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Artificial Intelligence-based control for torque ripple minimization in switched reluctance motor drives

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ABSTRACT. In this paper, various intelligent controllers such as Fuzzy Logic Controller (FLC) and Adaptive Neuro Fuzzy Inference System (ANFIS)-based current compensating techniques are employed for minimizing the torque ripples in switched reluctance motor. FLC and ANFIS controllers are tuned using MATLAB Toolbox. For the purpose of comparison, the performance of conventional Proportional-Integral (PI) controller is also considered. The statistical parameters like minimum, maximum, mean, standard deviation of total torque, torque ripple coefficient and the settling time of speed response for various controllers are reported. From the simulation results, it is found that both FLC and ANFIS controllers gives better performance than PI controller. Among the intelligent controllers, ANFIS gives outer performance than FLC due to its good learning and generalization capabilities thereby improves the dynamic performance of SRM drives.

Keywords: switched reluctance motor, torque ripple coefficient, fuzzy logic control (FLC), adaptive neuro fuzzy inference system (ANFIS), proportional-integral (PI) controller.

Controle baseado na inteligência artificial para minimização de torque ripple em motor de relutância comutada

RESUMO. Vários controladores inteligentes como as técnicas compensadoras de corrente baseadas em Fuzzy Logic Controller (FLC) e Adaptive Neuro Fuzzy Inference System (ANFIS) são usadas para minimizar o torque em motor de relutância comutada. Os controladores FLC e ANFIS são sintonizados por MATLAB. Leva-se em consideração o desempenho do controlador convencional Proporcional-Integral (PI) para comparação. Registram-se os parâmetros estatísticos como o mínimo, o máximo, a média, desvio padrão de torque total, coeficiente de ripple de torque e o tempo de resposta de velocidade para vários controladores. Os resultados de simulação mostram que os controladores FLC e ANFIS têm um melhor desempenho do que o controlador PI. Entre os controladores inteligentes, ANFIS proporciona um desempenho melhor do que FLC devido à boa aprendizagem e capacidades generalizadas, as quais melhoram o desempenho dinâmico do motor de relutância comutada.

Palavras-chave: motor de relutância comutada, coeficiente de ripple de torque, controle lógico de números difusos (FLC), sistema de interferência neuro-adaptativa difusa (ANFIS), controlador proporcional-integral (PI).

Introduction

The inherent simplicity, ruggedness and low cost of a switched reluctance motor (SRM) make it a viable machine for various general purposes adjustable to speed drive applications. The primary disadvantage of SRM is the higher torque ripples when compared to conventional machines, which results in acoustic noise and vibration (HANY et al., 2010). The origin of torque pulsations in SRM is the highly non linear and discrete nature of torque production mechanism. The total torque in an SRM is the sum of torques generated by each of the stator phases, which are controlled independently. Torque pulsations are the most significant at the commutation instants when torque production mechanism is being transferred from one active phase to another (XUE et al., 2009). The resonant vibrations of the stator are the dominant source of acoustic noise in an SRM (BAY; ELMAS, 2004).

The minimization of torque ripples is essential in high performance servo applications which require smooth operation with minimum torque pulsations. The excellent positive features of an SRM may be utilized in a servo system by developing techniques for reducing the torque ripples. There are essentially two primary approaches for reducing the torque pulsations: one method is to improve the magnetic design of the motor, while the other method is to use sophisticated electronic control (MIR et al., 1999). Machine designers are able to reduce the torque pulsations by changing the stator and rotor pole structures, but only at the expense of motor performance. The electronic approach is based on selecting an optimum combination of the operating parameters, which include supply voltage, turn on and turn off angles, current level and the shaft load (HUSAIN; EHSANI, 2002). Among these, a simple current modulation technique is widely used for the minimization of torque ripples in SRM (INANC; OZBULUR, 2003).

