Adaptive Neuro-Fuzzy Inference System (ANFIS) Based Direct Torque Control of PMSM Driven Centrifugal Pump

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Abstract- This article presents the Adaptive Neuro-Fuzzy Inference System based Direct Torque Control (ANFIS-DTC) for permanent magnet synchronous motor coupled with centrifugal pump. Direct Torque Control (DTC) is an inherent closed loop control with very less complexity, dynamic torque and speed response in comparison with the other vector control techniques. In the variable torque applications like pumps when speed of motor varies, the torque developed by the pump also varies correspondingly. To reduce the ripples in torque and to improve the response of the control algorithm, Adaptive Neuro-Fuzzy Inference System (ANFIS) is implemented along with DTC. In contrast with the conventional DTC and the Fuzzy logic based DTC, the proposed ANFIS based DTC has significantly reduced ripples in flux, torque and stator current. The results of the proposed ANFIS-DTC are validated through the Matlab simulations and the performance of the system is found satisfactory when it is tested with different rotational speeds.

Keywords Adaptive Neuro-Fuzzy Inference System (ANFIS), Centrifugal pump, Direct Torque Control (DTC), Permanent Magnet Synchronous Motor (PMSM), and Variable Frequency Drives (VFD).

1. Introduction

The centrifugal pumps have been used for several decades for various applications such as lifting water from low level to high level, water passage, irrigation and industrials. In olden days they were accomplished with constant speed induction motors and the flow rate / pressure is regulated through throttling valve that results in significant energy loss [1]. But after the improvements in power electronics nowadays, variable speed drives (VSD's), are preferred to control flow rate and pressure in a pumping system for higher energy savings [2].

Direct Torque Control (DTC) procedure was initially implemented for the control of induction motor in 1984, that exhibits better torque and flux response for medium power drives [1, 3]. In later 1990's DTC had been preferred for PMSM drive that emerged as the mostly used motor control strategy by overtaking its counterpart FOC, because of its excellent control performance [4, 5]. Conventional DTC uses a pair of hysteresis controllers; because of this, it suffers from heavy torque ripple and variable switching frequency [6]. Hence, DTC is implemented along with the intelligent control techniques to reduce the flux and torque ripples [7].

In this paper DTC along with Neuro- fuzzy control has been employed for better performance and reduced flux and torque ripples. The results have been compared with traditional DTC and DTC with Fuzzy logic control strategies. The hysteresis torque limits and the flux reference for the proposed control strategy is developed using the ANFIS control. Permanent magnet synchronous motor (PMSM) is preferred because of its better efficiency, high torque to volume ratio, better overloading capability, and excellent heat dissipation capability over asynchronous motor [8, 9]. The fundamental arrangement of the proposed scheme is shown in Fig.1.

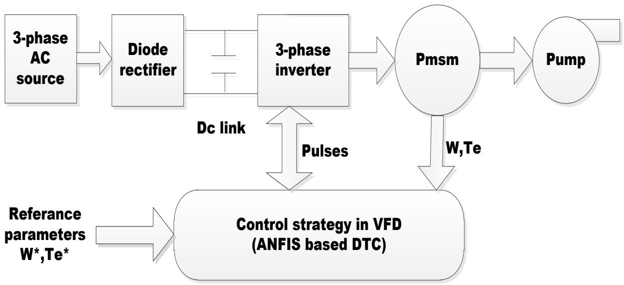


Fig. 1. Basic block diagram of the proposed system

This paper is arranged in following segments. Section 2 contains the modelling of PMSM; and section 3 represents centrifugal pump modelling. Section 4 explains the control strategy i.e. traditional DTC and DTC-ANFIS. In section 5 the simulation modelling and the results at different frequencies are illustrated. Comparison of the control techniques is made in section 6, and the section 7 ends with concluding the article.

2. Permanent Magnet Synchronous Motor

The Permanent Magnet Synchronous motors (PMSM) are generally preferred over the induction motors when efficiency of the drive is considered as the major priority for the application [10]. The modeling of PMSM is described in this section and Fig.2 illustrates the d-q reference frame modelling of PMSM.

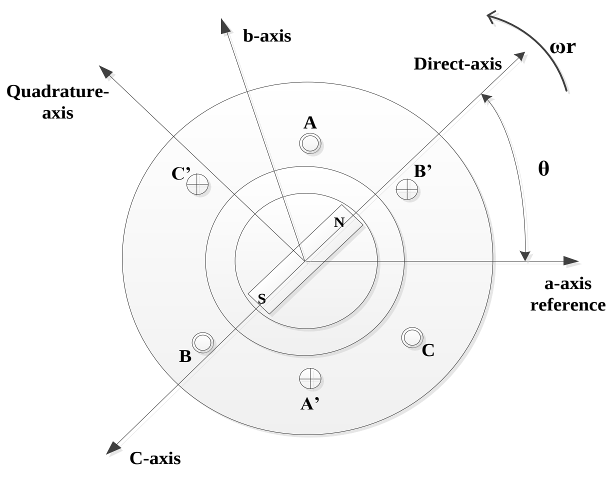


Fig. 2. PMSM in d-q axes reference frame

The output torque and power equations of PMSM drive is written as shown in Eq. (1) and Eq. (2).

$$P_{out} = \frac{3}{2}\omega_e(\lambda_{pm}I_q + (L_d - L_q)I_d I_q) \tag{1}$$

Where, $\omega_e = \frac{p}{2}\omega_m$

$$P_{out} = \frac{3}{2}\frac{p}{2}\omega_m(\lambda_{pm}I_q + (L_d - L_q)I_d I_q) \tag{2}$$

With the above equations the output torque of PMSM drive can be evaluated as illustrated in Eq. (3) and Eq. (4).,

$$T_e = \frac{P_{out}}{\omega_m} = \frac{3}{2}\frac{p}{2}(\lambda_{pm}I_q + (L_d - L_q)I_d I_q) \tag{3}$$

$$T_e = \frac{3}{2}\frac{p}{2}(\varphi_d I_q - \varphi_q I_d) \tag{4}$$

Where, $\varphi_d = L_d I_d + \lambda_{pm}$ and $\varphi_q = L_q I_q$

3. Centrifugal Pump

The centrifugal pumps are sub-class of kinetic / dynamic pumps. Centrifugal pumps are used to transport fluids by the converting rotational kinetic energy into pressure energy of the fluid [2, 11]. The centrifugal pump works on the principle of centrifugal force. More than 75% pumps installed for pumping water in industry are centrifugal pumps. Number of pump stages in centrifugal pump is determined by the number of impellers. The vertical cross sectional view of a single stage centrifugal pump showing, inlet, impeller, vane, volute, flange and outlet are shown in the Fig.3.

