorithm process can be summarized in the flowchart shown in Fig. 6. A set of good control parameters can yield a good step response that will result in performance criteria minimization in the time domain, this performance criteria is called Fitness Function (FF) which can be evaluated in the variable (ISE) shown in Fig. 7.

RESULTS AND DISCUSSION

The completely system simulation using MATLAB/Simulink program are presented including SRM model, inverter, current controller (inner loop hysteresis) and speed controller (outer loop FLC bloc sets). But the optimization algorithm is implemented by using MATALB/m-file program and linked with the system simulation program MATALB/Simulink . The performance of the system must be examined in each iteration and ants position during the optimization algorithm. Therefore, to check the system performance in each iteration and optimize the value of of scaling factors of FLC structure K_e, K_{ce} and K_o. Figure 6 shows the simulation of SRM drive based fuzzy logic control. The optimization criteria (Integral of the Square value of the Error (ISE), Eq. 4 is used to evaluate accuracy performance of the fuzzy controller.

The closed loop fuzzy speed controller with the process was tuned for the values K_e, K_{ce} and K_o were shown in Fig. 5. To get a better insight to the performance of SRM control, time domain simulations are performed.

Table 2 illustrates the scaling gains, proportional error input scale (K_e), error derivative input scale (K_{ce})and output scale (K_o), summarizes the performance indexes in

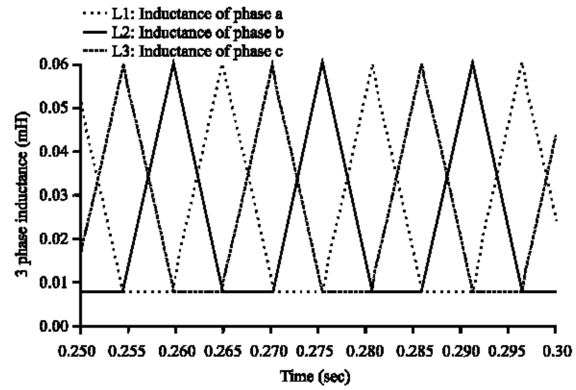

Fig. 8: Inductance profile for 3 phase SRM

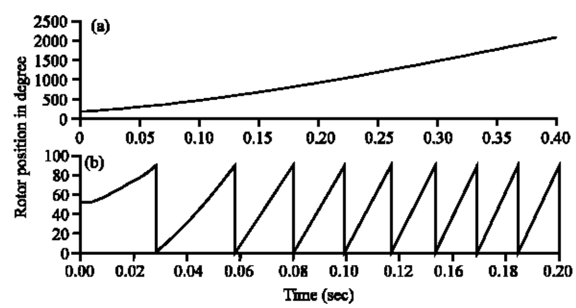

Fig. 9: Rotor position in degree vs. time in second

time domain including the settling time, rise time and Steady State Error (SSE). It also gives the value of Integral Square Value of Error (ISE). These performance indexes were obtained from the conventional fuzzy logic controller and meta-heuristic approach based ACO-FLC algorithm. The responses with proposed method are much faster with less rise time and settling time compared to the conventional controller (Table 2).

Respectively, both Fig. 8 and 9 show the inductance profile of all the three phases and the rotor position of SRM drives with corresponding time in seconds. The inductance is repeated at every 90° and each phase is

Table 2: Comparison between conventional FLC and ACO-FLC controller

Parameter and indexes	Gain (K_e)	Gain (K_{ce})	Gain (K_o)	Settling time (sec)	Rise time (sec)	SSE (rad/sec)	ISE
Conventional FLC controller	0.01	0.05263	78	0.01108	0.00975	2.02	39.54
Optimized FLC controller	0.00998	0.05114	76.8	0.01098	0.00967	2.96	39.42