The simple and popular current compensating techniques can be implemented using both classical and intelligent controllers. The classical controllers require exact mathematical model of the systems and are very sensitive to parameter variations (HANY et al., 2010). As SRM presents strong non linear characteristics, the dynamic control of SRM drive can be obtained by using intelligent controllers based on artificial intelligent techniques such as fuzzy logic (BOLGNANI; ZIGLITO, 1996) and neural networks methods (HAJATIPOUR; FARROKHI, 2008; LIN et al., 2006). However, in the case of servo control applications or when smooth control is required at low speeds, the elimination of the torque ripples becomes the main issue (HUSAIN; EHSANI, 2002).

In this case, the fuzzy logic controller is not sufficient because torque ripples change with the SRM speed and load. In this context, it is advantageous to include some learning mechanism like adaptive neuro fuzzy inference system (ANFIS) to the SRM control to adapt itself to the new dynamic conditions, because it has the ability to accommodate both data and existing expert knowledge on the problem and good generalization capability features (AKCAYOL, 2004).

In this paper, the application of a fuzzy logic controller and adaptive neuro fuzzy inference system based on adding a compensating current signal to the switched reluctance motor to minimize the torque ripples is investigated. The dynamic response of the SRM with proposed controllers are analyzed. For the purpose of comparison, the performance of the conventional PI controller is considered.

Model description of SRM drive

SRM has salient poles on both the stator and the rotor with coils placed around the stator poles and connected in diametrically opposite pairs to form the phases of the motor. It is fed by a three-phase asymmetrical power converter having three legs, each of which consists of two IGBTs and two free-wheeling diodes. During conduction periods, the active IGBTs apply positive source voltage to the stator windings to drive positive currents into the phase windings. During free-wheeling periods, negative voltage is applied to the windings and the stored energy is returned to the power DC source through the diodes, as shown in Figure 4. The fall time of the currents in motor windings can be thus reduced. By using a position sensor attached to the rotor, the turn-on and turn-off angles of the motor phases may be accurately imposed. This switching angle can be used to control the developed torque waveforms. The phase currents are independently controlled by three hysteresis controllers which generate the IGBTs drive signals. The IGBTs switching frequency is mainly determined by the hysteresis band (KRISHNAN, 2001).

The switched reluctance machine has strong similarity to series-excited dc and synchronous reluctance machines. In control, however, it is very remotely connected to these machines and therefore analogous control development is not possible. The inductance of a phase winding is a non linear function of current (i) and rotor position (θ).The inductance pattern of a phase repeats for every 90° for 6/4 SRM. The dynamic mathematical model of a SRM is composed of a set of electrical equations for each phase and equations of the mechanical system (KRISHNAN, 2001).

The voltage equation of a phase is given by

$$V = R_S i + \frac{d\lambda(\theta, i)}{dt} \tag{1}$$

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

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

where:
L is the inductance dependent on the rotor position and phase current

$$V = R_S i + L(\theta, i)\frac{di}{dt} + \frac{dL(\theta, i)}{d\theta} i\omega_m \tag{3}$$

The induced emf is obtained as

$$e = \frac{dL(\theta,i)}{d\theta} i\omega_m = i\omega_m K_b \tag{4}$$

where:
K_b may be constructed as an emf constant and is given by

$$K_b = \frac{dL(\theta,i)}{d\theta} \tag{5}$$

The torque in a phase is given by

$$T_e(\theta,i) = \frac{1}{2} i^2 \frac{dL(\theta,i)}{d\theta} \tag{6}$$

Under the simplifying assumption of magnetic linearity, the total torque equation becomes

$$T_{total}(\theta,i) = \sum_{phases} \frac{1}{2} i^2 \frac{dL(\theta,i)}{d\theta} \tag{7}$$

Which, on substitution into the mechanical equation, results in the following

$$T_{total} - T_l = J\frac{d\omega_m}{dt} + B\omega_m \tag{8}$$

where:
T_l is load torque and ω_m is angular velocity.

From the above Equations (1-8), it is seen that torque is the product of the derivative of self-inductance and the square of winding current. Since the developed torque is independent of the sign of the current, positive torque is developed only during periods in which the derivative $\partial L/\partial\theta$ is positive. The dynamic model of a 6/4, 3 phase SRM is developed by using the above equations in the MATLAB/SIMULINK environment.

