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A Novel Technique for Tuning PI-controller in Switched Reluctance Motor Drive for Transportation Systems

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ABSTRACT

This paper presents, an optimal basic speed controller for switched reluctance motor (SRM) based on ant colony optimization (ACO) with the presence of good accuracies and performances. The control mechanism consists of proportional-integral (PI) speed controller in the outer loop and hysteresis current controller in the inner loop for the three phases, 6/4 switched reluctance motor. Because of nonlinear characteristics of a SRM, ACO algorithm is employed to tune coefficients of PI speed controller by minimizing the time domain objective function. Simulations of ACO based control of SRM are carried out using MATLAB /SIMULINK software. The behavior of the proposed ACO has been estimated with the classical Ziegler-Nichols (ZN) method in order to prove the proposed approach is able to improve the parameters of PI chosen by ZN method. Simulations results confirm the better behavior of the optimized PI controller based on ACO compared with optimized PI controller based on classical Ziegler-Nichols method.

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1. INTRODUCTION

The inherent simplicity, ruggedness and low cost of a SRM make it a viable machine for various general purpose adjustable speed drive applications [1], [2]. It has no permanent magnet (PM) or winding on the rotor. This structure not only reduces the cost of the SRM but also offers high speed operation capability for this motor. The performance of SRMs has been enhanced greatly due to advances in power electronics and computer science. It requires only simple converter circuit with reduced number of switches due to unidirectional current requirements. In addition, the inverter of the SRM drive has a reliable topology. The stator windings are connected in series with the upper and lower switches of the inverter. This topology can prevent the shoot through fault that exists in the induction and permanent motor drive inverter [3]. These advantages make this type of motors economically alternative to PMBLDC motor, squirrel cage induction motor and DC series motor [4], [5].

The SRM can be operated in the four quadrants and it is very much suitable for hazardous areas requiring high performances such a in electric vehicle propulsion, automotive starter-generators, aero-space applications. Nevertheless, it suffers some drawbacks such as; high torque ripple and significant acoustic noise as well as speed oscillations. Currently, much research is being done on SRM Control and torque constraint in order to make it compete with fully controlled DC and DC drives. In order to resolve these problems, it used essentially two primary approaches: one method is to improve the magnetic design of the motor, while the other method is to use sophisticated control mechanism. Machine designers are able to resolve these problems and achieve high dynamic performances by changing the stator and rotor poles structures, but only at the expensive of motor performance. The control Approach is based on the selection of an optimal combination of operating parameters, which include power supply voltage, turn on and turn off angles, size of hysteresis band, current level and shaft load. So, the design of a suitable controller to achieve Performance must take account of this non-linearity. The nonlinear characteristics of a SRM make it difficult to control. Design and tuning classic control theory are based on equations and model of the system while SRM modeling is a complex task.

The introduction of artificial intelligence (AI) has brought a new era into the industrial drive. Various heuristic controls based on AI have shown a good perspective of strengthening robustness and adaptive nature in constant torque variable speed or variable torque constant speed converter application [6]. Therefore, the superior performance of artificial intelligence (AI) based controllers urged power system and power electronic engineers to replace conventional speed control circuit with intelligent speed controllers. The simple and popular current compensating techniques can be implemented using both classical and intelligent controllers. It is noticed from literature survey that many approaches have been proposed for speed control of SRM. In the last few years, fuzzy logic control (FLC), has received much attention in the control applications, artificial neural network (ANN), neuro- fuzzy controller (NFC), robust controller have been employed to solve the problem of speed control of SRM. Moreover, various heuristic optimization techniques for tuning the PI controller has been reported in literature.

Particle Swarm Optimization (PSO) is a population based optimization algorithm, encouraged by social behavior of bird flocking or fish schooling [7]. Genetic Algorithm (GA) is illustrated in for optimal design of speed control of SRM. The GA has found application in the area of the automatic tuning process for conventional and intelligent controllers. Same research has been conducted using genetic algorithms to help on-line or off line control systems. In a novel heuristic optimization algorithm named gravitational search algorithm also called GSA is proposed, Bacteria Foraging [8], differential evolution (DE) and BAT [9] have attracted the attention in designing controller and speed control of various motors.

