Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol. 10, No. 3, September 2022, pp. 549~558
ISSN: 2089-3272, DOI: 10.52549/ijeei.v10i3.3775

ANFIS based Direct Torque Control of PMSM Motor for Speed and Torque Regulation

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Article Info

Article history:

Received Mar 8, 2022
Revised Aug 5, 2022
Accepted Sep 6, 2022

Keyword:

Adaptive NeuroFuzzy Inference System
Direct Torque Control
Permanent Magnet Synchronous Motors
Speed
Torque ripple

ABSTRACT

Nowadays, the Permanent Magnet Synchronous Motors (PMSM) are gaining popularity among electric motors due to their high efficiency, high-speed operation, ruggedness, and small size. PMSM motors comprise a trapezoidal electromotive force which is also called synchronous motors. Direct Torque Control (DTC) has been extensively applied in speed regulation systems due to its better dynamic behavior. The controller manages the amplitude of torque and stator flux directly using the direct axis current. To manage the motor speed, the torque error, flux error, and projected location of flux linkage are employed to adjust the inverter switching sequence via Space Vector Pulse Width Modulation (SVPWM). One of the most common problems encountered in a PMSM motor is Torque ripple, which is recreated by power electronic commutation and a better controller reduces the ripples to increase the drive's performance. Conventional controllers such as PI, PID and SVPWM-DTC were compared with the proposed Adaptive Neuro-Fuzzy Inference System (ANFIS) in terms of performance measures such as speed and torque ripple. In this work, the Two-Gaussian membership function of the ANFIS controller is used in conjunction with a PMSM motor to reduce torque ripple up to 0.53 Nm and maintain the speed with a distortion error of 2.33 %.

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1. INTRODUCTION

For the past few years, PMSM has recently been selected as the driving machine of Electric Vehicles (EV) because of its maximum reliability, high torque intensity and compact volume. It can be assembled into two primary groups: Vector Control (VC) and DTC [1-2]. Although VC provides good dynamic and steady-state performance, the bandwidth constraint prevents it from being used in high-performance environments [3]. DTC has a high torque response speed, but it also has a significant torque ripple [4]. Many control strategies have been created to address the inadequacies of traditional control approaches. The complicated working environment of electric vehicles exhibits substantial difficulties in the development of control mechanisms. The DTC provides advantages based on the switching voltage table, such as a simple structure and quick torque responses [5]. The following key issues arise as a result of this control strategy: torque ripple, unregulated moving regularity, and susceptibility to resistance fluctuation. Artificial intelligence can help tackle these issues and improve induction machine DTC [6].

Torque is still the most significant control target in an electric vehicle's control system. Many academics have been interested in Model Predictive Torque Control (MPTC) with its rapid torque response and unrestricted synthesis of numerous restrictions [7]. MPTC can predict the machine's behavior in the future and choose the best voltage smear to drive based on the designed cost function [8]. The ideal voltage vector chosen by minimizing the cost function is more precise and efficient than DTC. Other limitations can also be incorporated into the cost function to enhance the system's control performance [9]. MPTC offers a faster torque response than VC and is, therefore, better suited to applications demanding high torque response. However, MPTC suffers from significant torque ripple and a variable switching frequency [10]. To address this issue, the Duty Cycle Control (DCC) concept of DTC control is applied which significantly reduces torque ripple [11]. The correctness of the model parameters determines the machine behaviors anticipated by the model at the next extreme. Soft computational approaches for intelligent control, including neural networks, neuro-fuzzy and fuzzy logic are well-known and have been used by many researchers in the driving field [12]. This paper [13] establishes a hybrid intelligent controller, which reduces the torque, ripples and improves performance. However, numerous application has to focus not only on the driving field but also on the maturation of the underlying technology. Till now, so many control approaches were introduced, but, none of these approaches were successful in producing a perfect ripple-free speed and torque [14, 15].

