AN EFFICIENT TECHNIQUE FOR TORQUE RIPPLE MINIMIZATION WITH PERMANENT MAGNET STEPPER MOTOR

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Abstract: *In this paper presented an efficient technique is used for decreasing the torque ripple of the PMSM. The efficient technique is on the basis of the hybridization of ANN and fuzzy inference system that is called as ANFIS technique. The ANFIS technique is highly efficient in nonlinear systems because of the fact that once properly trained they can interpolate and extrapolate the random information with high accuracy. The main objective of the projected method is to reduce the torque ripples with the help of the regulating parameters, namely torque and speed. Initially the PMSM parameters are restrained and controlling the input parameters of the PMSM such as voltage and current. The torque and rotor angle of the PMSM is restrained for controlling the torque ripple and regulating the speed of the PMSM. From the measured parameters the error signal is considered from the actual and reference value of the rotor angle and torque of the PMSM. On the basis of the error signal the projected method is produced the control pulses, which is provided to VSC for supply the voltage and current signal to PMSM. The presented torque ripple minimization method is applied in MATLAB/Simulink working platform and the performances is assessed and compared with some available methods such as neural networks and fuzzy controller.*

Keywords: *Torque Ripple Minimization, Permanent Magnet Stepper Motor (PMSM), Adaptive Neuro-Fuzzy Inference System (ANFIS), Voltage Source Converter (VSC)*

1. Introduction

Nowadays, PMSM are widely used in both industry and consumer devices, which are characterized by a good performance in open loop configurations and allowing for simplification of the electrical design [1]. Performance and capabilities may be allowed implementing current basic and technological progressions confirming high torque and high power densities [2]. It is sensible to wonder whether instability may appear as a nonlinear system is controlled based on an approximate linear model [3, 4]. In this case, the sensor-less refers systems do not have position sensors, though current sensors are still expected to be accessible. Sensorless control is favorable to decrease the cost of the implementation, or when there is no space for a mechanical sensor [5]. Improved positioning function can thus be attained through the usage of more advanced control and sensing algorithms instead of via more exactly manufactured motors and sensors, with their related higher costs and lower reliability [6].

The position estimation error in the constant velocity period is investigated with the help of the position tracking error of micro stepping [7]. Micro stepping gives the expected currents for the position tracking to the PMSM. Then the torque produced by the currents moves the position to the anticipated position. Therefore, numerous micro stepping approaches with feedback control have been studied to progress the current tracking function of micro stepping [8]. A micro stepping technique with a proportional integral derivative (PID) controller has also been intended. The effects of random signals on the accurateness of the micro stepping control positioning were abridged by micro stepping with a PID controller, but the stability of the closed loop was not confirmed [9, 10]. A conventional PID controller is utilized for attaining torque modulation for position tracking. Velocity feed forward is utilized in order to progress the position tracking performance. The PID controller with velocity feed forward produces the anticipated torque, i.e., torque modulation [11, 12]. Although all of the approaches can overcome the restriction of the micro-stepping position control, they require position feedback [13].

In addition, the motor can lose stages if the variation of the load torque is fast. The usage of programmable architecture such as field-programmable gate arrays (FPGA) circuit permits the creation of micro step schedules [14, 15]. Specifically, large position tracking errors appear at the time of the nonzero velocity period as the electrical dynamics are much earlier than the mechanical dynamics in PMSM [16]. The stepper motors are recognized to comprise geometric inadequacies that are the source of non-sinusoidal flux density in the air gap that in turn provides rise to the torque ripple in the motor. The control design practice advocated here is exposed to be robust to these geometric inadequacies and consequently owns the added advantage of abridged torque ripple [17, 18]. Also, the artificial intelligent controllers are utilized to resolve the nonlinearity issue of the stepper motor drives. In recent years, fuzzy logic control methods have been implemented to the control of high-performance motor drives. Further, the artificial neural networks (ANNs) have been utilized to deal with the motion control issues of stepper motor drives [19]. This controller proposals easy integration into existing industrial applications without the obligation of additional hardware as it utilizes only the current sensors that are presently utilized in conventional micro-stepping. These approaches can decrease both torque and position ripple and also uniform position tracking performance without step-out or speed reversal even in high speed operation [20]. In this article presented an efficient technique for decreasing the torque ripple with the help of the regulating parameters, such as torque and speed of the PMSM. In an efficient technique, the ANFIS is utilized to control the torque and regulate the speed of the PMSM. The recent research works are offered in Section 2 and the comprehensive portrayal of the projected method is offered in Section 3. The experimental results and discussion are assumed in Section 4. Lastly, the Section 5 accomplishes the paper.

2. Recent Research Works: A Brief Review

In addition, numerous researchers have comprehensively explored different kinds of methods for torque ripple minimization. Some of them are studied here,

A self-tuning PI controller for the speed control of electrical motor drives has projected by Mohamed S.Zaky [21]. The PI controller gains were adjustable parameters and would be updated online depending on the speed error. To vary the design within a pre-determined range to remove the issues faced by the conventional fixed PI controller. .r (HSM) was related to the conventional PI controller under tracking performance, parameters variation and load torque disturbances.

The velocity control of a large-range piezo electrically actuated (piezo) stepper have described by Scott Wilcox *et al.*[22]. The chief influence of that was to spread the Poincare-map method for assessing the stability of the stepper dynamics in the occurrence of Coulomb friction nonlinearity that has a jump discontinuity with velocity. Moreover, inversion of the stepper-dynamics model was utilized to detect the piezo input for directing the stepper velocity, and model based predictions of the stepper velocity were assessed with the help of an experimental-stepper system.