New evolutionary algorithms know as Ant Colony Optimization (ACO) algorithm is proposed in this paper to design a robust speed control of SRM. This algorithm is a member of the ant colony algorithms family, in swarm intelligence methods, and it constitutes some metaheuristic optimizations. The original idea has since diversified to solve a wider class of numerical problems, and as a result, several problems have emerged, drawing on various aspects of the behavior of ants. ACO has been successfully employed to optimization problems in power system, the feature of this technique is different from other methods since it can be implemented easily and flexibly for many problems.

Hence, in this work, as the new contribution, ACO is utilized to find optimal values for proportional (Kp) and integral (Ki) for speed controller by minimizing the time domain objective function representing the error between reference speed and actual one, the system performance is improved. Simulation results assure the effectiveness and ability of the proposed controller in providing good speed tracking system with minimum overshoot/undershoot and minimal settling time. Also, the results show that the ACO based controller can better improve SRM performance for tuning controller than Ziegler-Nichols (ZN).

2. MODELING AND CONTROL OF SRM DRIVE

2.1. Principles of Performance and Modeling of SRM Drive

The principle of operation of the switched reluctance motor (SRM) is based on the tendency of the electromagnetic system to be located in stable equilibrium point with the minimum magnetic reluctance. The excitation is switched sequentially from phase to to phase as the rotor moves. The electromagnetic torque in SRM is produced by exploiting the rotor position-dependent reluctance of the magnetic path associated with each phase. When one of the stator winding is excited, the nearest rotor ploes are aligned with the excited stator poles and thus a reluctance torque is produced which tends to align the stator and rotor poles. The total torque is the sum of the torques generated by each phase. Nonlinear characteristics of SRM are due to the nonlinearity of the characteristics of flux-linkage.

The mathematical modeling explaining the dynamics of 6/4 SRM consists of electrical equation for each phase and the equation governing the mechanical systems [10]. Stator phase voltage is the input to SRM model. The electrical circuit for each phase is connected to 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 nonlinear magnetic characteristics associated with SRM because of saturation and changeable air gap with rotor position causes the magnetic flux linkage a nonlinear function of stator current (i) and rotor (θ). The voltage equation phase is given by:

$$\frac{\partial \psi_{i(\theta,I_i)}}{\partial t} + RI_i = V \tag{1}$$

With i = {1, 2, 3}
Where R is the resistance per phase and ψ is the flux linkage per phase and it is given by

$$\psi_{i(\theta,I_i)} = L(\theta)I_i \tag{2}$$

2.2. Objective Function Computation

The optimal choice of the proportional gain, integral gain of 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:

$$ISE_{speed} = \int_0^{\infty} \left(w_{ref} - w_m\right)^2 dt \tag{3}$$

Where e= wreference-wactual.
Based on this ISEspeed optimiztion problem can be stated as : minimize ISEspeed subjected to :

$$K_p^{min} \leq K_p \leq K_p^{max} , \quad K_i^{min} \leq K_i \leq K_i^{max}$$

This paper focuses on optimal tuning of PI controller for speed tracking of SRM using two methods which are the conventional Ziegler-Nichols method and the intelligence methods such as the ACO method. Ranges of PI controller are Kp [0.3-0.8] and Ki [10 - 20]. The aim of the optimization process is to search for the optimum controller parameters setting that minimize the difference between reference speed and actual one.

2.3. Design of Speed Controller

In PID controller, the derivative of the error is not used which is a PI (proportional-integral) controller. Speed controller designed for this work is a standard PI controller. It is a control feedback mechanism used in various industrial control systems. The PI controller attempts to minimize the error which is the difference between measured variable and desired value by adjusting the process inputs. The output of speed controller (outer loop) is the current command for the current controller (inner loop). The combination of proportional and integral terms is used to increase the speed of the response and to eliminate the steady state error.

2.3.1. Proportional Term

The output response of proportional term is equal to the current value of error. The proportional factor is adjusted by multiplying the error value by a proportional gain which is denoted by $K_{p.}$
The proportional factor is written by

$$P_{out} = K_p \Delta \tag{4}$$

2.3.2. Integral Term

The integral term is proportional to both the magnitude and duration of the error. In PID controller, the integral term is the sum of instantaneous error over time which gives the accumulated value and it has been corrected previously. The control action of integrator is to provide low frequency compensation [11]. Integral factor is written by

$$I_{out} = K_i \int \Delta dt \tag{5}$$

The integral term is used to increase the speed of the process towards the reference value and to eliminate the error which occurs in pure proportional controller. The proportional controller and the integral controller of the speed controller are connected in parallel.