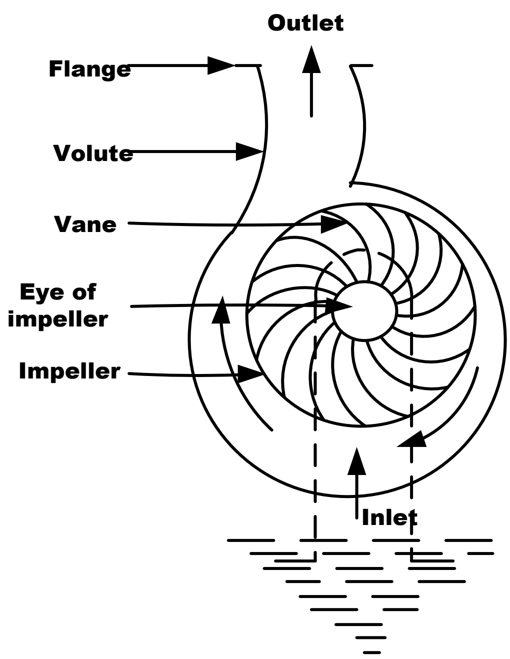


Fig. 3. Cross sectional view of centrifugal pump.

3.1. Design parameters of Pump

Some important terminologies related to pump efficiency calculation are described in this section. Hydraulic power (P_h) represents the energy imparted on the fluid being pumped to increase its velocity and pressure. Eq. (5) shows the hydraulic power that depends on the developed pressure discharge and flow rate. Shaft power (P_S) is the power supplied by the motor to the pump setup. It is typically calculated as the product of the torque and the angular velocity as given by Eq. (6). Centrifugal pump efficiency (η_P) is typically calculated as the ratio of hydraulic power of the pump to the shaft power as shown in Eq. (7). The final expression of pump efficiency is calculated as shown in Eq. (8).

$$P_h = \frac{\rho g H Q}{1000} , \quad (5)$$

$$P_s = \frac{T\omega}{1000} , \quad (6)$$

$$\eta_p = \frac{P_h}{P_s} \quad (7)$$

$$\eta_p = \frac{\rho g H Q}{T\omega} \quad (8)$$

4. Direct Torque Control

The Direct torque Control (DTC) is a inherent closed loop control method for controlling the electric drive applications. The two DTC control topologies with PMSM driven centrifugal pump is given below in detail.

4.1. DTC-Traditional

It is a closed loop control technique that is most widely preferred in recent days for inverter control of induction motor as well as PMSM. Unlike other control schemes, DTC does not require any type of coordinate transformation from one reference frame to other that results no parameter variation. The additional advantages of the DTC scheme are absence of feedback current control loop so no inherent delay in current control actions; absence of PID and PWM controllers; no sensor required for speed or position, which makes DTC as a sensor-less control [12]. Online flux and torque estimator makes the control closed loop. Hysteresis comparators are used to control flux and torque directly. The DTC controller contains torque and flux estimator block, a couple of hysteresis controllers for torque and flux control, voltage vector selection block, and pulse generating block for inverter switches. The basic Block diagram of conventional DTC is shown in Fig.4.

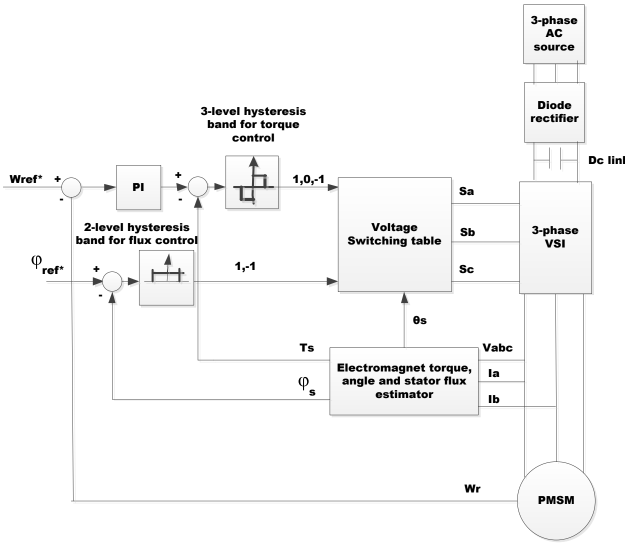


Fig. 4. Basic block diagram of DTC-traditional control

The voltage vector selection for different combination of flux and torque is provided in Table 1.

Table 1. Switching table for voltage vector selection

Flux selector $\Delta\varphi_s$	Torque selector ΔT_e	Voltage selectors					
		S1	S2	S3	S4	S5	S6
+1	+1	v_2	v_3	v_4	v_5	v_6	v_1
	0	v_7	v_0	v_7	v_0	v_7	v_0
	-1	v_6	v_1	v_2	v_3	v_4	v_5
-1	+1	v_3	v_4	v_5	v_6	v_1	v_2
	0	v_0	v_7	v_0	v_7	v_0	v_7
	-1	v_5	v_6	v_1	v_2	v_3	v_4

4.2. ANFIS based DTC

An Adaptive Neuro-Fuzzy inference system is a fuzzy scheme that employs a learning procedure resulting from artificial neural network (ANN) principle to find out its parameters (fuzzy sets and rules) by dealing with data examples. By mixing both neuro network (NN) and fuzzy logic control (FLC), it is possible to achieve advantages of both the controls in single implementation [13, 14].

ANFIS uses two types of learning algorithm, hybrid learning algorithm and back-propagation learning algorithm. It uses Takagi Sugeno-TS type of membership models. ANFIS process involves,

➢ Loading the data (in row and column form) either directly from Matlab workspace or already generated fuzzy ".fis" file.

- ➢ With this loaded data ANFIS toolbox will generate the corresponding “.fis” file.
- ➢ In this step the generated “.fis” file or loaded data will be trained.
- ➢ Now the trained data is embedded to the fuzzy block and run the simulation.