For PMSMs drives with distorted time impedances, an improved cascaded DTC method [16] was industrialized. A huge resonant gain resulted in a fast dynamic response but at the cost of a significant overshoot inaccuracy. To eliminate the massive torque ripples of conventional DTC, a new Predictive Torque Control (PTC) method [17] established on the predetermined mechanism for PMSM was industrialized. The TDTC has enormous flux and torque ripples. For the PMSM drive system, a unique duty ratio modulated direct torque control (DDTC) [18] was presented. The variation rate of d-axis current has no bearing on the torque modifications, whereas the q-axis current variation is proportionate to torque difference. For asymmetric three-phase PMSM, a modified parallel DTC-SVM method [19] has been proposed, although this will raise the danger of system instability. In PMSM, a novel hybrid DTC method [20] was presented, but it produces high current harmonics and flux ripples in all the conditions. To improve the dynamics of torque and flux, a hybrid control technique [21] for PMSM was established, but the switching loss was high. The Space Vector Pulse Width Modulation based DTC (SVPWM-DTC) [22] was suggested for PMSM; due to the bandwidth constraint, it causes a huge torque ripple in the motor. A novel Dual Cost Function Model Predictive Direct Speed Control (DCFMPDSC) [23] was presented with duty ratio optimization for PMSM drives. Even though several equations are involved, only one voltage vector is applied throughout the control period, resulting in a huge torque ripple.

2. PROPOSED METHOD

2.1. Direct Torque Control of PMSM motor

The basic operating principle of the DTC is to select a vector difference between the measured torque, expected torque and flux measurements. DTC can establish the mechanical positioning of the rotors without the use of an external sensor. Low-speed torque control is challenging because there is a huge amount of noise present in torque and switching frequency. The DTC may be able to control speed without the usage of mechanical sensors. Traditional DTC control consists of various features such as better torque control, modularity, and a powertrain that does not need a controller. As a result, the drive system is significantly influenced by the DTC control. The major goal of this research is to improve the PMSM drive's performance by developing a direct torque scheme that allows for even more speed control tracking and seamless torque response.

DTC is a control method for directly and independently controlling the torque of variable frequency drives. The torque and magnetic flux of motors are approximated using this method, which uses observed voltage and current. The error signals are created by comparing the estimated flux and torque to the reference values. To maintain the torque and flux within hysteresis limitations, the error signals are employed to operate the six switch inverter. Figure 1 represents the general illustration of the DTC of PMSM using an ANFIS controller.

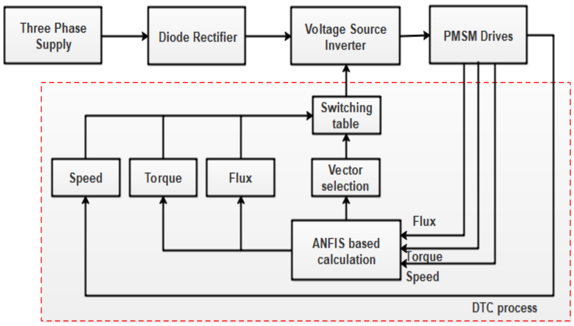


Figure 1. DTC for PMSM drive

The stator impedances and self-inductance of all primary winding are assumed to be equal in the modeling of the PMSM motor. The stator phase voltage equation of a PMSM motor is identical to the armature formula of DC machines, which can be written in matrix form as shown in equation (1).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix}\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (1)$$

Where $V_{a,}V_b\ and\ V_c$ represents the stator phase voltages, E_a, E_b and E_c are the trapezoidal back emf, i_a, i_b and i_c are the motor input current and R_a, R_b and R_c represents the terminal resistances. The L and M represent the self and mutual inductances respectively. The electromagnetic torque, T_e of the PMSM motor can be estimated by equation (2).

$$T_e = \frac{\mathrm{P}}{w_m} \quad (2)$$

Where,

Power, $\mathrm{P} = E_a i_a + E_b i_b + E_c i_c$

ω_m = rotor speed

The electromagnetic torque of the PMSM motor in the synchronously rotating frames can be estimated as equation 3.

$$T_e = \frac{3}{2}\frac{p}{2}\left[\left(\frac{dL_d}{d\theta_e} i_{sd} + \frac{d\varphi_{rd}}{d\theta_e} - \varphi_{sq}\right) i_{sd} + \left(\frac{dL_q}{d\theta_e} i_{sq} + \frac{d\varphi_{rq}}{d\theta_e} - \varphi_{sd}\right) i_{sq}\right] \quad (3)$$