The PI controller output is given by

$$K_p\Delta + K_i\int \Delta dt \quad (6)$$

Where Δ is the error or deviation of measured value from reference speed. The transfer function of PI speed controller in S-domain can be written as:

$$T_{speed}(s) = K_{p\_speed} + \frac{K_{I\_speed}}{s} \quad (7)$$

In the above equation K_{p_speed} and K_{I_speed} are the proportional gain and integral gain respectively of PI speed controller. The PI controller has been preferred to be used in industrial applications. The controller has simplicity, lowest cost, zero steady state error, ease of implementation, good speed response, robustness. It is extensively used in AC and DC drives where speed control is required. In this paper we will discuss two methods for tuning values of PI controller; they are the conventional Ziegler-Nichols method and the intelligence method such as the ACO method.

3. METHODS OF TUNING THE PI-CONTROLLER

3.1. Ziegler-Nichols Method

Up to now, tuning a PI (Proportional-Integral) controller for automatic control systems has often been performed by trial and error, including using classical methods such as Ziegler-Nichols, Iterative Feedback Tuning (IFT) methods, and many others. As we know, the Ziegler Nichols classical method provides parameter values obtained from the critical gian K_c of the system. The critical gain of a system is obtained by increasing the proportional gain unit the system starts oscillating [12]. From this critical gain, the other parameters of the PI controller are obtained according to the table I in the appendix. However the problem of tuning PI-controllers has remained an active research area. Furthermore with changes in system dynamics and variations in operating points PI-Controllers should be returned on a regular basis. This has triggered extensive research on the possibilities and potential of the so-called adaptive PI-controllers. Loosely defined, adaptive PI-controllers avoid time-consuming manual tuning by providing optimal PI-controller setting automatically as the system dynamics or operating points [13].

3.2. Design and Implementation of ACO Based Controller

In this work, an optimal speed controller for SRM based on ACO is presented. Control mechanism parameters such as proportional and integral gain have been optimized by using ACO. Block diagram of SRM with ACO based controller is shown in Figure 1. Ant colony optimization (ACO) was introduced as a novel nature-inspired metaheuristic by Marco Dorigo et al. [14]. ACO is method for solving optimization problems which were inspired from nature based on a real ant colony. The first algorithm was aiming to search for an optimal path in a graph, based on the behavior of ants seeking a path between their colony and source of food. In the nature world, ants (initially) wander randomly, and upon finding food return to their colony while laying down pheromone trails.

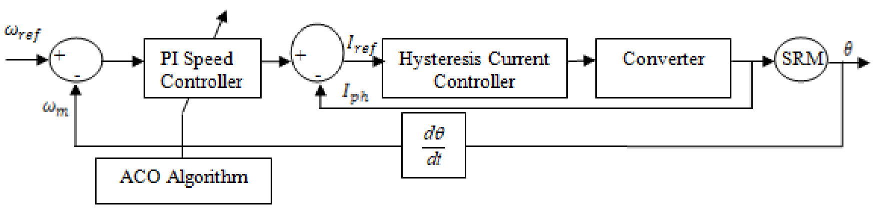

Figure 1. Block diagram of SRM with ACO based controller

Real ants are able to find the shortest path using only the pheromone trails deposited by other ants. The pheromone quantity depends on the length of the path and the quality of the discovered food source [15]. An ant chooses an exact path in connection with the intensity of the pheromone. Over time, however, the pheromone trail starts to evaporate, thus reducing its attractive strength. The pheromone trail on paths leading to rich food sources close to the nest will be more frequented and will therefore grow faster. In this way, the best solution has more intensive pheromone and higher probability to be chosen. The pheromone consistencies of all paths are updated only after the ant finished its tour from the first node to the last node. The amount of pheromone will be high if artificial ants finished its tour with a good path and vice versa.

4. SIMULATION RESULTS AND DISCUSSION

In this section, we presented the numerical results to demonstrate the superiority of the proposed ACO algorithm over the Ziegler-Nichols (Z-N) method [16]. The non-linear 6/4 SRM model represented in Figure 2. The SRM is fed in this simulation using the asymmetrical power converter in which, each leg consist of two IGBTs and two freewheeling diodes. Thus the phase currents are independently controlled by an hysteresis current controller which engender the IGBTs drive signals by comparing the measured currents with the references. The IGBTs switching frequency is determined using the hysteresis bandwidth for a previous optimal study fixed at ΔI=± 0.1A. The firing angles; turn-on and turn-off angles are kept constant at 0 deg and 30 deg, and demagnetizing angle (ϴd) (i.e.,the angle where the phase current decays to zero when negative voltage is applied directly after turning-off) is kept at 60 deg.