The ANFIS based DTC block diagram is given by Fig. 5 and the graphic user interface (GUI) for ANFIS in Matlab is given in Fig.6.

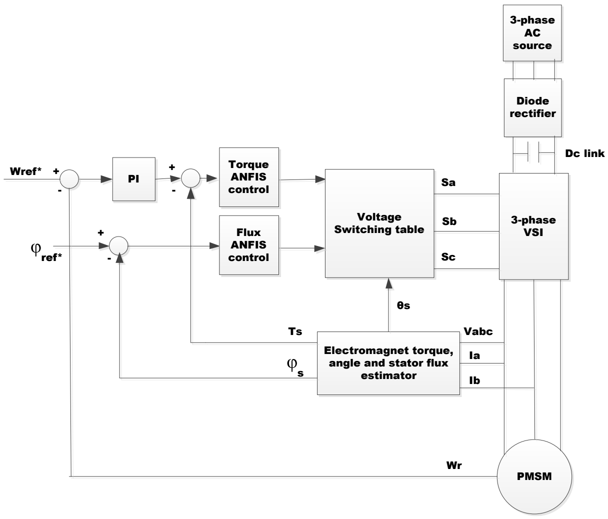


Fig. 5. Block diagram of ANFIS control.

A basic neural structure with two inputs, five intermediate layers and a output is shown in Fig.6. The weights of the each neuron are represented as ‘w’.

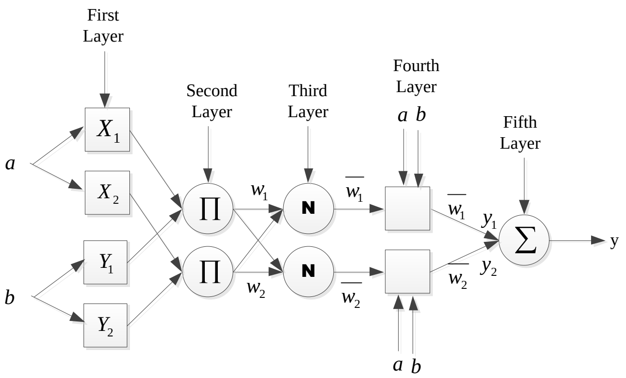


Fig. 6. ANFIS model with 2 inputs (a and b) and 1 output(y)

5. Simulation and Results

The complete model is simulated in the MATLAB Simulink environment as shown in Fig.7, with the source, VFD (Rectifier, DC Link, and Inverter), PMSM, centrifugal pump and the control technique.

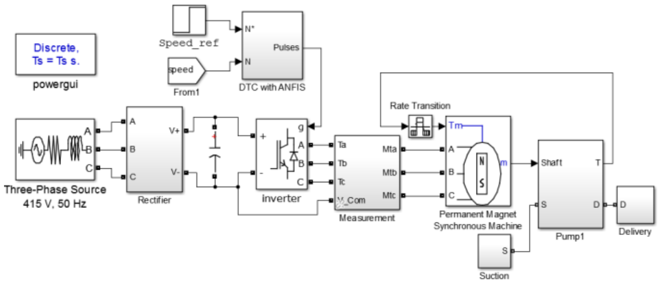


Fig. 7. Proposed simulation model.

The conventional speed controller with PI controller is used as shown in Fig.8 with the proportional gain value of 5, and the integral constant of 10.

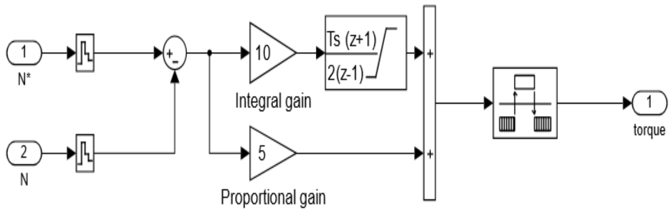
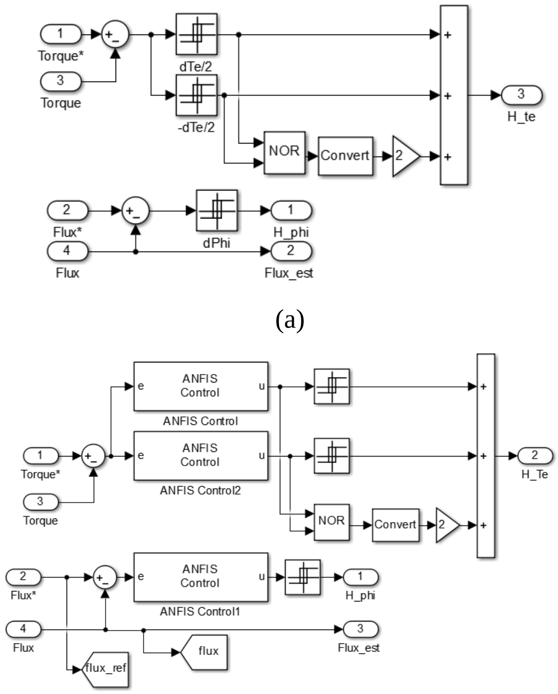


Fig. 8. Speed control with PI controller.

Figure 9 explains the Torque and flux control blocks in a conventional DTC and the ANFIS controlled DTC respectively.

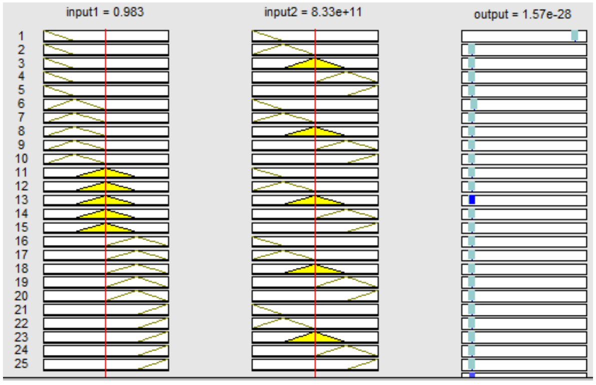


(a)

(b)

Fig. 9. Torque and flux controller (a) Conventional DTC (b) DTC with ANFIS.