A theoretical result to the yet unsolved issue of tracking, via state feedback, periodic reference signals (with known period) for the rotor position of full order model indeterminate permanent magnet step motors with non-sinusoidal flux distribution and indeterminate position dependent load torque have delivered by Cristiano Maria Verrelli *et al.*[23]. The resulting control was of simple structure and integrates three repetitive learning estimation systems simplifying the classical integral actions.

The stepper motor was a satisfactory choice for driving the control rods of modular high temperature gas-cooled reactor (MHTGR) has projected by Zhe Dong [24], and has already been implemented to under-construction HTR-PM plant. Since a stepper motor itself was a nonlinear dynamic scheme that could intensely influence power-level control performance, it was expressive to progress nonlinear power-level control laws of MHTGRs by bearing in mind the stepper motor dynamics. It was evident that power-level control method was crucial in guaranteeing safe, stable and effectual operation of MHTGRs. Interested by this and based upon the back stepping method and physically-based control design method, a nonlinear power-level control by concerning the MHTGR and stepper motor as a complete dynamical scheme. It was demonstrated theoretically that the newly-built power-level controller can guarantee worldwide asymptotic closed-loop stability by producing proper motor stator voltages.

The RF power feeding the Radio Frequency Quadrupole (RFQ) offers rise to the temperature upsurge in the RFQ that in turn results in shifting the resonant frequency of the RFQ have projected by S.Alsari *et al.* [25]. The frequency shift and the stability in the RFQ frequency can be maintained on the basis of the reflected power or signal phase data. We have, however, inspected restoration of the RFQ nominal frequency on the basis of the RF signal phases driving a stepper motor. The concept and the scheme set-up and electronics are defined in detail. Results of the measurements demonstrating the full restoration of the RFQ nominal frequency on the basis of the RF signal phases and stepper motor are offered. Furthermore, measured sensitivity of tuner with respect to its position is given.

A simplified torque modulated micro stepping (STMMS) on the basis of singular perturbation theory for position control of the PMSMs have projected by Wonhee Kim *et al.*[26]. As a two phase frame PM stepper motor model comprises slow and fast dynamics, singular perturbation theory is implemented to recover the transient response and to decrease the ripple. The torque moderated micro stepping method is implemented with a simplified current tracking control law attained from singular perturbed system examination. Using implemented conditions and stability proofs, this eradicates the high-bandwidth control efforts for the current tracking obligatory in the preceding approaches.

The mechanical speed of the stepping motors (SM) without position sensors in order to attain a rapid-response manufacturing whenever any equipment on the basis of such electrical machines have convoluted by Antoni Arias *et al.*[27]. Such global method starts justifying why the traditional PI controller is not adequate and it includes the analytical tuning of the current controllers, in view of implementation tiny problems (but of paramount importance) like the delays resulted by the processor and the sample and hold current measurements. It is demonstrated and justified that issues that are frequently omitted, play a crucial role when trying to maximize the speed of the SM, as the electrical fundamental frequencies of the SM move close to the sampling frequency. Consequently, the analytical procedure to tune and apply the current controllers will have to be performed in discrete-time domain, i.e. with the help of the Z-transform and treating the SM drive as a sampled data scheme.

Mohamed S. Zaky [28] has proposed a robust speed controller using a chatter-free continuous variable structure control (CVSC) with adaptive feedback gain. The switching surface of the proposed CVSC with an integral component is designed to guarantee the exponential stability and insensitivity to uncertainties and disturbances. The switching function of the discontinuous VSC (DVSC) is substituted by the continuous function to remove chattering. The feedback gain is designed and tuned using the Lyapunov theory. It is adapted online relying on the speed error and the machine parameters to eliminate the problems of the conventional CVSC.

The generic review shows that, the accurate control of the torque ripple is essential in numerous implementations of PMSMs. The usage of an implementation necessitates performing high precision operation in spite of mechanical configuration changes like load torque disturbances and also inertia variations. The issues of PMSMs are non-uniformity in the developed torque (torque ripple). These torque pulsations vary periodically with rotor position and are replicated as ripple. This ripple is parasitic, and can lead to mechanical vibration, acoustic noise and drive system issues. Classic control approaches that make usage of linear models for designing controllers are valid only for small variation around an operating point. The usage of classic closed loop algorithms like PID control is inadequate as these algorithms are frequently sensitive to mechanical configuration vicissitudes. This issue can be resolved by implementing advanced closed loop control methods like self-tuning regulation (STR) or nonlinear feedback control in which the controller is imposed to adapt itself to the motor operating conditions. In adaptive approaches, the control laws like model reference adaptive control and STR are nonlinear control laws that are demanding to derive. Furthermore, it agonizes from disadvantages of slow response, large overshoots, and oscillations. Due to the extensive usage of PI control it is extremely desirable to tune this controller gains. At the time of the past decades, a lot of attention has been provided to the issue of designing adaptive controllers and self-tuning regulators. Dissimilar methods have been adopted for pole-assignment regulators, in which the controllers are chosen in such a manner that the closed-loop-system poles are positioned at pre-specified positions depending on the prerequisite system performance. An optimal algorithm for closed loop control of hybrid stepper motor drives is a third order sliding mode controller (SMC). Lately, artificial intelligence control methods have to represent motion control schemes that are difficult using mathematical models. An ANN control system displays good results in stepper motor speed trajectory tracking. Though, when the scheme is subjected to a sudden load disturbance, the ANN profits a long recovery time to cope the vicissitudes as it necessitates large amount of computations for learning and adaptation. In these approaches have some disadvantages, like the torque and flux ripples without attaining the minimum and the steady-state with the objective of decreasing the ripples is adopted in the transient state as well without any alteration. To abandoning these torque ripple issues we need operative artificial intelligent based method. Hereafter the ANFIS based effectual method is accessible for attractive concern of this problem in the paper.