Where,

$$\varphi_{sq} = L_q i_{sq} + \varphi_{rq}$$

$$\varphi_{sd} = L_d i_{sd} + \varphi_{rd}$$

and p is the number of poles, i_{sd}, i_{sq}, L_d and L_q represents the d and q axes currents and inductances respectively, Θ_e represents electric angle, θ_r represent the rotor angle and φ_{rd}, φ_{rq}, φ_{sd} and φ_{sq} are the rotor and stator flux linkages in the d and q axes respectively. This electromagnetic torque equation can be simplified by converting it into a stationary $\alpha\beta$ frame, which is written as Eqn. 4

$$T_e = \frac{3}{2}\frac{p}{2}\left[\frac{d\varphi_{r\alpha}}{d\theta_e} i_{s\alpha} + \frac{d\varphi_{r\beta}}{d\theta_e} i_{s\beta}\right] \quad (4)$$

Where $\varphi_{r\alpha}$ and $\varphi_{r\beta}$ are the α and β axes rotor flux linkages. The stator flux linkages are estimated from the measured stationary α-β reference frame stator current and voltage. The stator flux linkage and its vector position are given as in equations (5, 6 and 7).

$$\varphi_{s\alpha} = V_{s\alpha} t - R_s \int i_{s\alpha} dt + \varphi_{s\alpha}(0) \quad (5)$$

$$\varphi_{s\beta} = V_{s\beta} t - R_s \int i_{s\beta} dt + \varphi_{s\beta}(0) \quad (6)$$

$$\theta_s = \tan^{-1}\frac{\varphi_{s\beta}}{\varphi_{s\alpha}} \quad (7)$$

Where $\varphi_{s\alpha}(0)$ and $\varphi_{s\beta}(0)$ are the initial stator flux linkage values, which is given as equation (8)

$$\varphi_{s\alpha}(0) = 0$$

$$\varphi_{s\beta}(0) = \frac{2K_b\pi}{3\sqrt{3}} \quad (8)$$

Where K_b is the back emf constant, from the above equation (8), flux, torque and sector angle can be estimated.

Table 1. Switching Table for DTC control

Flux	Torque	Sector					
		1	2	3	4	5	6
1	1	V2	V3	V4	V5	V6	V1
	0	V0	V7	V0	V7	V0	V7
	-1	V6	V1	V2	V3	V4	V5
0	1	V3	V4	V5	V6	V1	V2
	0	V7	V0	V7	V0	V7	V0
	-1	V5	V6	V1	V2	V3	V4

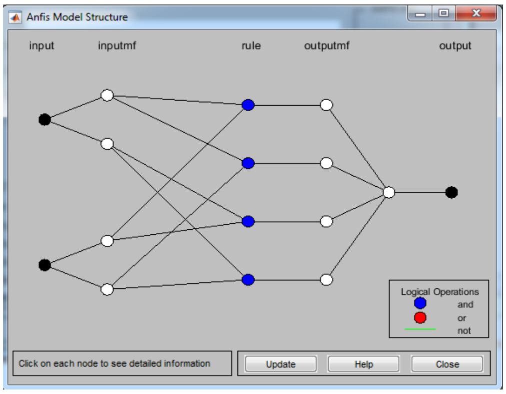
The calculated flux and torque are associated with the sample standards, and an error signal is generated. The voltage course is selected and inverter switching is controlled based on the errors and sector angle. Table 1 shows the DTC switching table of a PMSM motor, where binary 1 and 0 indicate the ON and OFF states, respectively.