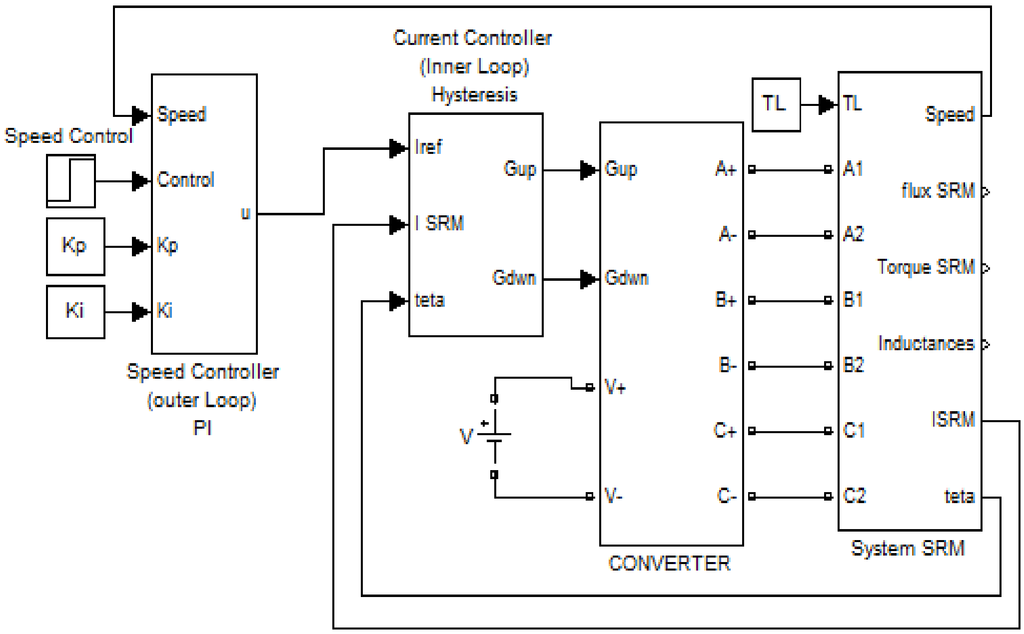

Figure 2. Matlab/Simulink for SRM drive system

The closed loop PI speed controller with the process was tuned for the values Kp and Kd were shown in Figure 1. To get a better insight to the performance of SRM control, time domain simulations are performed. Table 1 illustrates the optimal PI parameters KP and Ki also summarizes the performance indexes in time domain, including the settling time, rise time, under shoot and steady state error. These performances indexes were obtained from the classical approach based Z-N PI method and a meta-heuristic approach based on the ACO-PI algorithm. It can be seen that the time domain characteristics for ACO are smaller than Z-N method. Hence, compared with Z-N, ACO greatly improves the time domain characteristics of SRM.

Table 1. Comparison between conventional PI (Ziegler Nichols : ZN) and ACO-PI controller

	K_p	K_i	Settling time (s)	Rise time (s)	Under shoot	Steady state error
ZN	0.568	12	0.0271	0.0174	-	1.94 rad/s
ACO	0.686	14.2	0.0166	0.0125	-	1.1 rad/s

Figures 3 and 4 shows 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 separated by 30° as shown in Figure 3. The rotor position is identified continuously and modulated for a complete mechanical rotation (360° or 6.2828 rad) as shown in Figure 4.