The generation of hysteresis torque and flux in a conventional DTC controller is shown in Fig.9a. The flux and torque values are maintained through the relay blocks. The proposed ANFIS controller shown in Fig.9b, takes error from the reference and actual torque values and generates hysteresis torque limit such that the actual torque follows the reference value. Similarly the ANFIS controller is introduced for maintaining the reference flux from the reference and actual flux in the PMSM. The rule viewer of the flux and torque for the proposed ANFIS controller is illustrated in Fig.10 with the inputs and output relationships.



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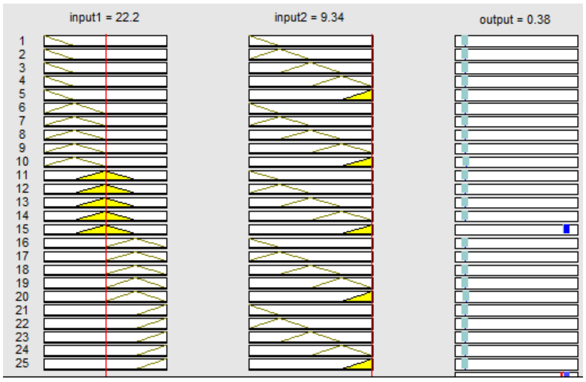


(b)

Fig. 10. ANFIS rules (a) Flux controller (b) Torque controller.

This article prefers centrifugal pump as load and the simulation of centrifugal pump is done in Matlab simulink environment using the Sim-Hydraulics blocks as shown in Fig.11.

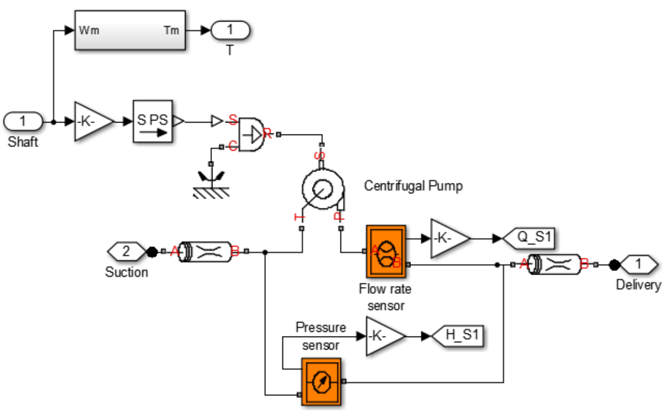
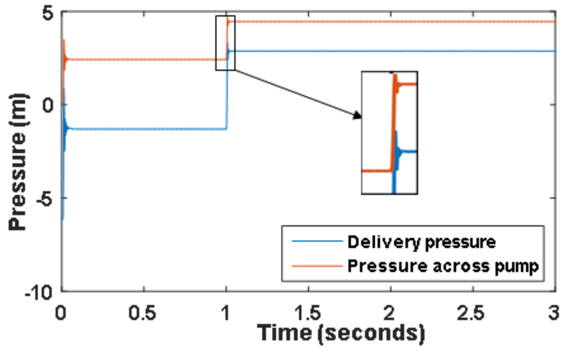


Fig. 11. Pump simulated model.

The pressure developed by the pumps varies with the pump characteristics. Normally pressure experienced at the delivery point of the pumping system will be lower than the pressure developed across the pump due to frictional and head losses in the pump. The simulation waveforms of delivery pressure and the pressure across the pump are revealed for different DTC control strategies in Fig.12. The simulation results highlights that the ripple in pressure when using the proposed ANFIS control strategy is comparatively very less when compared with the conventional DTC, and DTC with fuzzy logic controller.



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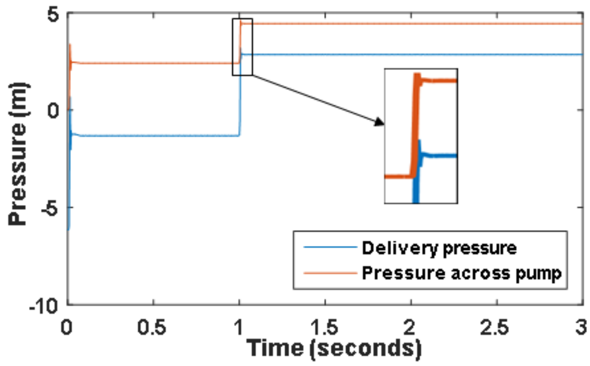

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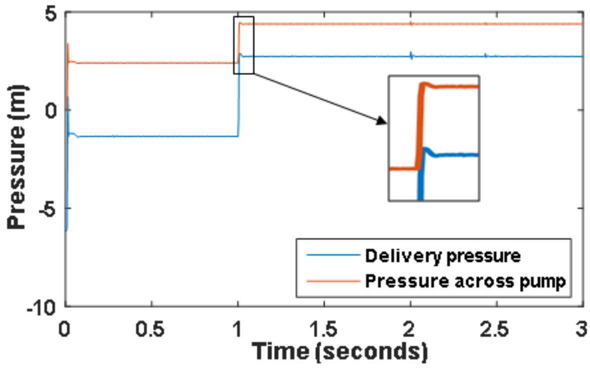
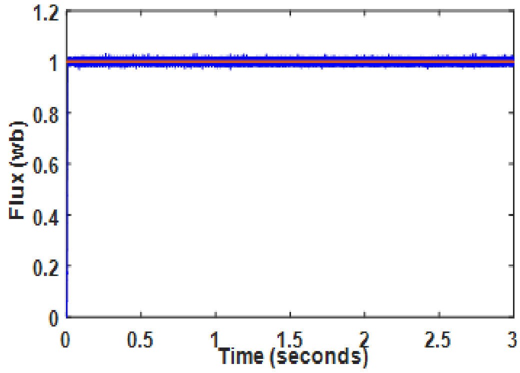


(c)

Fig. 12. Pump output pressure (a) Conventional DTC (b) DTC – FLC (c) DTC – ANFIS.



