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Performance Evaluation of Fuzzy DTC based PMSM for Pumping Applications

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Abstract

Background/Objectives: This paper presents fuzzy logic based Direct Torque Control on PMSM coupled with centrifugal pump for pumping applications and the performance evaluation of the proposed method. **Methods/Statistical analysis**: The proposed method is compared with the other DTC schemes such as, Conventional DTC, DTC with space vector modulation (SVM), MPDTC, DDTC and Field oriented control (FOC) for the performance evaluation. The mentioned strategy is analyzed and reviewed for centrifugal pump load under, various performance features in Mat Lab simulation. To pick the best, among all above mentioned control strategies, comparison has been done at various frequencies and speeds. **Findings:** It is found that the proposed DTC- FLC is having less torque ripple output among all the control strategies. Various motor control parameters analyzed are electromagnetic torque, stator current, rotor speed, stator flux etc., and pump parameters like flow rate and pressure are evaluated. **Application/Improvements:** The proposed DTC with FLC is having less torque ripple than existing DTC and MPDTC control strategies.

Keywords: Centrifugal Pump, Direct Torque Control, Fuzzy Logic, Permanent Magnet Synchronous Motor, VFD, Space Vector Modulation

1. Introduction

Centrifugal pumps have been used from several decades for a variety of purposes as lifting water from low level to high level, irrigation, water passage and many more. In past days it was executed at constant speed and operated by throttling valve, but after the improvement in power electronics and the growth of variable speed drives (VSD's), it can be operate at variable speed with high total of energy savings[1].Because of VSD's it became possible to control the pump parameters like pressure and flow. Permanent magnet synchronous motor(PMSM) is been elected to drive the pump because to its better efficiency, high torque to volume ratio, better overloading capability, and excellent heat dissipation capability over asynchronous motor[2].

The projected system collection contains a three phase ac source, a 3-phase rectifier, a dc link, a three phase inverter with DTC-FLC control followed by PMSM together with centrifugal pump. The fundamental arrangement of the projected scheme is shown in Figure 1.

DTC procedure was basically implemented for induction motor[3,4]. It was relatively easy and had rapid torque and flux response with low to medium power drives[5]. In delayed DTC had been offered for PMSM drive[6] also and turned out to be the mostly used motor control strategy by overtake its counterpart FOC, because of its excellent control performance[7].

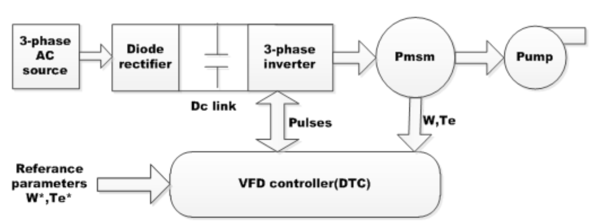

Figure 1. Basic block diagram of the proposed system.

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Conventional DTC uses a pair of hysteresis controllers, because of this; it suffers from heavy torque ripple and variable switching frequency[8]. A very capable solution to conquer such troubles is to apply the space vector, which straightly depends on the base values of torque and flux. In DTC-SVM, predictive voltage regulator is used, which calculate the vital stator voltage trajectories and apply them by via SVM technique[9-16].

In this paper DTC with fuzzy logic regulator has been employed and results have been compared with both above mentioned techniques. Fuzzy logic theory was recognized the 60's and is based on the principle of fuzzy sets. The objective of Fuzzy logic is to pact with the vagueness and ambiguity of loads of real-world problems. FLC can handle complex nonlinear structures, which have an amount of ambiguity. It does not prerequisite precise system modeling and parameters; this makes FLC very suitable for motor drive control[17-21]. It is the modification in conventional DTC where the fuzzy regulator is placed in the outer speed loop for the reduction of further torque ripple[22]. Here three DTC strategies have been analyzed and compared through Matlab simulation and a significant conclusion has been made with the summary of the results, which will aid in further research in this area and guide the researchers to treasure the suitable control technique to acquire the desired objective.

This paper is arranged in following sections. Section 2 contains the modeling of PMSM; section 3 represents pump modeling. Section 4 explains the control strategy i.e. DTC with Fuzzy logic controller (DTC-FLC). Consequently, section 5 displayed all the results at different frequencies. The comparison of all techniques is made in section 6, and paper ends with the conclusion in section 7.