Torque ripple minimization

Because of the saliency of the stator and rotor, the torque ripple is produced when the former phase is being excited opposite voltage and the latter phase has been excited. The point of intersection between the two excited phases must be advanced to a higher value to minimize the torque ripple. To attenuate the torque ripple, the addition of a compensating current signal is proposed, as shown in Figure 1. This signal is dependent of the rotor position and the reference current which in turn depends on the motor speed and the torque load value.

The output compensating current signal produced by the controllers, I_{comp} is added to the reference current signal, which ideally, should be constant in steady state, but producing significant ripple. The compensating signal should then be adjusted in order to produce a ripple free output torque. In fact, it is a function that possesses high mathematical complexity and therefore the production of this signal is quite complicated.

In this paper, intelligent controllers such as fuzzy logic controller (FLC) and the adaptive neuro-fuzzy inference system (ANFIS) are used to provide compensating current I_{comp} to minimize the torque ripples in SRM drives. The intelligent controllers has two inputs, reference current (I_{ref}), rotor position (θ) and one output, compensating current (I_{comp}), by means of a relation such as $I_{comp} = f(\theta, I_{ref})$. Consequently new reference current (I'_{ref}) is obtained by the addition of a phase current (I_{pha}) and compensating current (I_{comp}) as shown in Figure1.

A better general view of the torque ripple is obtained by calculating torque ripple coefficient as follows.

$$T_i = \frac{T_{\max} - T_{\min}}{T_{mean}} \tag{9}$$

where:
T_{max}, T_{min} and T_{mean} are the maximum, minimum and average values of the total torque.

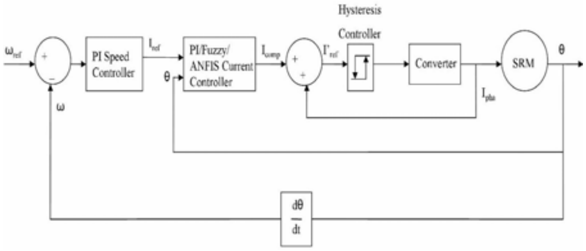

Figure 1. Block diagram of SRM with Controller.

Intelligent controllers

In current research, the intelligent controllers, such as fuzzy logic controller (FLC) and the adaptive neuro-fuzzy inference system (ANFIS), are used to control the SRM drive to minimize torque ripple and thereby to improve the dynamic response of SRM drives.

Fuzzy logic controller may be used to design nonlinear controllers which are well justified by the universal approximation theorem. The fuzzy logic system may, in principle, approximate relations between variables, regardless of their analytic dependence. Therefore, it may be considered a model-free estimator. Also, fuzzy controllers are easy to implement and, with adaptive schemes, these controllers may be made robust. First, compensating current is injected in each phase by using FLC. The motor model is designed and membership functions are chosen according to the parameters of the motor model.

ANFIS combines the benefits of artificial neural networks and fuzzy inference system in a single model (JANG, 1993). The learning mechanism makes the controller more independent of the motor characteristics. Initial values of both membership functions and rule base are obtained using knowledge of dynamic behaviour of the SRM and then membership function parameters are optimized by ANFIS. If the system has some load modification and/or change of speed, the controller will be capable of adapting itself to this new operating point, searching for the required torque ripple minimization. The strategy to produce the compensating signal is done by learning mechanism through the new intelligent methodologies such as the adaptive neuro-fuzzy inference systems.

Fuzzy Logic Controller (FLC)

Fuzzy control is one of the appropriate control schemes for torque control of SRM drives. The mamdani fuzzy controller uses the rotor position and reference current as inputs and produces the compensating current as the output. The inputs are divided into membership functions which are designed to give an optimum number of rules and allow the SRM to conduct over the entire positive torque producing region. Max-product rule of inference scheme is used and the output is determined using the center of average for defuzzification.