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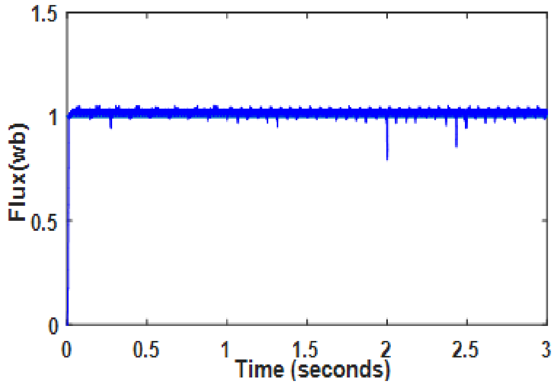

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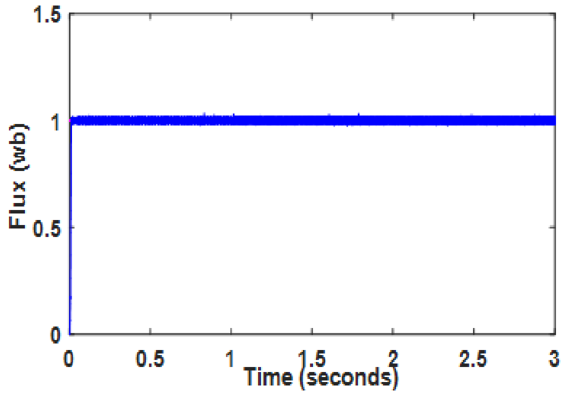
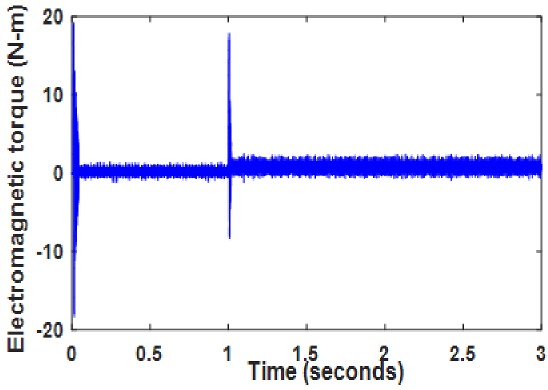


(c)

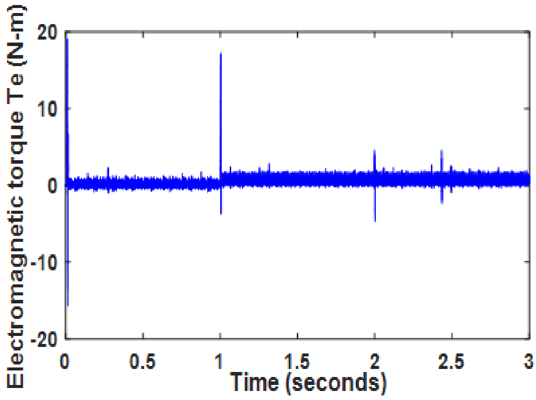
Fig. 13. Stator flux of PMSM (a) Conventional DTC (b) DTC – FLC (c) DTC – ANFIS

Figure 13 shows the stator flux in the PMSM for three different DTC control strategies where ANFIS controlled DTC is expressing very less ripple in stator flux in comparison with the Conventional DTC and DTC with fuzzy controller.

The electromagnetic torque developed by PMSM for different control methods (Conventional DTC, DTC with Fuzzy Logic Controller, and ANFIS controlled DTC) are shown in Fig.14. The comparison shows that the proposed ANFIS controlled DTC is having smooth torque developed when compared with the other control methods.



(a)



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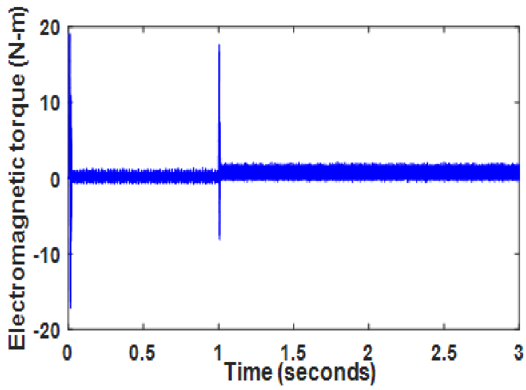
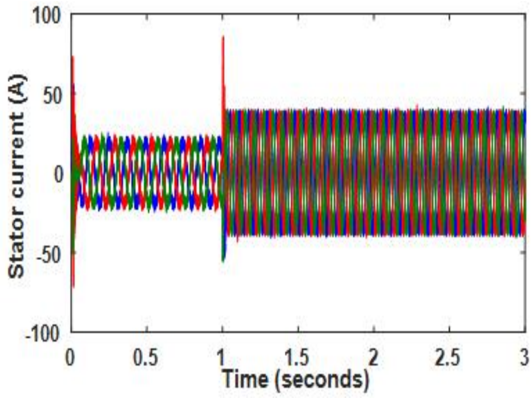


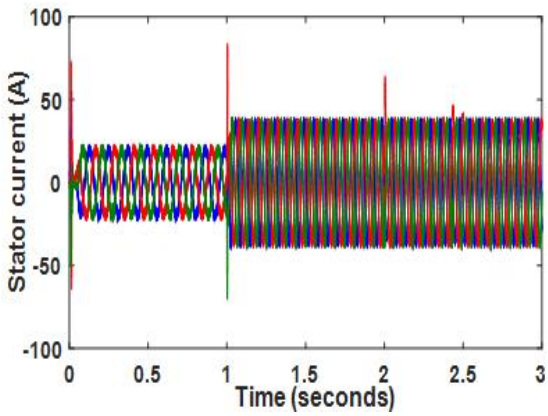
(c)

Fig. 14. Electromagnetic torque developed in motor (a) Conventional DTC (b) DTC – FLC (c) DTC – ANFIS.

The simulation results of the stator current of PMSM are given in Fig.15. In comparison of the stator current for three different control methodologies, the proposed ANFIS controlled DTC exhibits less ripples and sinusoidal in nature.