3. Description of Proposed Model

In this study proposed an effective method is utilized for decreasing the torque ripple of the PMSM. The projected method is used the ANFIS method to control the rotor angle and assess the torque of the PMSM. ANFIS is an adaptive network that is functionally equivalent to a fuzzy inference scheme, in which the output has been attained with the help of the fuzzy rules on inputs. In this method is highly effective in nonlinear schemes because of the fact that once appropriately trained they can interpolate and extrapolate the random information with high accuracy. In this parameters are assessed from the PMSM and it is on the basis of the input parameters of PMSM like voltage and current. The projected controlling model is designated in subsequent figure 1.

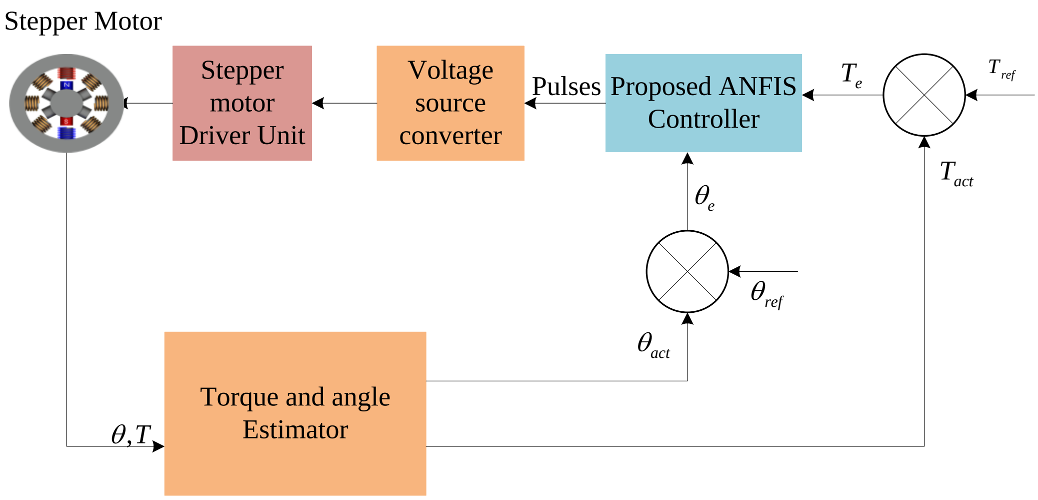


Fig. 1 The proposed torque ripple controlling model for PMSM

In this figure clarifies the controlling procedure of the projected model. Primarily, the PMSM parameters such as torque and rotor angle are assessed with the help of the torque and rotor angle estimator. Then the parameters are related to the actual and reference values then it provides the error value of the torque and rotor angle. The error value is lessened using the projected method and designated the optimal error value. On the basis of the error value the optimal control pulse is produced and provided to VSC for distributing the voltage signal to the PMSM. The stepper motor driver unit is constrains the motor on the basis of the input power supply. To decrease the torque ripple is on the basis of the angle of the rotor winding. The torque is depends on the power parameters and also the rotor angle of the PMSM. When the rotor angle error is diminished, then the torque ripple is also abridged. The rotor angle error value gets controlled on the basis of the ANFIS method. The comprehensive explanation is designated in a subsequent segment.

3.1. Modelling of Stepper Motor

For investigation of control approaches, the PMSM model is utilized. The PMSM comprises of a slotted stator with two phases and a permanent magnet rotor. One side of the rotor is a north pole and the other side is a south pole. The teeth on each side of the rotor are out of arrangement by a tooth-width. It is significant to note that the estimation and control architecture does not undertake the obtain ability of any of the motor/load parameters [29]. The mathematical model for the PM stepper motor is provided below equations as (1), (2), (3) and (4),

$$\frac{di_a}{dt} = \dot{i}_a = \frac{1}{L}\left(v_a - Ri_a + K_m\omega\sin(N_r\phi)\right) \quad (1)$$

$$\frac{di_b}{dt} = \dot{i}_b = \frac{1}{L}\left(v_a - Ri_b + K_m\omega\sin(N_r\phi)\right) \quad (2)$$

$$\frac{d\omega}{dt} = \dot{\omega} = \frac{1}{J}\begin{pmatrix} K_m i_b \cos(N_r\phi) - \\ K_m i_a \sin(N_r\phi) - B\omega - \tau_L \end{pmatrix} \quad (3)$$

$$\frac{d\phi}{dt} = \dot{\theta} = \omega \quad (4)$$

Where, i_a is the current in winding A, i_b is the current in winding B, ϕ is the angular displacement of the shaft of the motor, ω is the angular velocity of the shaft of the motor, v_a is the voltage across winding A, v_b is the voltage across winding B, N_r is the number of rotor teeth, J is the rotor and load inertia, B is the viscous friction coefficient, L and R are the inductance and resistance, respectively, of the phase windings, K_m is the motor torque (back-EMF) constant, and τ_L is the load torque [30]. The model inattentions the slight magnetic coupling within the phases, the small change in inductance as a function of the rotor position, the detent torque and the variation in inductance due to magnetic saturation.