Implementation of Fuzzy Logic Controller

For this model, a DC supply voltage of 400 V is used. The converter turn-on and turn-off angles are kept constant at 40 deg and 75 deg, respectively, over the speed ranges. The reference current is limited to 60 Amps and the hysteresis band is chosen as ± 10 Amps. In FLC, reference current (I_{ref}), rotor position (θ) are considered as inputs and compensating current (I_{comp}) as output. The fuzzy rules act on reference current (with seven member functions for 50-70 Amps) and angular position (with seven member function for 40-75 Degrees) as inputs and compensating current (with seven member functions for +10 to -10 Amps) as output as shown in Figure 2. Consequently, new reference current (I'_{ref}) is obtained by the addition of the phase current (I_{pha}) and the compensating current (I_{comp}).

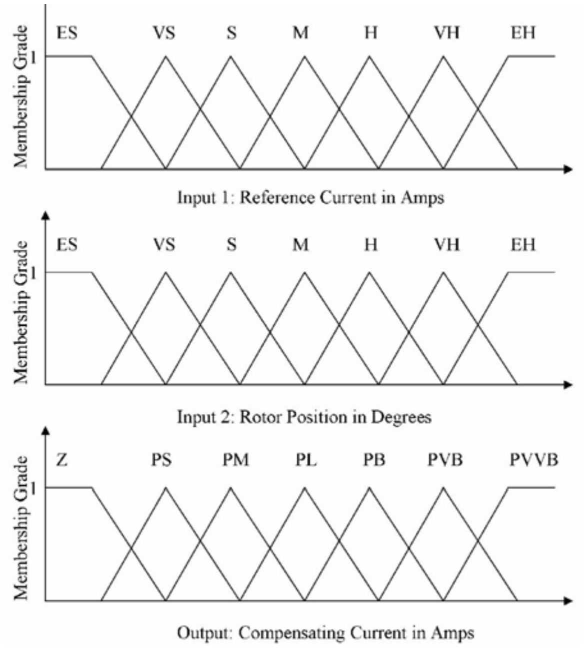

Figure 2. Fuzzy Membership function for input and output variables.

Linguistic Variables for Inputs: ES-Extremely Small; VS-Very Small; S-Small; M-Medium; H-High; VH-Very High; EH-Extremely High.

Linguistic Variables for Output: Z-Zero; PS-Positive Small; PM-Positive Medium; PL-Positive Large; PB-Positive Big; PVB-Positive Very Big; PVVB-Positive Very Very Big.

The rule base developed for the control of SRM drive is given in Table 1. In the regions of ES, VS and S of both inputs, ripples are more and for torque ripple minimization, fuzzy rules PVB or PVVB are developed. However, in the VH and EH regions, torque reduces by far slowly; consequently, fuzzy rules PB and PM have been determined. In addition, fuzzy logic rules for maximum compensation in near zero speeds up to rated speed has been used. Even in higher speed, fuzzy logic rules for compensating current is limited to PB because high ripple in high current will damage the SRM.

Table 1. Fuzzy Rules for SRM drive control.

Current(A) Rotor position(θ)	ES	VS	S	M	H	VH	EH
ES	PVVB	PVB	PL	PM	PB	PVB	PVVB
VS	PVVB	PVB	PL	PS	PB	PL	PVVB
S	PVVB	PVB	PB	Z	PM	PB	PVB
M	PVVB	PB	PM	PB	PVB	PB	PM
H	PVB	PB	PM	Z	PM	PB	PL
VH	PB	PS	PS	Z	PS	PM	PB
EH	PM	PS	PS	Z	PS	PM	PB

Adaptive Neuro Fuzzy Inference System (ANFIS)

The SRM drive has been designed to operate in a speed control mode. The compensating function should then be learned to produce the necessary adjustments to the current signal and thus reducing the torque ripple. The first step of compensation corresponds to the offline training of the neuro-fuzzy controller. This is adjusted iteratively through the learning algorithm, with the torque ripple signal used as the training error information.