2.2. PID controller based Speed regulator

Hand tuning, Ziegler Nichols tuning, loop exchange, analytical approaches, optimization, pole positioning, and auto-tuning are all options for tuning PID controllers. The mathematical model was used for the variable structure controller. The controller in this study was tuned using MATLAB's automatic tuning tool. The PID controller was fine-tuned to achieve a steady-state inaccuracy of less than 1% and a rise time of less than one second. The PID controller must have a strong proportional gain and a significant integral gain to provide a large control signal. The control action must gradually go to a stable equilibrium as the system error decreases. A PID controller was used to implement closed-loop speed control. A proportional plus integral and differential (PID) controller is a common method for speed control in industrial drives. PID controller is a traditional controller is built for PMSM motor drive to evaluate the drive's response. PID controller tuning is adjusting the proportional and integral values to achieve the best possible control for a given operation. The rising time will be reduced by proportional controller gains (Kp), but it failed to eliminate the steady-state error. Although an integral control gain (Ki) will eliminate the steady-state error, it may exacerbate the sudden response. The controller receives the error signal and performs proportional and integral computations on it. The total of the comparative gain and error along with the amalgamation of integral gain and error is referred to as the output of the controller. There are certain disadvantages to using a PID controller. 1) It necessitates manual parameter estimation for different speeds. 2) The PID controller's speed response has a dip in speed just after step time. The use of a fuzzy logic speed controller can help to overcome these problems. It certainly makes the control loop simple because it allows autonomous speed control more than a range and does not require calculations for various speeds.

2.3. ANFIS Controller

ANFIS is a method that uses a combination of ANN and Fuzzy logic. To optimize the response in fuzzy systems, the rule base and membership functions must be manually created. As a result, calibrating a fuzzy logic system is a time-consuming process, so it cannot produce the desired results. The fuzzy logic is used to generate the basic ANFIS structure, which is then developed by the neural network. The ANFIS structure is used for all processes such as fuzzification, defuzzification, and rule base evaluation. ANFIS provides a straightforward model for designing a fuzzy inference system using a neural network. The Sugeno paradigm of ANFIS is employed in this paper, along with four rules. The ANFIS-based speed regulator has two variable inputs: speed error and change in error. The torque reference is the system's output, which is fed into the DTC.



Click on each node to see detailed information

Figure 2. Structure of ANFIS

Using ANFIS, the torque reference is constructed each time from the speed error (N*-N) and changes in speed error. The network has 20 nodes and has been trained for 12 epochs. The tuning of ANFIS is done using the grid partitioning method. In the system, the learned model replaces the PID controller. The equations of the speed error (N*-N) and the variation in speed error are auto-tuned, resulting in an excellent performance. The I/O data sets of the given system are the data set necessary for ANFIS learning training. The ANFIS controller's architecture can be summarized as follows:

i) Significant of fuzzy inference systems;
ii) Analyzing overall count of training data set;
iii) Describing data pairs count;
iv) Describing iteration count;
v) Learning from the output.

Figure 2 depicts the ANFIS architecture. Apart from the neural network block, it is the same as the fuzzy inference system. The ANFIS structure is divided into five layers, which is described as follows:
1st layer: It's the input layer, and it's made up of input variables. Every node in this layer analyses triangular/Gaussian/Two-Gaussian membership functions, and input variables are sent to the next layer.
Layer 2: This layer is identified as the membership function (MF) layer, and it allows you to check loads of every MF. It takes the input variables from the input layer and calculates the MFs for the fuzzy groups of the corresponding input parameters. It also calculates membership values to regulate the amount of applicable input value that is passed on to the next layer to determine that layer's input.
Layer 3: In this layer, each neuron fulfills the necessary conditions of fuzzy rules. The network structure is equal to the fuzzy procedures count, and each node of these layers estimates the normalized weights. It's acknowledged using the rule layer.
Layer 4: Also recognized using defuzzification layer; it creates output values based on the application of rules. The fuzzy singletons that characterize an additional set of conditions for the neuro-fuzzy network are used to weight links between layers 3 and 4.
Layer 5: It collects all of the defuzzification layer's deliverables and turns the fuzzy sets to a crisp value and this layer is known as the output layer.

3. SIMULATION RESULTS AND DISCUSSIONS

This paper discusses the speed management of a PMSM motor drive that is controlled using the DTC technique. Torque is calculated in the rotating dq - reference frame in this approach. Based on the simulation results, this method can be employed for high-performance applications. Modifications in the load can also help to improve dynamic performance. Because the drivetrain is sensitive to resistance changes, parameter adaptation can be used to boost performance even more. MATLAB simulation tools are used to execute the DTC of PMSM motor. The speed regulator serves as both a PID controller and an ANFIS. Speed, current, and flux graphs are used to assess the ability. Figure 3 shows MATLAB/Simulink model of DTC control of a PMSM motor using ANFIS. The sample rate is set to 50 seconds. The hysteresis bands are tuned at 1.8 N.m and 0.088 Wb, individually. The reference speed and speed of PMSM is compared and resultant speed is given to DTC controller. Stator currents, stator back emf, rotor speed and electromagnetic torque are measured at the output of PMSM drive.