3.2. Characteristics of Proposed Stepper Motor Model

Deliberate a two-phase PM stepper motor under current command. Represent the currents flowing in the stator windings i_a and i_a . Let θ be the angle of the rotor (in radians), so that $\theta = 0$ when the PM flux in winding A is maximized. Pretentious linear magnetics and a sinusoidal PM flux in the windings, the torque T_e (in Nm) fashioned by the motor is given using equation (5),

$$T_e = -Ki_a \sin(N_p\theta) + Ki_b \cos(N_p\theta) \quad (5)$$

Where, K is the torque constant (in Nm/A) and N_p is the number of pole pairs (or rotor teethes) of the motor. In practice, the torque is not precisely sinusoidal, and reluctance effects (such as the detent torque) affect the overall torque. Nevertheless, the approximation is adequate for our investigation. The torque can also be transcribed as equation (6) and (7),

$$T_e = -KI\sin(\theta_e - N_p\theta) \tag{6}$$

Here,

$$I = \sqrt{i_a^2 + i_b^2}, \theta_e = \angle(i_a, i_b) \tag{7}$$

Where, I is the magnitude of the two-dimensional current vector with apparatuses i_a and i_b and is the angle of the vector with respect to the X axis. Open-loop control of position contains in implementing currents such that the angle θ_e is mottled by discrete increments. The dynamic response of a motor can be designated with the help of a nonlinear differential equation as (8),

$$j\frac{d^2\theta}{dt^2} = -B\frac{d\theta}{dt} + KI\sin(\theta_e - N_p\theta) \tag{8}$$

Where, J is the inertia of the motor, and B is a constant related to viscous friction. Static friction and load effects (except for the load inertia that may be added to the inertia of the motor) have been deserted. Nevertheless, if the rotor stays close to the equilibrium position well-defined by the current vector (i.e., $|\theta_e - N_p\theta|$ is small), an approximate linear differential equation can be attained as equation (9),

$$j\frac{d^2\theta}{dt^2} = -B\frac{d\theta}{dt} + KI(\theta_e - N_p\theta) \tag{9}$$

The roots of poles of the system are given as equation (10),

$$s^2 + \frac{B}{J}s + \frac{KIN_p}{J} = 0 \tag{10}$$

Since viscous friction is small in stepper motors, the roots are usually poorly damped. If θ_e abruptly changes, the response of the motor is oscillatory [31]. The resonant frequency (Hertz) of the scheme can then be assessed from equation (11),

$$f_r = \frac{1}{2\pi}\sqrt{\frac{KIN_p}{J}} \tag{11}$$

To control the rotor angle and measured the resonant frequency, then to minimize the error of the torque and rotor angle on the basis of the ANFIS controller. Primarily the system is trained on the basis of the fuzzy rules and testing method is started with the optimal information. The architecture and procedure of the ANFIS is offered in a subsequent segment.

3.3. Torque Ripple Minimization using ANFIS

An ANFIS scheme is an amalgamation of neural network and fuzzy schemes in such a way that neural network is utilized to regulate the parameters of fuzzy scheme. A neural network is utilized to automatically tune the scheme parameters. The ANFIS is a very powerful method for modeling nonlinear and complex schemes with less input and output training information with quicker learning and high precision. The neuro-fuzzy scheme with the learning capability of neural network and with the compensations of the rule-base fuzzy scheme can progress the performance significantly and can give a mechanism to incorporate past observations into the classification procedure. In neural network the training essentially builds the scheme [32]. Nevertheless, with the help of a neuro fuzzy scheme, the scheme is built by fuzzy logic definitions and is then sophisticated with the help of neural network training algorithms. The technique is enlightened briefly in the subsequent segment.

3.3.1. Principles of ANFIS

The modeling method utilized by ANFIS is similar to numerous error minimization methods. Usually, ANFIS model has five layers like input layer, input and output membership layer, rules layer and output layer is hypothesized. Subsequently the input/output the information is gathered for training the proposed scheme. ANFIS can be utilized to train the FIS model to outdo the training data offered to it by modifying the membership function parameters conferring to a selected error criterion. Operation of ANFIS looks like feed-forward back propagation network. Consequent parameters are considered forward while premise parameters are intended backward.

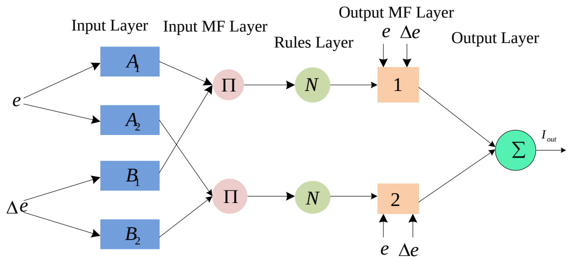


Fig.2 The proposed architecture of ANFIS

In this figure 2 exemplified the architecture of ANFIS that clarifies the procedure of the projected error minimization method. In this inference scheme is utilized five layers to construct ANFIS. Each layer comprises numerous nodes defined with the help of the node function. Adaptive nodes, represented by squares, characterize the parameter sets that are adjustable in these nodes, whereas fixed nodes, represented by circles, characterize the parameter sets that are fixed in the scheme. The output information from the nodes in the previous layers is the input in the present layer. In fuzzy segment, only zero or first order Sugeno inference scheme or Tsukamoto inference scheme can be utilized [33]. This segment familiarizes the basics of ANFIS network architecture and its hybrid learning rule. The projected method objective function is assessed by equation (12),