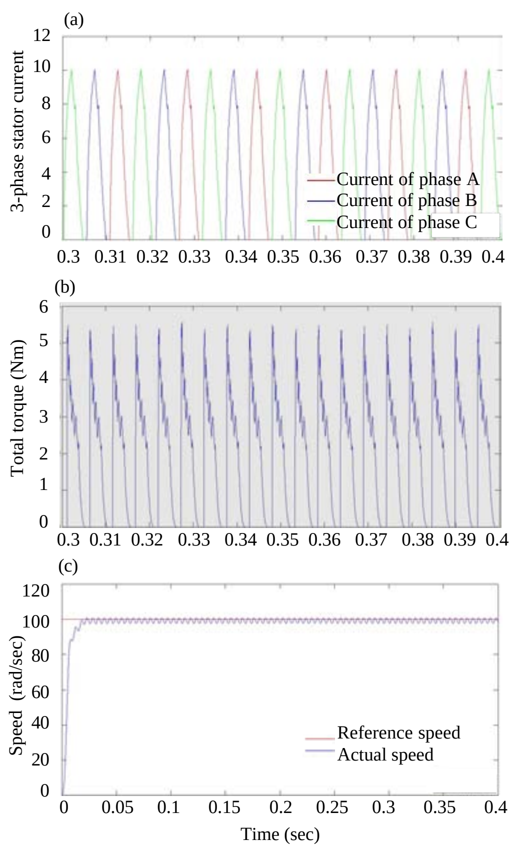

Fig. 10: Performance analysis using conventional fuzzy logic controller: a) 3 phase currents (A); b) Total torque (Nm); c) Speed (rad/sec)

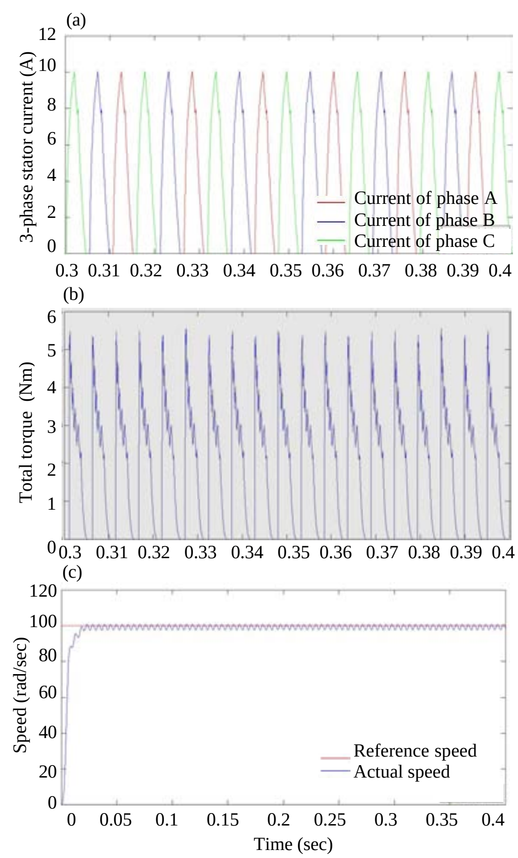

Fig. 11: Performance analysis using optimized fuzzy logic controller: a) 3 phase currents (A); b) Total torque (Nm); c) Speed (rad/sec)

separated by 30° as shown in Fig. 8. The rotor position is identified continuously and modulated for a complete mechanical rotation (360° or 6.2828 rad) as shown in Fig. 9.

The 3-phase current profile, total torque and tracking of speed with the reference speed corresponding to the optimal parameter for a minimum objective function that was given in Table 2 using conventional fuzzy logic controller and optimal fuzzy logic controller based on ACO algorithm are shown in Fig. 10 and 11, respectively. It can be seen from the Fig. 8-11 that the adequate values for the scaling factors obtained by ACO based controller provide better performance by improving the phase current profile and better tracking of speed as compared to conventional fuzzy logic controller. The time required for speed tracking by conventional FLC based speed controller is 0.01108 sec. As it required 0.01098 sec for tracking of speed with the reference speed by ACO based controller, respectively as reported in Table 2. Hence, the proposed ACO is capable of providing sufficient speed tracking compared with conventional fuzzy logic controller. But we see the ACO method does not reduce the torque dip.

CONCLUSION

This study applies the ACO based fuzzy controller to Switched Reluctance Motor (SRM) 6/4 poles. The fuzzy rules are optimized off line while the parameters of the fuzzy controller are tuned on line. The choice of the adequate values for the scaling factors of FLC structure is often done by a trial-error hard procedure. This tuning problem becomes difficult and delicate without a systematic design method. To deal with these difficulties, the optimization of these scaling factors is proposed like a promising solution. This efficient tool leads to a robust and systematic fuzzy control design approach. The control design methodology is systematic, practical and simple without the need of exact analytic plant model description. The obtained most favorable fuzzy controller based ant colony algorithm has given better performance than conventional FLC controller in terms of speed rise time, settling time. This control seems to have a lot of promise in the applications of power electronics which can be applied in industrial motor control field. After having applied the proposed ACO-FLC method we can conclude in this study advisable that the use of optimized fuzzy logic controllers is possible to achieve very good results. In particular with this application, we are demonstrating statistically that there is a significant difference when the controllers are developed manually or automatically.

RECOMMENDATION

Therefore, with the results presented in this study we can recommend the usage of optimization methods to find some important parameters in this case, ACO was only used to find the optimal values for scaling factors of FLC structure.

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