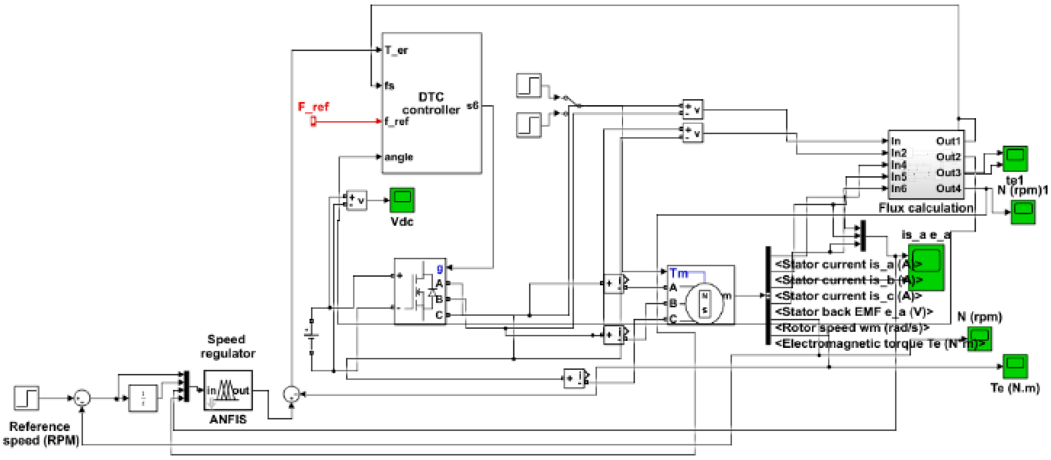


Figure 3. DTC control of PMSM motor with ANFIS controller

The speed of the motor is used as feedback, and the speed inaccuracy is calculated by comparing it to the reference speed. The ANFIS controller is given the anticipated speed error, variation as well as reference value of 4000. The ANFIS controller calculates the torque reference, which is related to the definite electromagnetic torque of the PMSM motor. The flux and torque are utilized to control the inverter's switching pattern. The induced load torque is 0.2Nm, and the load torque is sustained for one second. The PMSM motor's specifications are listed in Table 2.

Table 2. Specification of PMSM motor

PARAMETERS	VALUES
Weighting factor	1
Viscous friction	0.0017 kgm/s^2
Stator Resistance	0.636 ohm
Rated current	11.36A
Rated speed	4000 rpm
Rated torque	1.8 Nm
q-axis inductance	0.02H
PM motor Flux	0.088Wb
Number of Pole Pairs	2
Moment of inertia	0.0017 kgm^2
d-axis inductance	0.012H

The speed regulation for PID controller is shown in figure 4, which has magnitude of 4000rpm and Fures 5 and 6 shows torque and EMF & stator current waveform of PMSM respecgively.