2. PMSM Modeling

The Permanent Magnet Synchronous motors (PMSM) are generally chosen over the induction motors when the efficiency of the drive is taken as the major necessity for the application. The modeling of PMSM is described in this section with the d-q axes reference frame of PMSM as shown in Figure 2.

The output torque and power equations of PMSM drive is inscribed as:

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

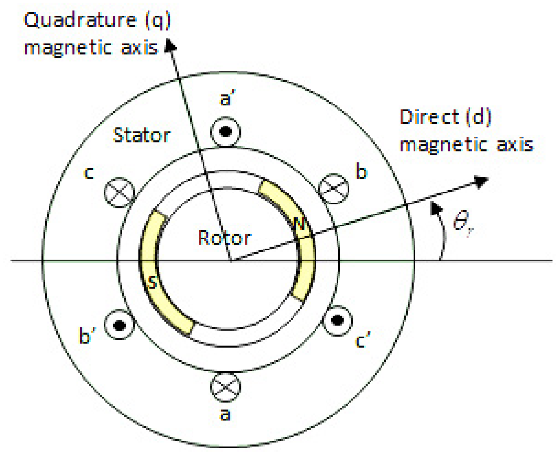


Figure 2. PMSM in D-q axes reference frame.

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,

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

Or

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

Where

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

3. Modeling of Pump

Centrifugal pump is most widely used pump in various industries along with in domestic applications. Flow rate of the pump is directly proportionate to the motor speed and the pressure is proportionate to the square of motor speed. The equations intricate in designing of centrifugal pump are given as:

Affinity law equations for pump are:

$$\frac{Q_1}{Q_2} = \frac{D_1}{D_2} \qquad \frac{Q_1}{Q_2} = \frac{D_1}{D_2}$$

$$\frac{H_1}{H_2} = (\frac{D_1'}{D_2})^2, \qquad \frac{H_1'}{H_2} = (\frac{N_1}{N_2})^2 \tag{4}$$

Hydraulic power

$$P_{hyd} = \rho QgH \quad (5)$$

Flow rate

$$Q = \frac{T\omega}{gH * 1000} \quad (6)$$

Theoretical Hydraulic power using Euler pressure

$$P_{hyd0} = p_{Eref} * Q_{ref} \left(\frac{\omega}{\omega_{ref}}\right)^3 \quad (7)$$

Friction losses

$$P_{fr} = (T_0 + K_p * p)\omega \quad (8)$$

Mechanical power at pump driving shaft

$$P_{mech} = P_{hyd0} + P_{fr} \quad (9)$$

Torque at driving shaft

$$T = \frac{P_{mech}}{\omega} \quad (10)$$

Pump total efficiency

$$\eta = \frac{P_{hyd}}{P_{mech}} \quad (11)$$

Where, P_{hyd} = Base hydraulic power

P_{hyd0} = Theoretical hydraulic power

P_{mech} = Driving shaft power

P_{fr} = Losses due to friction

p_{Eref} = Euler pressure

T_0 = Constant torque at driving shaft

K_p = Torque-pressure constant

p = Pressure in psi

Q_{ref} = Pump volumetric delivery at reference

ρ = Density

g = gravity force (9.8m/s^2)

4. Control Strategy

4.1 DTC with Fuzzy Logic Controller

To minimize the torque oscillations, fuzzy logic controller is used in the outer speed loop. In addition to that FLC is used to reduce the static error as well the response time taken by the system. The PI controller used in the conventional DTC is replaced by the fuzzy controller . Process of alteration of mathematical variable into a linguistic variable is called as Fuzzification. With the help of 7 fuzzy subsets i.e. negative big (NB), negative medium (NM), negative small (NS), zero(Z), positive small (PS),positive medium (PM),positive big (PB) names of membership functions are allocated to both the input of linguistic variables but for the output linguistic variable two additional fuzzy subsets are added i.e. negative very small (NVS) and positive very small (PVS), which makes the fuzzy output more precise. The basic configuration of fuzzy logic controller (FLC) is shown in Figure3. In the proposed FLC block two inputs, speed error and change in speed error is given and torque is taken as output.