Implementation of Adaptive Neuro Fuzzy Inference System

The ANFIS is a Sugeno adaptive network based fuzzy inference system (JANG, 1993). In this paper, the fuzzy inference system under consideration has two inputs, reference current (I_{ref}), rotor position (θ) and one output, compensating current (I_{comp}), by means of a relation such as $I_{comp} = f\,(\theta, I_{ref})$.

Neuro-Fuzzy System Structure

ANFIS network structure, which maps the inputs by the membership functions and their associated parameters, and therefore through the output membership functions and corresponding associated parameters, is shown in Figure 3. They are the synaptic weights and bias, being associated to the membership functions adjusted during the learning process. The computational work for the parameters acquisition and their adjustments is helped by the gradient-descendent technique which shows how much the error decreases. When the gradient is obtained, any optimization routine may be applied to adjust the parameters and, therefore, decrease the error. The ANFIS neuro-fuzzy system operation may be summarized in two steps.

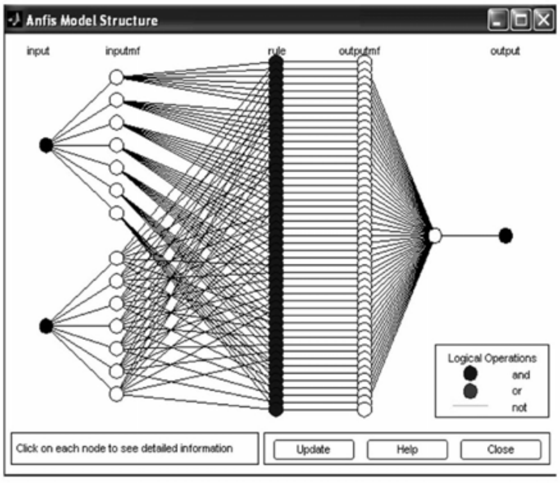

Figure 3. Structure of ANFIS.

a) The set of membership functions has to be chosen, i.e., their number and corresponding shape. The number and types of membership functions used in current research is seven and generalized bell shape respectively.

b) The input–output training data are used by the ANFIS system.

Learning scheme

A second part consists in the iterative training of the neuro-fuzzy controller. Training data were obtained from simulations of FLC of the complete SR drive system. This data set is then passed to the training algorithm, so that the torque ripple is interpreted by the controller in terms of compensating current (I_{comp}) for each reference current (I_{ref}), rotor position (θ) pair. The controller output is then readjusted to reduce the torque ripple. The process is repeated until some minimum value torque ripple has been reached. The information about the ANFIS is given in Table 2.

Table 2. ANFIS information.

Number of iterations	100
Number of nodes	131
Number of linear parameters	147
Number of nonlinear parameters	42
Total number of parameters	189
Number of training data pairs	5000
Number of fuzzy rules	49

When the iteration counter reaches maximum number of iterations, the learning process will stop. The choice of stopping criteria is very important for the stability of the method, since the converter may not be able to produce the required compensated currents at any speed or load. The main reason is that, after training, the controller can require current magnitudes that could not be reached by the converter. Therefore, a compromise between the converter capabilities and the currents required by the controller is needed.

The optimization of the neuro-fuzzy system was performed by a hybrid technique that uses the back propagation and the mean-squared error method. The rule set was initially generated by the grid partition technique. After training, the controller signal may be generated and added to the phase current (I_{pha}) to produce new reference current (I'_{ref}).

Simulation results and analysis

A three-phase 6/4 SRM as a prototype motor is used in simulation by MATLAB/SIMULINK environment. The load torque is taken as 10 Nm and the speed of SRM is 3000 RPM. In this work, intelligent controllers such as fuzzy logic controller

(FLC) and adaptive neuro fuzzy inference system (ANFIS) are employed to minimize the torque ripples in switched reluctance motor. For comparison sake, conventional PI controller is also considered. The simulation is carried out for 0.35 seconds. For clarity over the responses, the time scale variation for flux linkages, 3ϕ currents and total torque is taken as 0.325 – 0.35 second and for voltage, it is taken as 0.335 – 0.35 second.