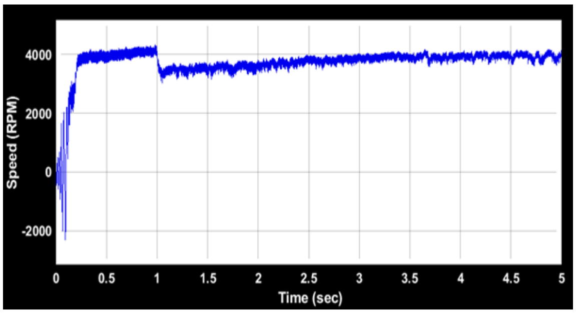


Figure 4. Speed Regulation for PID controller

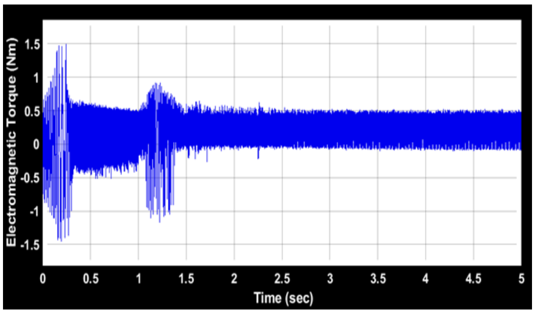


Figure 5. Electromagnetic Torque for PID control

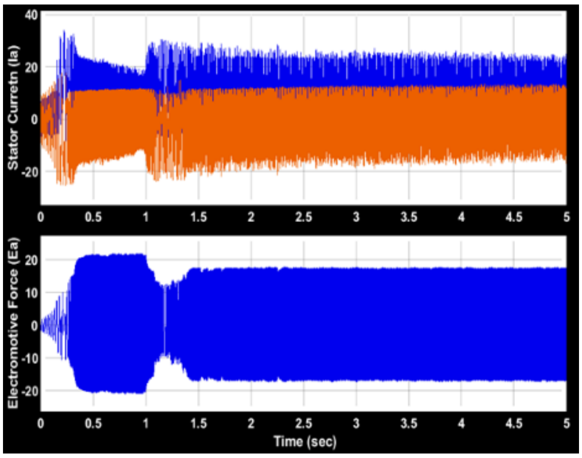


Figure 6. EMF and Current waveforms for PID controller

The PMSM motor's DTC is critical in many applications. PI, PID is used to regulate the PMSM motor using DTC. When compared to the PID controller, the results reveal that ANFIS produces better outcomes. It also has the potential to improve the system's stability. The rules are applied to all three controllers, and the PI and PID controllers achieve a steady-state in 3.5 and 2.5 seconds, respectively. The proposed ANFIS achieved a stable state at 2.1 seconds which is better than existing PI and PID controllers. Figures 7, 8 and 9 show the speed, EMF and torque results of the ANFIS controller.