(a)



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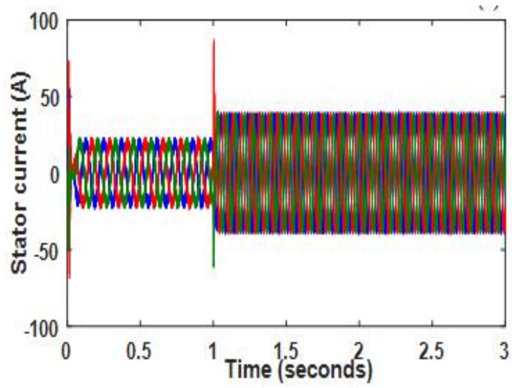
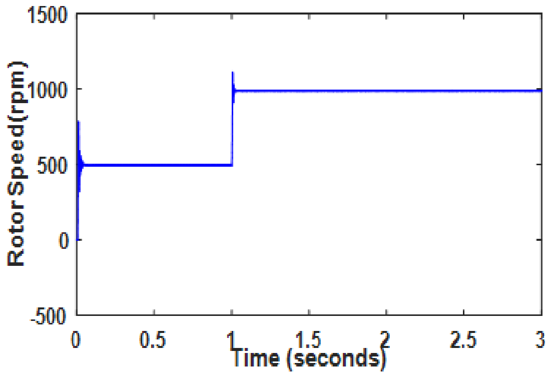


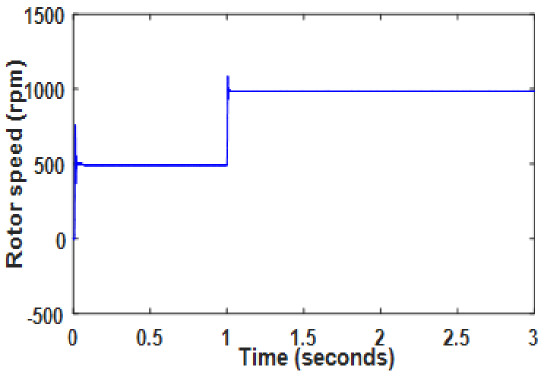
(c)

Fig. 15. Stator current (a) Conventional DTC (b) DTC – FLC (c) DTC – ANFIS

The speed requirement of the motor varies with respect to time and load demand. Hence to estimate performance of the proposed method, the control methods are tested with two different speeds. In MATLAB simulation, initially a speed command of 500 rpm is given for the control strategy and it is changed to 1000 rpm to find the response and settling time as shown in Fig.16. The analysis of the illustrated graphs shows the proposed ANFIS controller fed DTC has less oscillation and it responds faster when compared with the other control methods.



(a)



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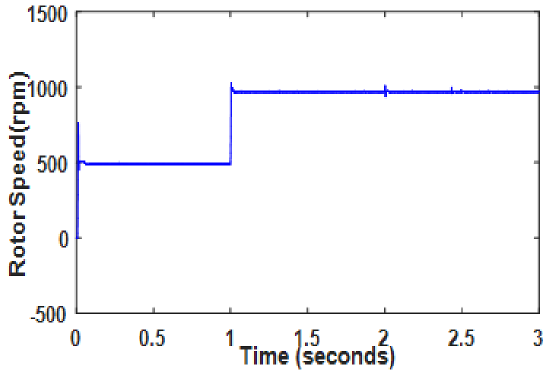
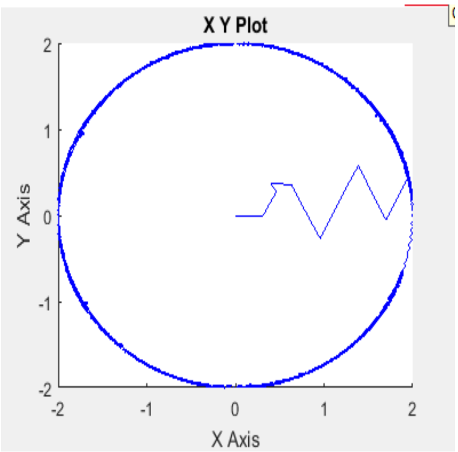


(c)

Fig. 16. Rotor speed of PMSM (a) Conventional DTC (b) DTC – FLC (c) DTC – ANFIS

The stator flux trajectory of PMSM is provided for different control strategies as shown in Fig.17. The comparison shows that the DTC with ANFIS exhibits the improved stator flux trajectory in comparison with the other two DTC control methods.



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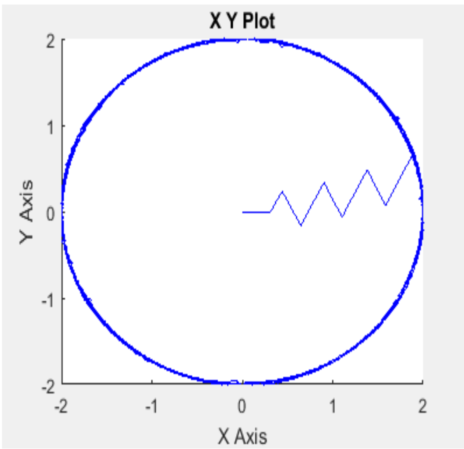

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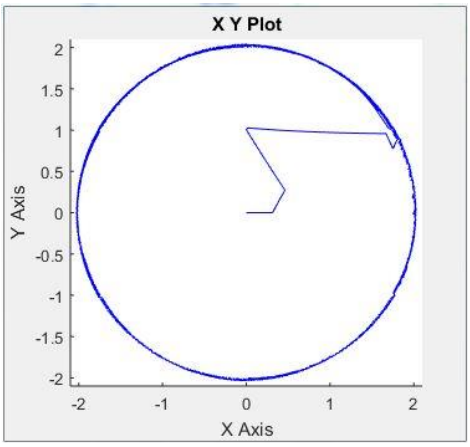

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Fig. 17. Stator flux trajectory of PMSM (a) Conventional DTC (b) DTC – FLC (c) DTC – ANFIS

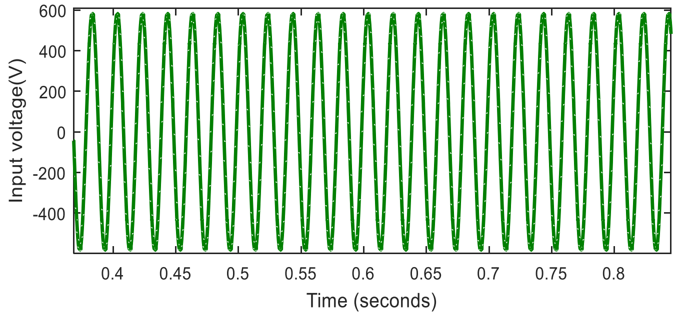

Fig. 18. Input voltage to the VFD

The input voltage across the VFD, DC link output voltage and the Inverter output voltage are shown in Fig.18, Fig.19 and Fig.20 respectively for the PMSM controlled with the ANFIS based DTC control method. The DC link output voltage is ripple free and the input voltage to the VFD remains sinusoidal.