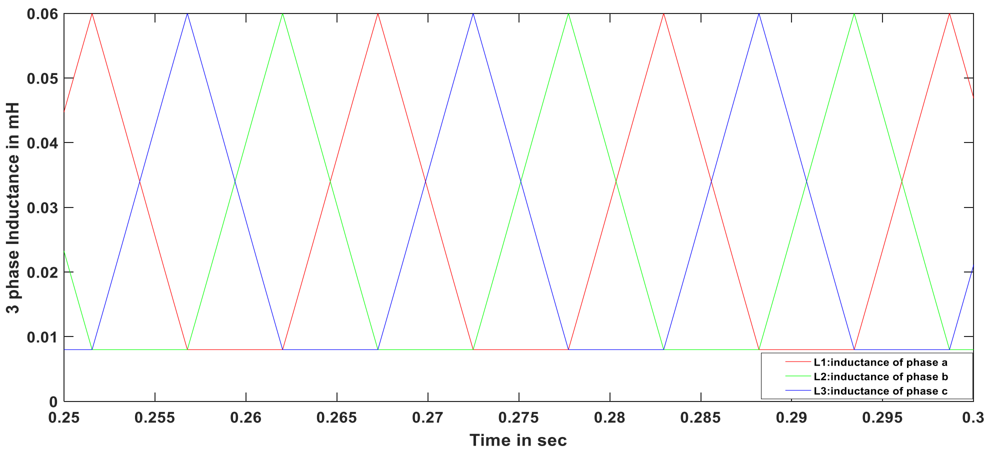

Figure 3. Inductance profile for 3 phase SRM

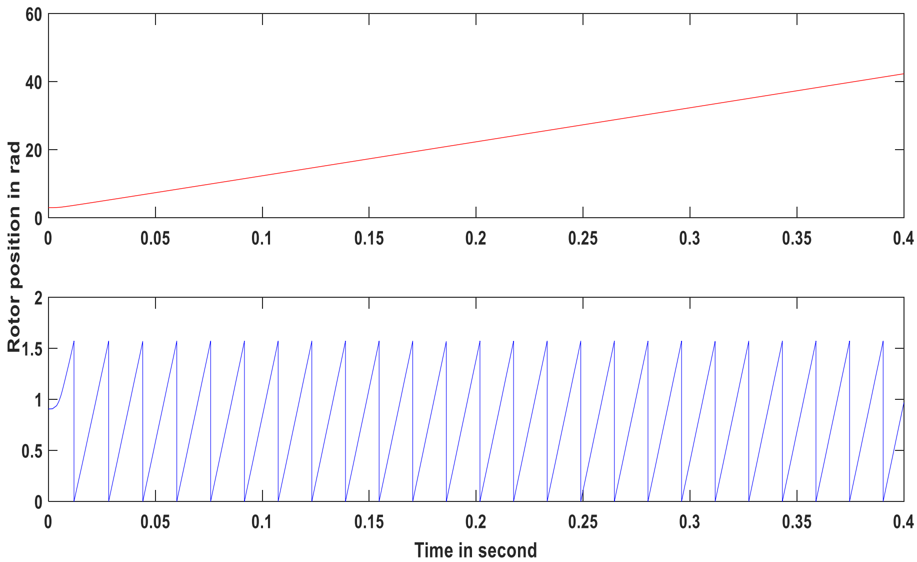

Figure 4. Rotor position in degree Vs time in second

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 given in table 1 using Z-N method and ACO algorithm are shown in Figures 5 and 6 respectively. It can be seen from the Figures 3-6 that optimal parameters obtained by ACO based controller provides better performance by reducing the torque dip between two phases, improving the phase current profile and better tracking of speed as compared to Ziegler Nichols method. The time required for speed tracking by Z-N based speed controller is 0.0271s. Whereas it required 0.0166 s for tracking of speed with the reference speed by ACO based controller respectively as reported in Table1. Hence, the proposed ACO is capable of providing sufficient speed tracking compared with ZN.