$$F = Min(e) = Min\{\theta^{ref} - \theta^{act}\} \tag{12}$$

Where, e is the error value within the reference rotor angle (θ^{ref}) and actual rotor angle (θ^{act}). The ANFIS structure of two input one output is presented and the two inputs are error e and change in error Δe. The change in error is assessed as equation (13),

$$\Delta e = e(s) - e(s-1) \tag{13}$$

Where, $e(s)$ is the instant state error value $e(s-1)$ is the preceding state of error, In this linked structure, the input and output nodes signify the training values and the prophesied values, correspondingly, and in the hidden layers, there are nodes working as membership functions (MFs) and rules. This architecture has the benefit that it eradicates the difficulty of a normal feed forward multilayer network, where it is challenging for an observer to understand or adapt the network. The circles characterize fixed node functions and squares signify adaptive node functions. Deliberate a first order Sugeno-fuzzy inference scheme that comprises two rules is given as equations (14) and (15),

Rule 1: If e ***is*** A_1 ***and*** Δe ***is*** B_1,

then $f_1 = p_1 x + q_1 y + r_1$ (14)

Rule 2: If e ***is*** A_2 ***and*** Δe ***is*** B_2,

then $f_2 = p_2 x + q_2 y + r_2$ (15)

At this time, p_1, p_2, q_1, q_2, r_1 and r_2 are linear parameters and $A1, A2, B1$ and $B2$ are nonlinear parameter. ANFIS is an application of a fuzzy logic inference scheme with the architecture of a five-layer feed-forward network. With this way ANFIS utilizes the recompenses of learning competence of neural networks and inference mechanism similar to human brain delivered by fuzzy logic. At this time, demonstrates graphically the fuzzy reasoning mechanism to derive an output from a given input vector $[e, \Delta e]$. The firing strengths w_1 and w_2 are frequently attained as the product of the membership grades in the evidence portion, and the output (I_{out}) is the weighted average of each rule's output. More plainly, the output can be articulated as equations (16),

$$I_{out} = \frac{w_1 f_1 + w_2 f_2}{w_1 + w_2} \tag{16}$$

The Sugeno model fuzzy is complementary for adaptive network based learning familiarized below. To enable the learning (or adapting) of the Sugeno model fuzzy, it is convenient to put the fuzzy model into the outline of adaptive networks that can calculate gradient vectors methodically [34]. Nodes within a layer of ANFIS perform analogous missions that are quantified with the help of their node functions, as designated below. Note that O_i^j represents the output of the i^{th} node in layer j. The layers of this structure are well-defined as follows,

Layer 1:

Each node of this layer produces the membership grades of an input variable with the node functions designated as equation (17) and (18),

$$O_i^1 = \mu_{Ai}(e); i = 1,2 \tag{17}$$

$$O_i^1 = \mu_{Bi-2}(\Delta e); i = 3,4 \tag{18}$$

Where, i is the membership grade of a fuzzy set (A_1, B_1, A_2, B_2) and O_i^1 is the output of the i^{th} node in layer 1.

Layer 2:

The output node in these layer products all incoming signals as equation (19),

$$O_i^2 = w_i = \mu_{Ai}(e) \times \mu_{Bi}(\Delta e), i = 1,2,\ldots,5 \tag{19}$$

Layer 3:

The nodes of the Layer 3 analyze the ratio of the rule's firing strength relative to the sum of all rule's firing strengths specified by the subsequent equation (20),

$$O_i^3 = \overline{w}_i = \frac{w_i}{w_1 + w_2}, i = 1,2 \tag{20}$$

Layer 4:

All nodes in the layer 4 are the adaptive node with a node output is provided as equation (21),

$$O_i^4 = \overline{w}_i f_i = \overline{w}_i (p_i x + q_i y + r_i), i = 1,2 \tag{21}$$

Where, $\overline{w}_i$ is a normalized firing strength and p_i, q_i and r_i are called the resultant parameters.

Layer 5:

Every node in layer 5 calculates the overall output as the summation of all incoming signals as equation (22),

$$O_i^5 = \sum_{i=1}^{2} \overline{w}_i f_i = \frac{w_1 f_1 + w_2 f_2}{w_1 + w_2} \tag{22}$$

The ANFIS structure can be tuned routinely with the help of a least square estimation (for output membership functions) and a back propagation algorithm (for output and input membership functions). In the projected control scheme, the ANFIS structure is trained by giving the vector as input [35]. Then, the suitable control pulse output is provided to the voltage source converter and produces the supply to stepper motor on the basis of the generated control pulse of the ANFIS. Then the expected method is implemented in the MATLAB/Simulink platform and the accomplished assessments are elucidated in the trailed result and discussion section 4.

4. Results and Discussions

In this segment, the performance investigation of the projected method is assessed and related to the available methods. The projected method is implemented with Intel(R) core(TM) i5 processor, 4GB RAM and MATLAB/Simulink 7.10.0 (R2015a) platform. The Simulink model of the projected scheme is represented in the figure 3 that is utilized to decrease the torque ripple of the PMSM with the aid of projected method. At this time, the projected method diminishes the torque ripple and stabilizing the speed of the PMSM. Primarily, the controlling parameters are controlled from the PMSM such as torque and rotor angle. Lastly, the projected method is assessed with two cases and related to some available methods. The projected PMSM scheme parameters are offered in table 1.