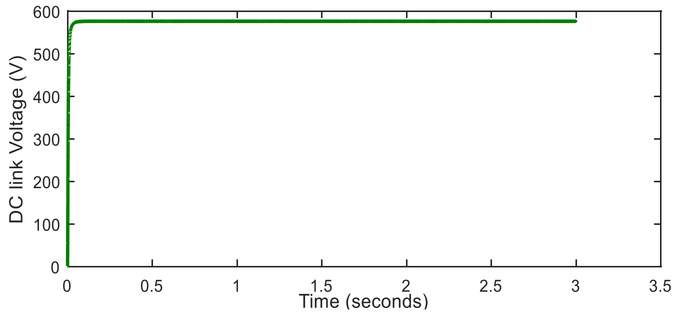

Fig. 19. DC link output voltage

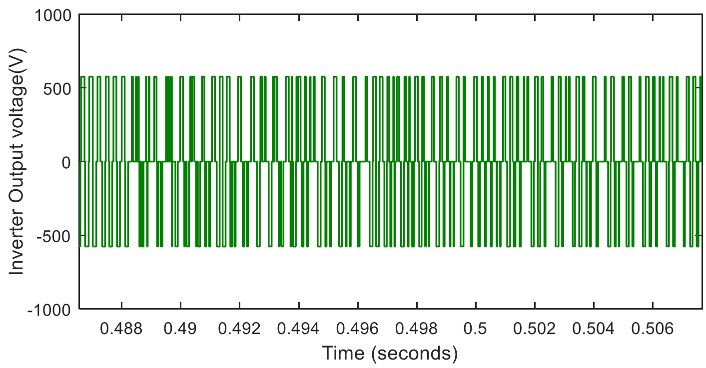

Fig. 20. Inverter Output Voltage

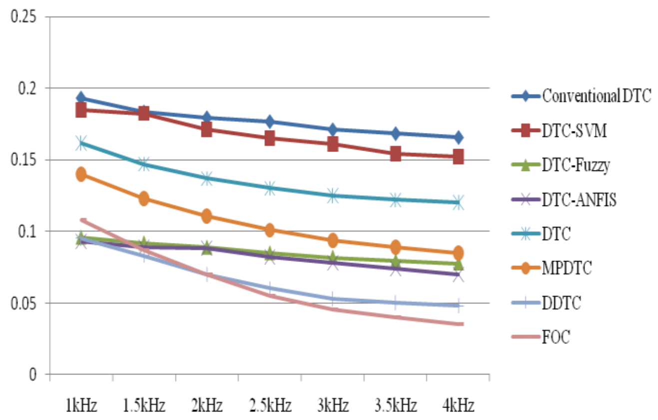

Fig. 21. Torque ripple for all proposed and existing DTC topologies at 500 rpm.

The proposed ANFIS DTC is compared with the other DTC control techniques, i.e., conventional DTC, DTC-SVM, DTC Fuzzy, MPDTC, DDTC, FOC [6]. As per the comparative chart shown in Fig.21, it can be concluded that among all the proposed control strategies, DTC with ANFIS control have least torque ripple at 500 rpm. Almost till 2 kHz switching frequency both DTC -ANFIS and DTC-Fuzzy have same torque ripple values. DTC with Space vector modulation have more ripple than the two control strategies mentioned above but has less ripple when compared with the conventional DTC approach.

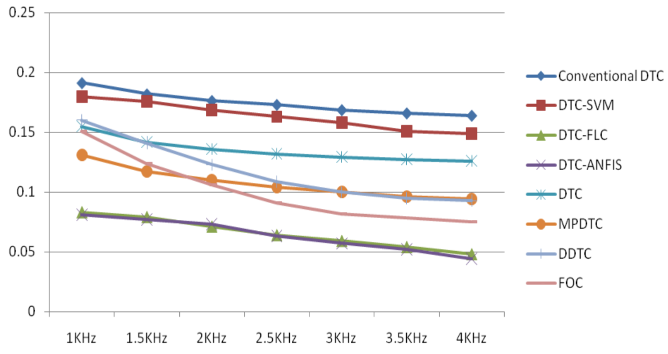

Fig. 22. Torque ripple for proposed and existing DTC strategies at 1000 rpm.

The proposed ANFIS DTC is compared with the other DTC control techniques, i.e., conventional DTC, DTC-SVM, DTC Fuzzy, MPDTC, DDTC, FOC [6]. At 1000 rpm rotor speed, DTC-ANFIS and DTC- FLC resulted with similar electromagnetic torque ripple with very little difference as shown in Fig.22. Torque ripple in tabular form at both the speeds, at various switching frequencies for different control topologies is shown in Table 2.

Table 2. Torque ripple at 500/1000 rpm.

Freq.[a] (KHz)	Proposed control topologies				Existing control topologies			
	Conv.[b] DTC	DTC-SVM	DTC-FLC	DTC-ANFIS	DTC [6]	MPDTC [6]	DDTC [6]	FOC [6]
1	0.1931/ 0.1913	0.185/ 0.1798	0.096/ 0.083	0.093/ 0.081	0.162/ 0.155	0.14/ 0.131	0.095/ 0.16	0.108/ 0.151
1.5	0.1834/ 0.1819	0.1824/ 0.176	0.092/ 0.079	0.089/ 0.077	0.147/ 0.142	0.123/ 0.117	0.083/ 0.141	0.087/ 0.124
2	0.1793/ 0.1764	0.1713/ 0.1687	0.089/ 0.071	0.088/ 0.073	0.137/ 0.136	0.111/ 0.11	0.07/ 0.123	0.07/ 0.106
2.5	0.1766/ 0.1731	0.1649/ 0.1631	0.085/ 0.064	0.082/ 0.063	0.13/ 0.132	0.101/ 0.104	0.06/ 0.109	0.055/ 0.091
3	0.1709/ 0.1687	0.1608/ 0.1581	0.082/ 0.059	0.0782/ 0.057	0.125/ 0.129	0.094/ 0.1	0.053/ 0.1	0.0454/ 0.081
3.5	0.1682/ 0.166	0.154/ 0.1511	0.0795/ 0.054	0.0739/ 0.052	0.122/ 0.127	0.089/ 0.096	0.05/ 0.095	0.04/ 0.078
4	0.1655/ 0.1640	0.1519/ 0.1489	0.0778/ 0.048	0.0699/ 0.044	0.12/ 0.126	0.085/ 0.094	0.048/ 0.094	0.035/ 0.075

a) Frequency; b) Conventional DTC

Table 3. Flux ripple for proposed DTC's at 3 KHz switching frequency and at 500/1000 rpm