The expression for speed error and change in speed error are,

$$E(n) = \omega^*(n) - \omega(n-1) \quad (12)$$

$$\Delta E(n) = \frac{E(n) - E(n-1)}{T} \quad (13)$$

Output torque expression taken from the FLC block is,

$$T_e(n) = T_e(n-1) + \Delta u(n) \quad (14)$$

Where ω= speed and T= sampling time

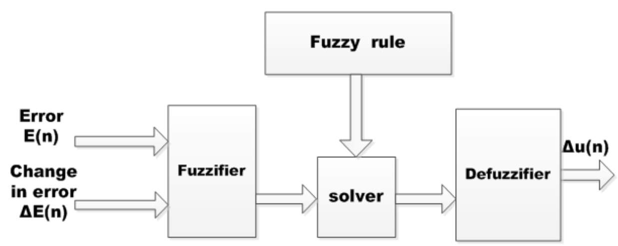
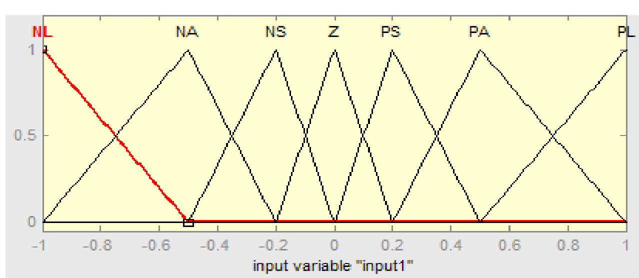
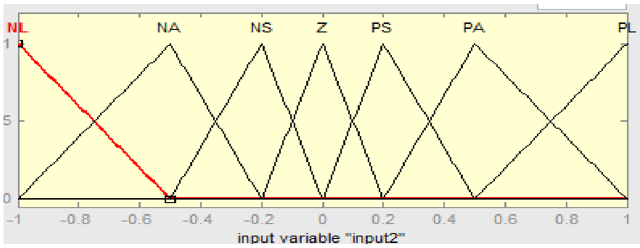


Figure 3. Fuzzy logic controller.

The input and output membership functions for the controller are shown in Figure 4.



(a)



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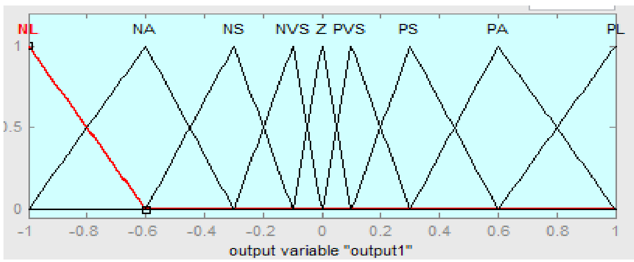


(c)

Figure 4. Membership functions for fuzzy inputs (a) and (b) and output (c).

The fuzzy control rules are given in following Table 1.

Table 1. Fuzzy rules

dE/dt ΔE	NB	NM	NS	Z	PS	PM	PB
PB	Z	PVS	PS	PS	PB	PB	PB
PM	NVS	Z	PVS	PS	PM	PM	PB
PS	NS	NVS	Z	PVS	PM	PB	PS
Z	NM	NS	NVS	Z	PVS	PS	PM
NS	NB	NM	NS	NVS	Z	PVS	PS
NM	NB	NB	NM	NS	NVS	Z	PVS
NB	NB	NB	NB	NM	NS	NVS	Z

The fuzzy surface acquired with the above rules is shown in Figure 5.

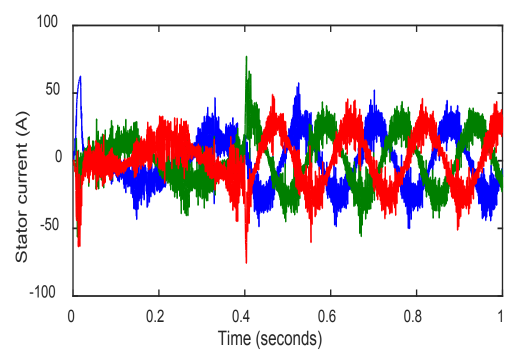
5. Simulation Results

Here in this section the outputs of motor and pump will be displayed with the proposed DTC-FLC control mentioned in section 4 using Matlab simulation of PMSM coupled with the centrifugal pump. The base or reference values considered for speed and flux are given below.