Table 1. The parameters of the proposed system

Parameters	Values
Winding resistance (Ohm)	0.7
Number of phases	2
Winding Inductance (H)	1.4e-3
Step angle (degree)	1.8
Maximum Flux Linkage (Vs)	0.005
Maximum Detent Torque (Nm)	0.002

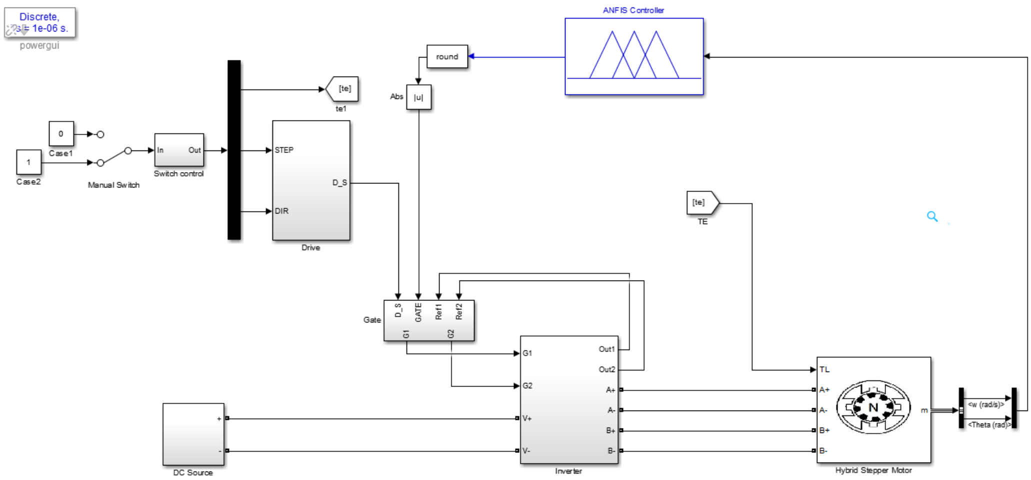


Fig. 3 The Simulink model of the proposed system

The ANFIS controller is self-tuning approach selects the optimum values in order to diminish the torque ripple. In the ANFIS controller, the proportional and integral gain value differs along a tuning curve that gives better speed response.

4.1. Performance Analysis of Proposed Technique

The projected method performance assessed and investigated with some cases and related to remaining methods such as ANN and Fuzzy controller. Primarily, the parameters are restrained from the PMSM and assessment the controlling parameters. Then the parameters are investigated with the help of two cases. There are,

Case 1: The dynamic response of torque

Case 2: The dynamic response of rotor angle

Then the cases are elucidated as follows,

Case1: The dynamic response of torque

In this case, the performance investigation is used the variation of torque that is demonstrated in figure 4. The input torque is assessed from the PMSM and the total sampling time is 2 seconds. Every 0.4 seconds the torque is varied within-10 to 10 Nm. Then the investigation is accomplished and restrained the parameters such voltage, current, torque and speed that is demonstrated in figure 5. The voltage amplitude is 50V and the current magnitude is 600, then the torque is measured and the speed is synchronized between -1 to 1e^5 (rad/sec). When the torque upsurges the speed is declines that is the speed and torque is inversely proportional

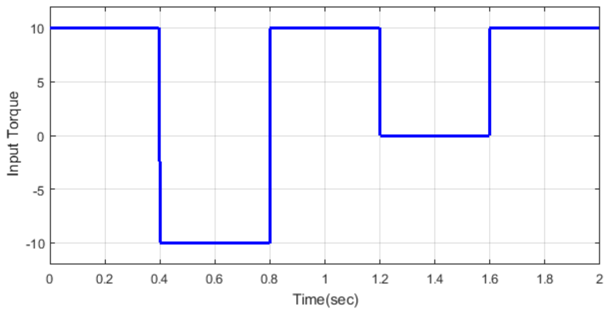
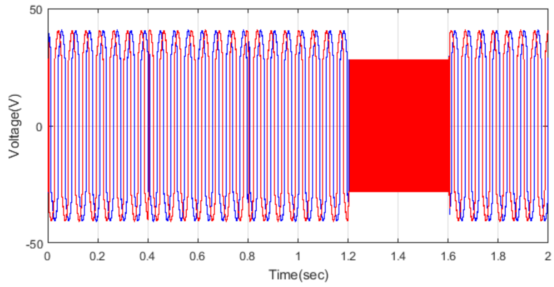
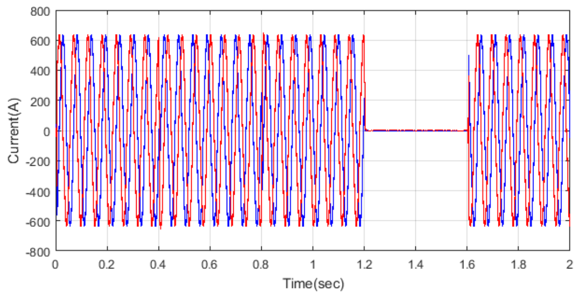