Speed (RPM)	Conv. DTC	DCT-SVM	DTC- FLC	DTC-ANFIS	DTC [6]	MPDTC [6]	DDTC [6]	FOC [6]
500	0.00683	0.00536	0.00651	0.00622	0.005	0.0055	0.0034	0.0026
1000	0.00694	0.00571	0.00674	0.00649	0.0056	0.0054	0.0042	0.004

Table 4. Comparison of all four proposed DTC strategies at low and high frequencies

Characteristics	At low frequency				At high frequency			
	Conv.[a] DTC	DTC-SVM	DTC-FLC	DTC-ANFIS	Conv. DTC	DTC-SVM	DTC-FLC	DTC-ANFIS
Stator current ripple	High	Less than Both	Less than conv. DTC	Less than DTC-FLC	Less	Least	Less than conv. DTC	Less than DTC-FLC
Torque ripple	High	Greater than conv. DTC	Less than conv. DTC	Less than DTC-FLC	Less	Less than conv. DTC	Least	Less than DTC-FLC
Flux ripple	High	Less	Greater than conv. DTC	Greater than DTC-FLC	Less	Least	Greater than conv. DTC	Greater than DTC-FLC
Control complexity	Less	High	Less	High	Less	More	Less	High
Steady state response	Good	Less than conv. DTC	Greater than conv. DTC	Best	Good	Better	Greater than conv. DTC	Best
Transient response	Good	Poor	Greater than conv. DTC	Best	Good	Poor	Greater than conv. DTC	Best

a) Conventional DTC

The torque ripple and flux ripple are also significant performance indices when controlling the drive. The calculation of flux ripple and the torque ripple are done according to the Eq. (9) and Eq. (10).

$$T_{ripple} = \sqrt{\left(\frac{1}{N_m}\sum_{i=1}^{N_m}(T_e(i) - T_e^{*})^2\right)} \tag{9}$$

$$\varphi_{ripple} = \sqrt{\left(\frac{1}{N_m}\sum_{i=1}^{N_m}(\varphi_s(i) - \varphi_s^{*})^2\right)} \tag{10}$$

The flux ripple has to be as low as possible. The flux ripple at various frequencies for different control techniques is evaluated using the Eq. (10). The chart showing comparison among them is projected in Fig.23 for analysing the performance of the various control techniques with switching frequencies ranging from 1 kHz to 4 kHz.

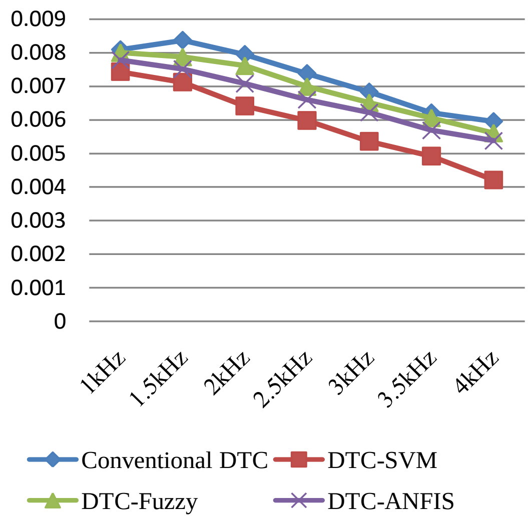

Fig. 23. Flux ripple for the proposed DTC strategies at 500 rpm.

The proposed ANFIS control strategy for PMSM is simulated with the speed commands of 500 rpm and 1000 rpm respectively. The flux ripple at two given speeds for the proposed ANFIS control is compared with the other DTC control methods as shown in the Table 3.

The summary of various performance parameters (i.e., Stator current ripple, Torque ripple, Flux ripple, Control complexity, Steady state response, Transient response) of different control strategies at low as well as high frequencies are given in Table 4. It concludes performance comparison of different DTC control techniques across the different range of frequencies.

For better understanding of control strategy performances, the comparison has been done at low as well as high frequencies. It must be noted that, the study has been performed at particular system parameters of PMSM. Results may vary if the values of the control parameters are changed or if the evaluations are made with different machine.

Table 5. System parameters specifications

Parameter	values	Parameter	values
Rated power [kW]	2.2	Input Voltage [V]	415
Rated frequency [Hz]	50	No of Phases	3
Nominal speed [rpm]	1500	Frequency [Hz]	50
Pole pairs	2	DC link capacitance [µF]	2
Flux linkage [Wb]	0.175	Switching frequency [kHz]	1- 4
Stator resistance [Ω]	0.8	Rectifier ON resistance [Ω]	0.001
Armature inductance [mH]	0.085	Rated Power [kW]	2.2
Torque constant	0.525	Rated Speed [rpm]	1500
Machine inertia [Kg-m2]	0.0008	Reference density [kg/m3]	1000
Viscous coefficient [kg.m2/s]	0.00031	Rated Flow [m3/s]	15
Matlab simulation time	3 sec	Rated Head [m]	10
Solver used	ode 45		

Table 5 provides the information on the system parameters considered for the MATLAB simulation of the proposed ANFIS controlled DTC control methodology.

6. Conclusion

The new speed control based on Adaptive Neuro-Fuzzy - Direct Torque Control (ANFIS-DTC) is proposed for the PMSM to drive centrifugal pump. The Conventional DTC, DTC with Fuzzy and DTC with ANFIS are compared on the various performance aspects (i.e., stator current, electromagnetic torque, stator flux, rotor speed and pump output pressure) through Matlab Simulink environment. In the event of eliminating overshoot and ripples in torque, flux and speed, the proposed ANFIS –DTC controller exhibits satisfactory results in comparison with the conventional DTC and DTC with fuzzy logic control. The simulation results confirm that the application of ANFIS for DTC enhances the performance of the drive with improved flux and torque control capability. The simplified design and the reduced complexity are the additional features achieved through the proposed control method. In terms of pump output also, DTC-ANFIS results smooth pressure compared to traditional DTC and DTC with fuzzy logic control. The simulation results and the comparison study specify that proposed ANFIS based DTC control exhibits improved performance.

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