Reference flux = 2Wb

Reference speed = 100r/min up to 0.4s and 200r/min beyond 0.4s

The parameters of PMSM drive is given in Table 2. The stator current, electromagnetic torque, rotor speed, stator flux, flux trajectory, and pump output at the switching frequency of 2 KHz and 5 KHz are shown in Figure 6-11 respectively. The stator flux ripple and electromagnetic torque ripple at 500 rpm, and 1000 rpm are taken at various frequencies (1K, 2K, 3K, 4K,5K) and shown in Figure 12-14. In this paper results at 2 KHz and 5 KHz are shown, though the comparison has been done at all above mentioned frequencies.



(a)

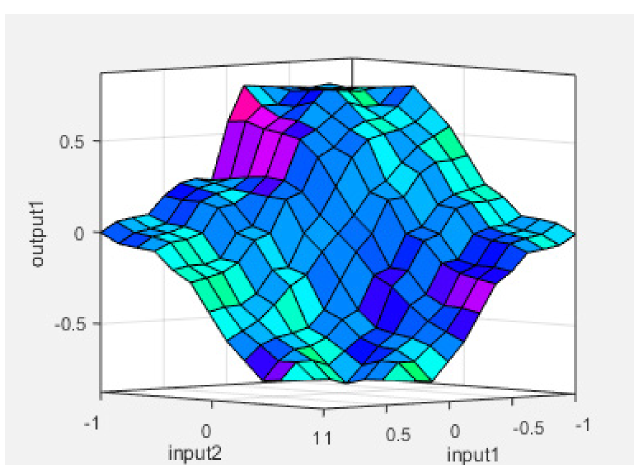


Figure 5. Fuzzy surface.

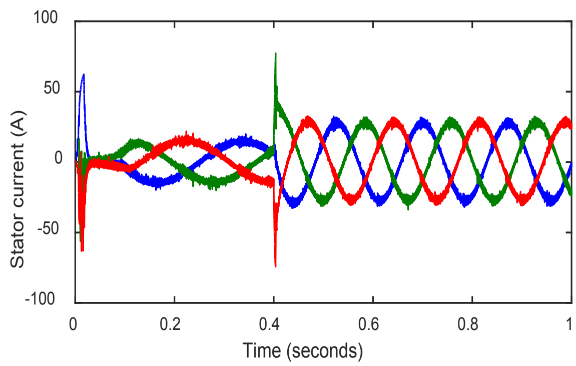
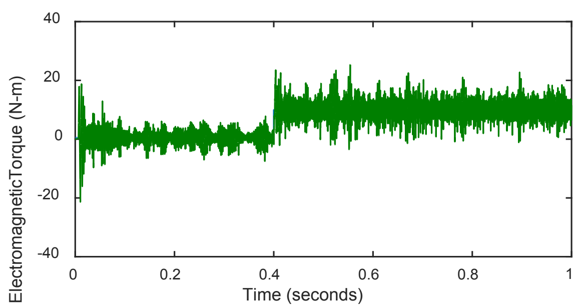


Figure 6. Stator current at 2 KHz (a) and 5 KHz (b) switching frequency.



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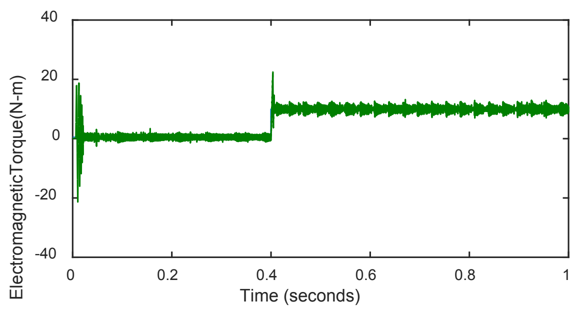
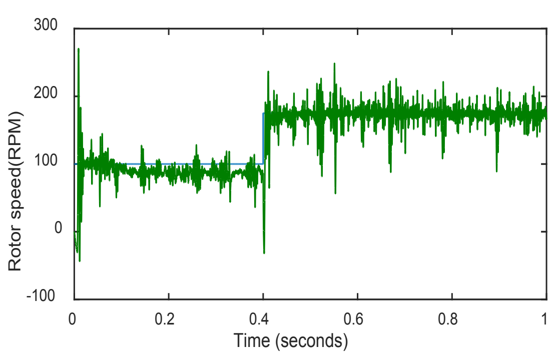


(b)

Figure 7. Electromagnetic torque at 2 KHz (a) and 5 KHz (b) switching frequency.