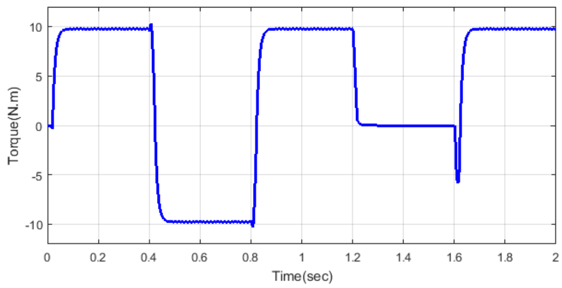
Fig.4 The assessed torque in case 1



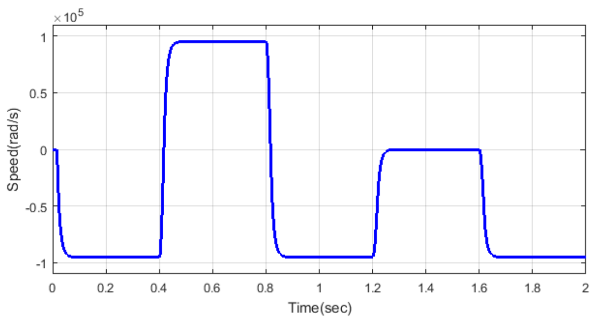
(a)



(b)



(c)



(d)

Fig.5 The measured parameters (a) voltage, (b) current, (c) torque and (d) speed in case 1

The torque of a motor is proportional to the current flowing through it. The angular velocity of a motor is proportional to the voltage across it. Henceforth, the parameters are restrained and assess their effectiveness. To assess the function of the projected method with the measured parameters are utilized to normalize the torque ripple of the PMSM. When the torque is augmented the speed is diminished and the torque diminished then the speed augmented. Then the rotor angle variation case is assessed in a following.

Case 2: The dynamic response of rotor angle

The outputs of the PMSM parameters are restrained and this case is investigation on basis of the variation of rotor angle. The assessed rotor angle is comes maximum 30 degree that is designated in figure 6. Afterwards that, the rotor angle is zero and continues constant then only the torque ripple is diminished and normalizes the speed of the PMSM. The assessed parameters like voltage, current, torque and speed are exemplified in figure 7. On the basis of the rotor angle the torque is varies and if the step is specified as 1 then only the PMSM runs the stable speed.

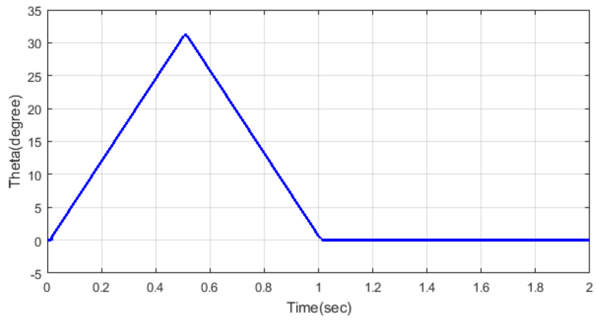
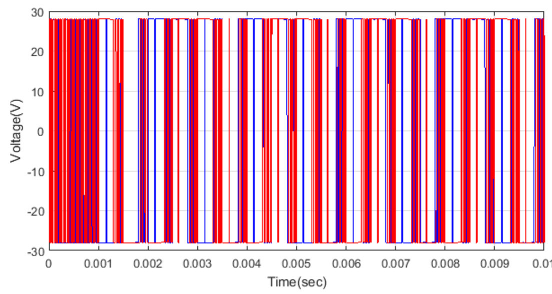
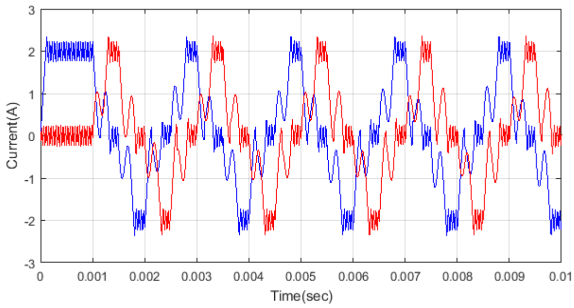


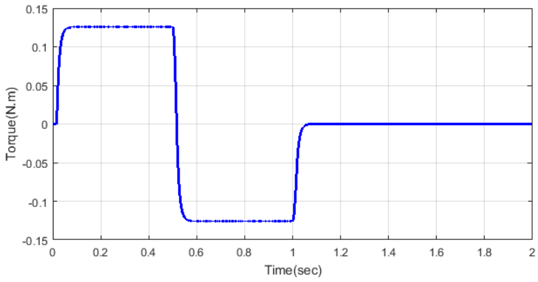
Fig.6 The measured rotor angle in case 2



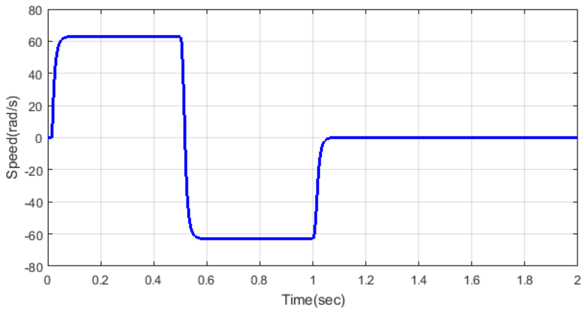
(i)



(ii)



(iii)