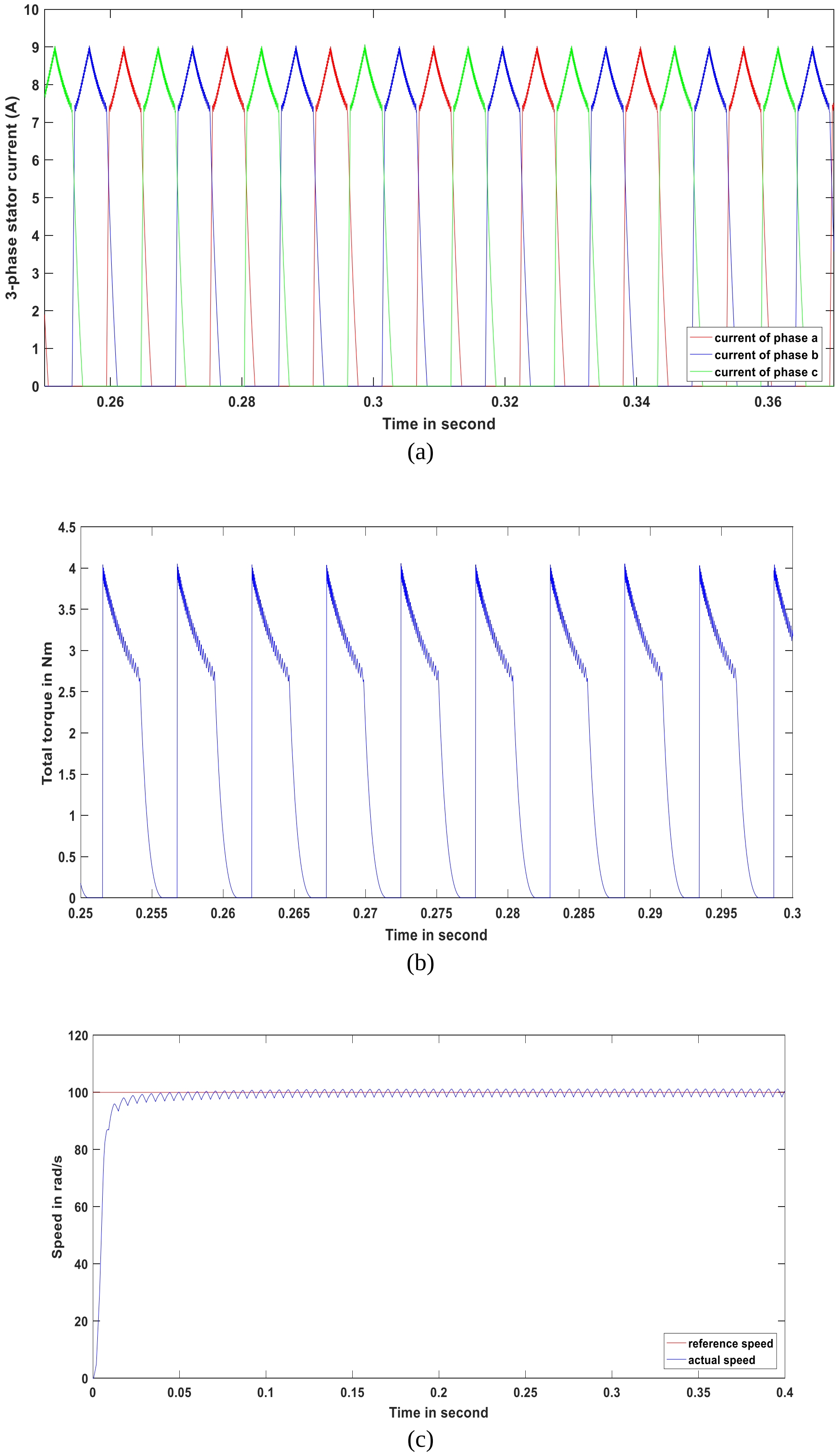

Figure 5. Performance analysis of speed control of 3-phase SRM based on Z-N method
(a) 3 phase currents in Amps (b) Total torque in Nm (c) Speed in rad/s