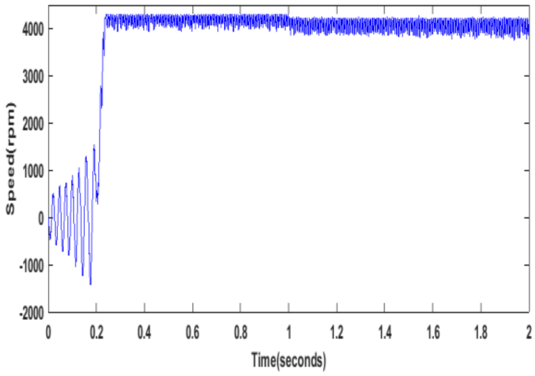


Figure 7. Speed Regulation for ANFIS controller

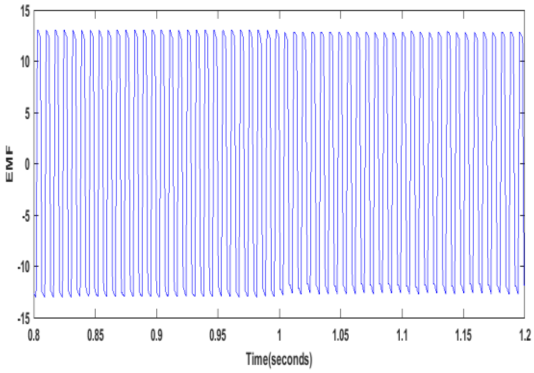


Figure 8. EMF waveform for ANFIS controller

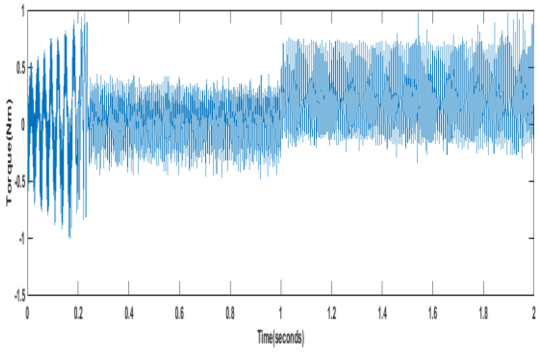


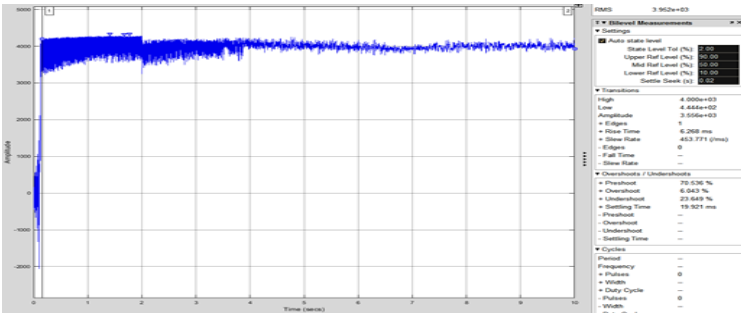
Figure 9. Electromagnetic torque for ANFIS controller

The results of the steady state comparison are exposed in Table 3. From this table it is clear that proposed ANFIS controller is better steady state response compared to PI and PID controllers.

Table 3. Comparison for Steady State Performance of PMSM motor

Parameters	PI Controller	PID controller	Proposed ANFIS controller
Steady State Comparison	3.5 sec	2.5 sec	2.1 sec

Figure 10 and 11 shows the transient performance of Speed and Torque using the ANFIS controller. The controller factors are calculated individually in this paper, which leads to changes in the hardware component assembly. The controller parameters for traditional and modified PID are not varied in this paper. As a result, the hardware components can be combined to analyze the transient response properties about the same set of controller parameters.



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RMS                    3.952e+03
Bilevel Measurements
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     Upper Ref Level (%):  90.00
       Mid Ref Level (%):  50.00
     Lower Ref Level (%):  10.00
         Settle Seek (s):  0.02
▼ Transitions
High                   4.000e+03
Low                    4.444e+02
Amplitude              3.556e+03
+ Edges                1
+ Rise Time            6.268 ms
+ Slew Rate            453.771 (/ms)
- Edges                0
- Fall Time            --
- Slew Rate            --
▼ Overshoots / Undershoots
+ Preshoot             70.536 %
+ Overshoot            6.043 %
+ Undershoot           23.649 %
+ Settling Time        19.921 ms
- Preshoot             --
- Overshoot            --
- Undershoot           --
- Settling Time        --
▼ Cycles
Period                 --
Frequency              --
+ Pulses               0
+ Width                --
+ Duty Cycle           --
- Pulses               0
- Width                --
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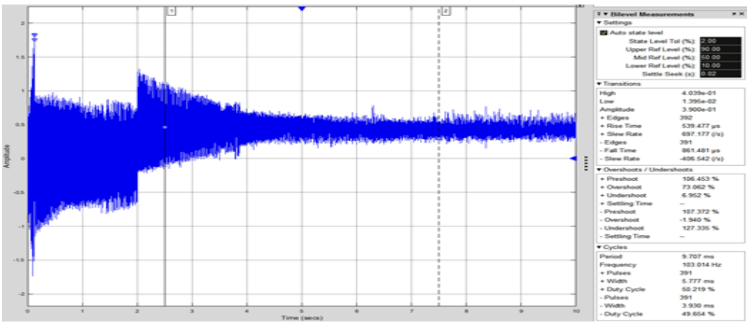
Figure 10. Transient response of Speed for ANFIS controller