Figure 4 shows the voltage profile of the three phases of SRM Drives. Figure 5 to 7 shows the simulation results of flux linkages, 3ϕ currents, total torque and speed for torque control scheme based on PI, FLC and ANFIS controllers. It may be observed that the torque control employs PI controller which produces more ripples. Under the FLC, ANFIS controller it may be seen that the torque ripple decreases, obviously comparing with PI torque control scheme. And also the settling time is also improved for FLC, ANFIS controller.

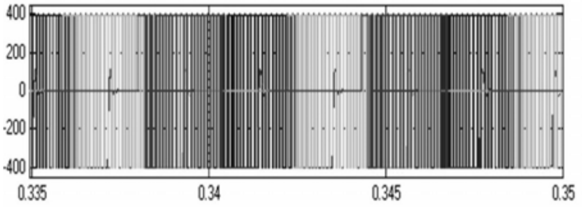

Figure 4. Voltage profile.

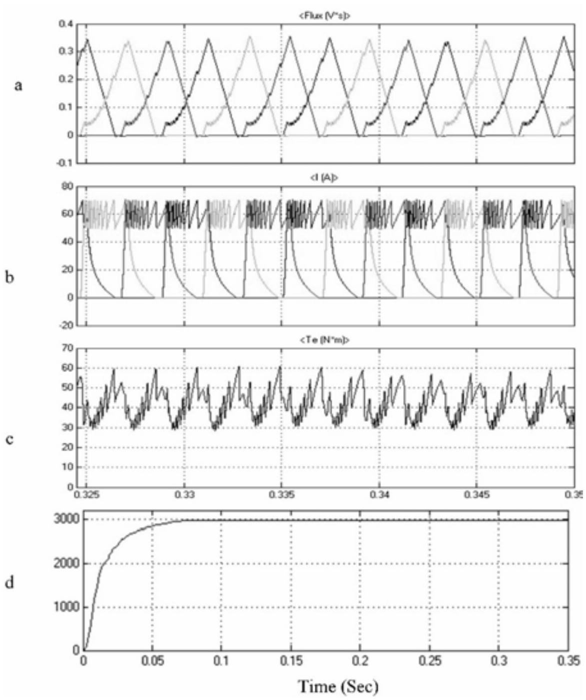

Figure 5. Performance of SRM drive with PI controller (a) Flux Linkages (wb) (b) 3Φ Currents(Amps) (c) Total Torque(Nm) (d) Speed(RPM).

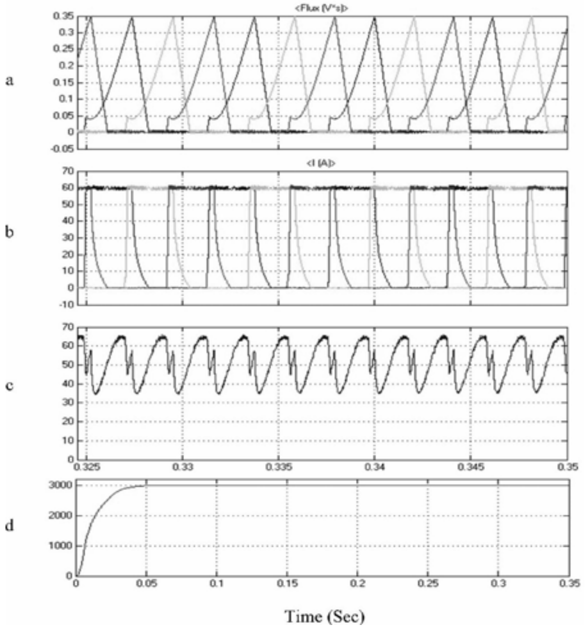

Figure 6. Performance of SRM drive with Fuzzy Logic controller (a) Flux Linkages (wb) (b) 3Φ Currents(Amps) (c)Total Torque(Nm) (d)Speed(RPM).