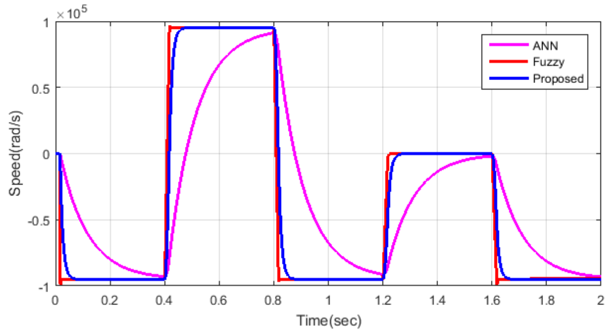
(iv)

Fig.7 The measured (i) voltage, (ii) current, (iii) torque and (iv) speed in case 2

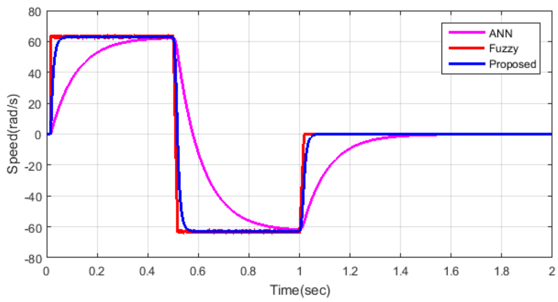
The two phase voltage and current is restrained as 0.01 sec and the conforming torque and speed is assessed as normal sampling time. On the basis of the investigation the wished-for method is amendable the speed and decreasing the torque ripple on the basis of the rotor angle. Lastly, to prove the efficiency of the projected method by associated the speed and torque parameters with other method such as ANN and Fuzzy. The comparison investigation is accomplished in a subsequent segment.

4.2. Comparison Analysis of Speed and Torque

In this comparison investigation, the torque and speed is assessed and related to the above implemented cases. The comparison examines of speed in both cases are demonstrated in figure 8 that displays the variation of speed with other methods. By the comparison investigates the sampling time taken as 2 seconds is investigated. The projected method is associates with the ANN and Fuzzy algorithms, the ANN algorithm is enchanting gradually speed variation and it taking 0.4 sec to reach stable speed and the fuzzy taking as less than 0.2 sec and it has some reverse saturation then it continues the reference speed. But the projected method is taking less than 0.2 sec and it is linearly stretched the reference speed. So the projected method is better than the other methods on the basis of the time taken to reach the stable speed.



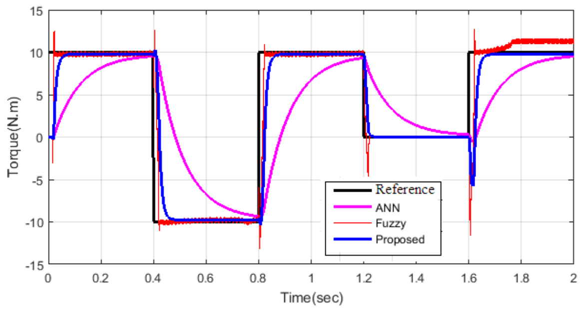
(i)



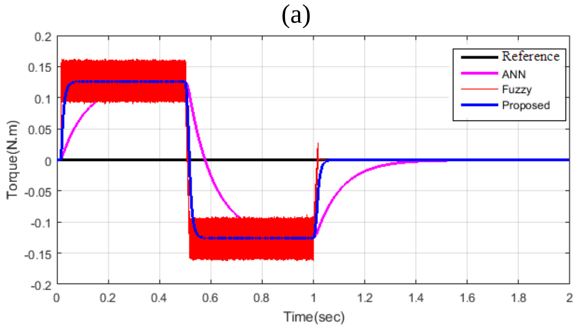
(ii)

Fig.8 The comparison analysis of speed in (i) case 1 and (ii) case 2

Then the torque comparison is labeled in figure 9 that related with the reference torque and the assessed available methods. On the basis of the reference torque the ANN is happening from zero and it is taking 0.4 sec to reach the reference torque. Then the fuzzy controller is taking less than 0.1 sec and it has some torque ripples are produced. Lastly, the projected method is reached the reference torque within 0.005 second and less the torque ripple. The torque ripple is appraised the peak value and the reference value of the torque and speed.



(a)



(b)

Fig.9 The comparison analysis of torque in (a) case 1 and (b) case 2

In this comparison investigation, the torque ripple is assessed on the basis of the ratio of peak to peak actual torque and rated torque of the PMSM. On the basis of the assessment the ANN is accomplished as greater than 15% and the fuzzy controller is as 11%. Lastly, the projected method almost 9% is diminished the ripple of the torque in the PMSM. From this assessment of the torque ripple minimization the projected method is better than the other conventional methods. Furthermore, the computation time is also designed and associated with the available methods. It is evidently illustrates that, the anticipated technique achieves better results when associated with the other methods.

5. Conclusion

Finally, an efficient method is utilized for decreasing the torque ripple in the PMSM. The effective method is used the ANFIS method that integrates both neural networks and fuzzy logic rules. It has potential to capture the benefits of both in a single outline. Its inference scheme parallels to a group of fuzzy IF–THEN principles that have learning capability to approximate nonlinear purposes. Henceforth, ANFIS is measured to be a universal estimator. Then the torque and rotor angle of the PMSM is restrained for controlling the torque ripple and modifiable the speed of the stepper motor. The torque and speed is delimited on the basis of the voltage and current parameters of the PMSM. The projected method is produced the control pulses on the basis of the error variation of the rotor angle and the torque and implemented to VSC. On the basis of the control pulse the VSC is implemented the voltage and current to the stepper motor. Lastly, the projected method is assessed with some dissimilar cases and related to some prevailing method such as neural networks and then fuzzy controller.

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