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Bilevel Measurements
▼ Settings
☑ Auto state level
     State Level Tol (%):  2.00
     Upper Ref Level (%):  90.00
       Mid Ref Level (%):  50.00
     Lower Ref Level (%):  10.00
         Settle Seek (s):  0.02
▼ Transitions
High                   4.039e-01
Low                    1.395e-02
Amplitude              3.900e-01
+ Edges                392
+ Rise Time            539.477 μs
+ Slew Rate            697.177 (/s)
- Edges                391
- Fall Time            861.481 μs
- Slew Rate            -406.542 (/s)
▼ Overshoots / Undershoots
+ Preshoot             106.453 %
+ Overshoot            73.062 %
+ Undershoot           6.952 %
+ Settling Time        --
- Preshoot             107.372 %
- Overshoot            -1.940 %
- Undershoot           127.335 %
- Settling Time        --
▼ Cycles
Period                 9.707 ms
Frequency              103.014 Hz
+ Pulses               391
+ Width                5.777 ms
+ Duty Cycle           50.219 %
- Pulses               391
- Width                3.930 ms
- Duty Cycle           49.654 %
```

Figure 11. Transient response of Torque for ANFIS controller

Table 4 shows the comparative analysis of transient responses with existing controllers. Even if conventional PI and PID have better results in the rise and settling times, the overshoot is much more noticeable which destroys the other transitory performance criteria.

Table 4. Comparison for transient response of PMSM motor

Constraints	PI Controller	PID controller	Proposed ANFIS controller
Settling Time (sec)	0.41	0.341	0.19
Rising time (sec)	0.251	0.105	0.053
Overshoot time (%)	8.166	7.888	6.043

Table 4 clearly illustrates that the recommended ANFIS outperforms the conventional controllers in terms of settling time, rising time and overshoot time. Based on several control system metrics such as steady state error, rising time, peak overshoot, and settling time, the two controllers' performance is compared. In most respects, the control approach with the suggested ANFIS controller outperforms the standard PID controller. Table 5 shows the comparison of torque ripple.

Table 5. Comparison for Torque Ripple

Parameters	Existing PI Controller	SVPWM-DTC Controller [22]	Proposed ANFIS controller
Torque Ripple (Nm)	0.91	0.6	0.53

Table 5 shows that the proposed ANFIS achieves less torque ripple of 0.53 Nm which is much better than the existing SVPWM-DTC [22]. The introduction of flux linkage oscillations is achieved through voltage harmonics. The number of pole pairs in a mechanical motor with a speed of 2000 rpm is 3, and 12th harmonics frequency is 1.2 kHz. The proposed ANFIS achieves 0.53 Nm less torque ripple, which is better than the current SVPWM-DTC [22]. Figure 12 shows the FFT analysis of the PMSM motor. It gives lower THD as compared to DCF-MPDS, which is taken as base paper. Where Table 6 shows the comparative analysis of Total Harmonic Distortion.

Table 6. Comparison for THD

Parameters	DCF-MPDS Controller [23]	Proposed ANFIS controller
Total Harmonic Distortion	4.43 %	2.33 %

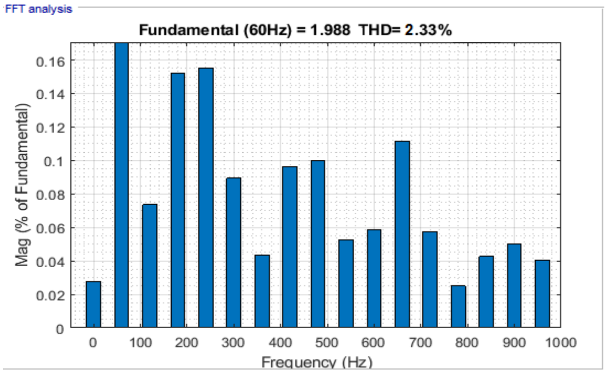

Figure 12. FFT Analysis

Figure 12, clearly shows that the proposed ANFIS achieves a better THD of 2.33 % which is less when compared with existing DCF-MFDS [23] which accomplishes 4.43% only. As THD decreases quality of output waveform increases. Hence ANFIS produces quality output voltage.

4. CONCLUSION

The torque is fully controlled while the stator flux amplitude is regulated indirectly by direct axis current in a DTC control of the PMSM motor. The ANFIS speed controller is used to achieve closed loop operation. By exchanging the speed regulator with a conventional PID and ANFIS controller, the DTC control of a PMSM motor with its dynamic qualities has been improved. The PID controllers are manually tweaked to produce results with a time delay. In the conventional PID controller, it takes an extended time to reach a stable state and the time delay is minimized by the proposed ANFIS controller. The ANFIS controller is used to manage the direct torque of a brushless DC motor. A MATLAB/Simulink simulation is used to enhance the feasibility of DTC using the ANFIS technique. The results reveal that the proposed approach provides less torque ripple of 0.53 Nm and provides less THD of 2.33% which improves system performance when compared with DCF-MPDS Controller. ANFIS controller is simple to create and install because the equation and rule libraries are self-tuned. In the future, this research work can be extended with different optimization techniques or hybrid intelligent techniques.

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