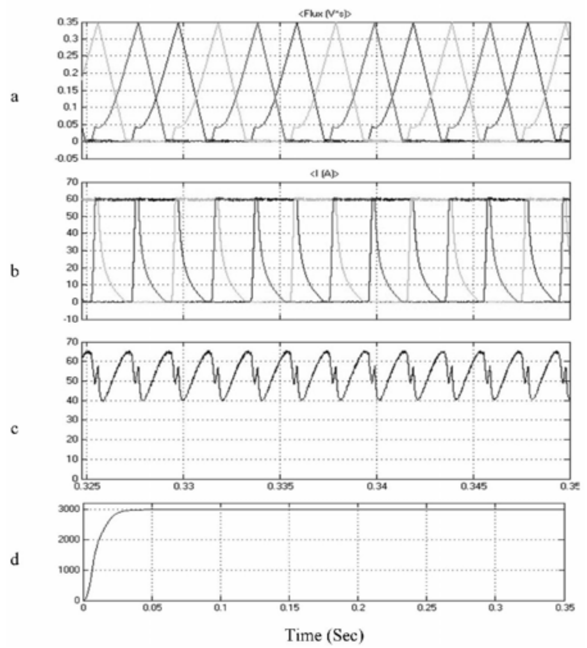

Figure 7. Performance of SRM drive with ANFIS controller (a) Flux Linkages (wb) (b)3Φ Currents (Amps) (c)Total Torque(Nm) (d)Speed(RPM).

In Table 3, the statistical parameters such as the minimum, maximum, mean values of total torque and torque ripple coefficient (T_i) for various controllers are reported. It also shows the standard deviation of total torque (σ_T) and settling time (t_s) of the responses. For the PI speed controller, which lies in outer loop, the proportional and integral gain (K_p, K_i) has been taken as 34 and 0.15 respectively. For PI current controller, which lies in inner loop, the proportional and integral gain (K_p, K_i) is taken as 50 and 0.05 respectively. These parameters are obtained by means of using graphical tuning (bode plot) method which is available in control design tools of MATLAB/SIMULINK environment. These parameters are well tuned to yield better results for torque ripple reduction than without controller.

Results reveal that mean torque is increased and the torque ripple coefficient and standard deviation of total torque (σ_T) are reduced for FLC and ANFIS controller. In FL controller, torque ripple coefficient is reduced than PI controller. But in ANFIS, it is still decreased when compared with PI controller and with FL controller. The settling time is also improved in both cases but ANFIS has better performance when compared with PI controller and FL controller. The torque ripple is reduced when compared with the graphical results reported in (INANC; OZBULUR, 2003) and the torque dip between two phases is well reduced when compared with the graphical results reported in (HANNOUN et al., 2011).

Table 3. Performance of Intelligent Controllers.

Method	Torque in Nm				T_i	t_s Sec
	Max.	Min.	Mean	σ_T		
With PI Controller	59.12	28.57	42.41	8.13	0.72	0.072
With FLC	63.15	36.24	51.28	7.17	0.52	0.050
With ANFIS	65.64	40.17	54.48	6.53	0.47	0.048

Conclusion

In current research, fuzzy logic controller (FLC) and adaptive neuro fuzzy inference system (ANFIS) based current compensating techniques are employed for minimizing the torque ripples in switched reluctance motor. The statistical parameters of total torque, torque ripple coefficient and settling time of speed are reported. For the purpose of comparison, the performance of conventional PI controller is also considered. Simulation results show that both FLC and ANFIS controllers give better performance than PI controller. Among the intelligent controllers, ANFIS improves the dynamic performance of SRM drives better than FLC, due to its good learning and generalization capabilities.

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APPENDIX

Main dimensions of SRM

Parameter	Value	Parameter	Value
Type	6/4	Unaligned Inductance	0.67 mH
No. of Phases	3	Aligned Inductance	23.6 mH
Stator Resistance	0.01 ohm	Power	64 KW
Inertia	0.0082 kg.m.m	Maximum Current	100 Amps
Friction	0.01 N.m.s	Max. Flux Linkage	0.486 V.s