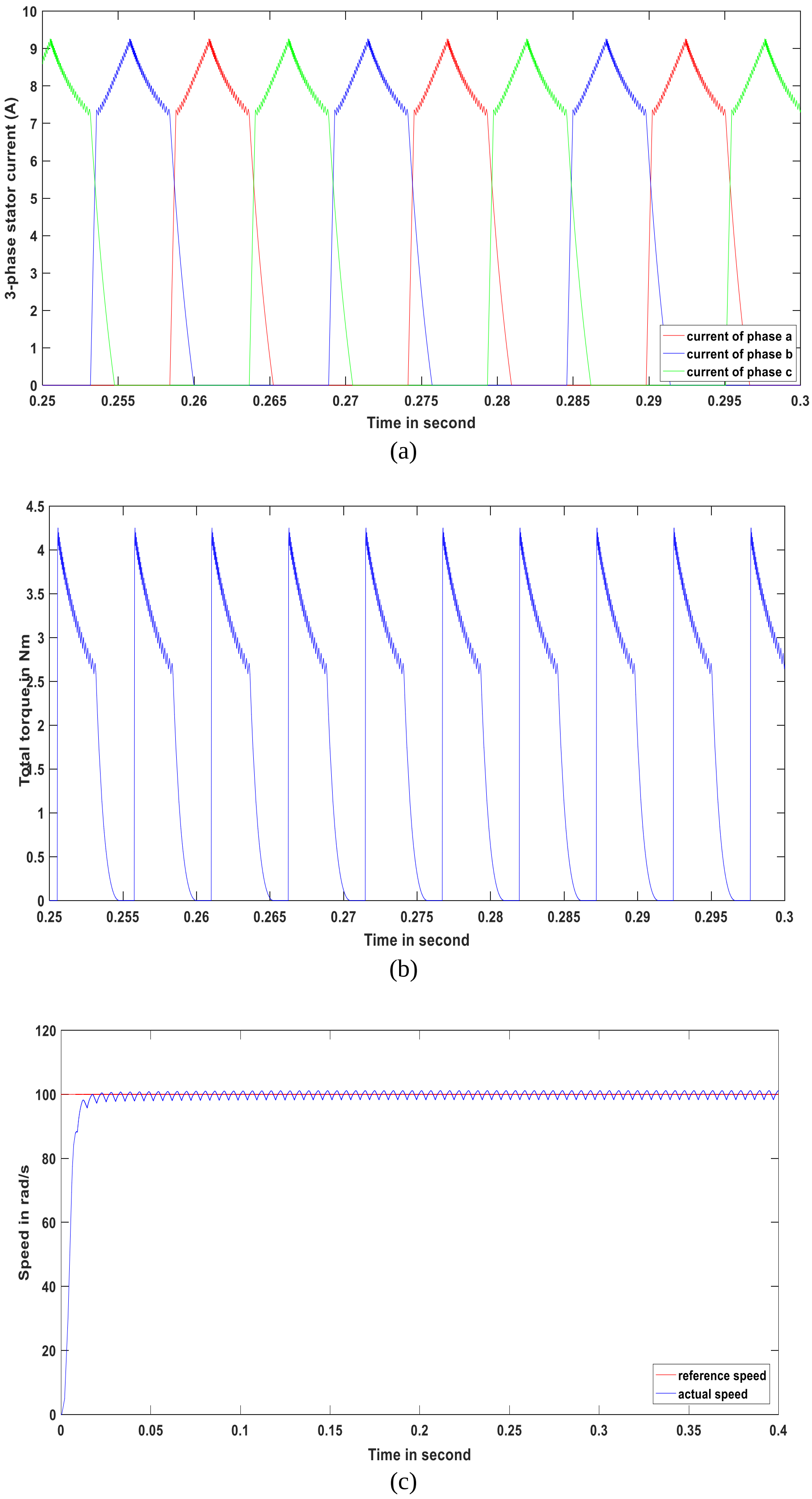

Figure 6. Performance analysis of speed control of 3-phase SRM based on ACO method (a) 3 phase currents in Amps (b) Total torque in Nm (c) Speed in rad/s

5. CONCLUSION

This study presents an innovative meta-heuristic method to automated PI tuning for speed control of switched reluctance motor (SRM) 6/4 poles using ant colony algorithm. The design problem of the proposed controller is formulated as an optimization problem and ACO is employed to search for optimal parameters of PI controller. By minimizing the time domain objective function in which the difference between the reference and actual speed are involved. The tested dynamic model with the peoposed new strategy of optimization has improved a better robust control action compared with conventional PI controller with less percentage of torque ripples. Simulation results demonstrate that the new tuning methods using Artificial Intelligence (AI) have a better control system performance compared with classic approach.

APPENDIX

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

(a) 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 8mH; Phase resistance R=1.30Ω; Moment of inertia J=0.0013 Kg/m2; Friction F=0.0183 Nm/s; Inverter Voltage V=150 v.

(b) Ziegler Nichols Tuning Rule parameter values:

Control Type	Kp	Ki	Kd
P	0.50 Kc	-	-
PI	0.45Kc	1.2Kp/Pc	-
PID	0.60Kc	2.0Kp/Pc	KpPc/8

(c) ACO parameters:

Nodes number n=10; Ants number m=5; maximum number of iteration tmax=5; maximum distance for every ant’s tour dmax= 49; Parameter, that determines the relative importance of pheromone vs distance β=0.2; searching defined coefficient ρ=0.6; Pheromone disintegration parameter α=0.1; algorithm parameter qa =0.6; Initial pheromone level τ0= 0.1.

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