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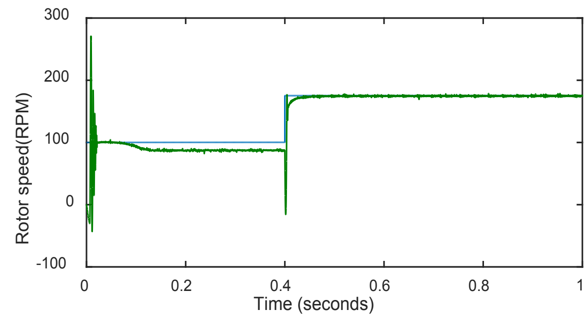
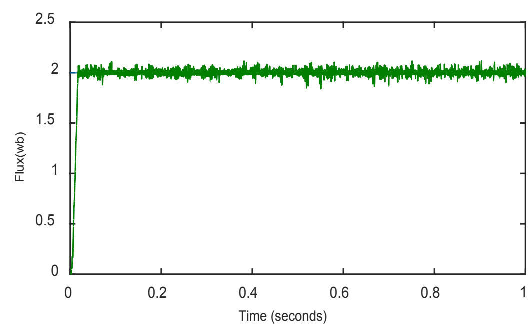


(b)

Figure 8. Rotor speed at 2 KHz (a) and 5 KHz (b) switching frequency.



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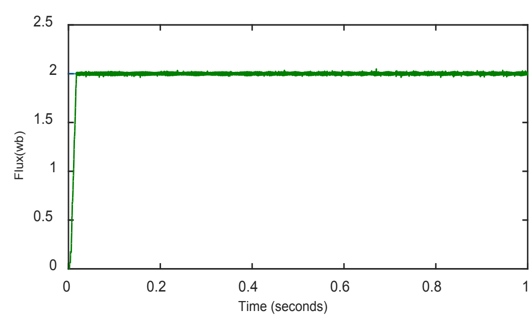
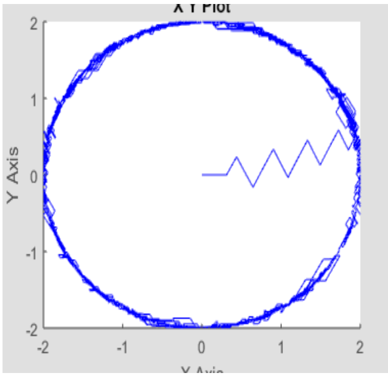
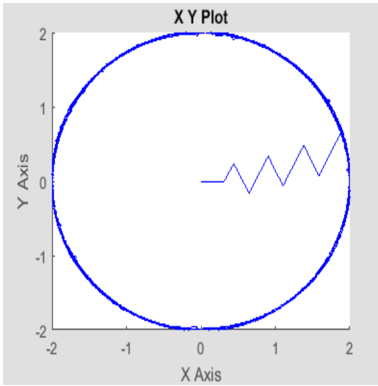


(b)

Figure 9. Stator flux (reference flux =2) at 2 KHz (a) and 5 KHz (b) switching frequency.

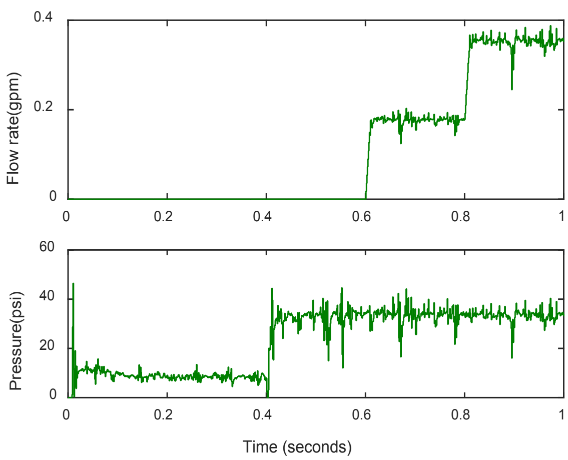


(a)



(b)

Figure 10. Flux trajectory at 2 KHz (a) and 5 KHz (b) switching frequency.



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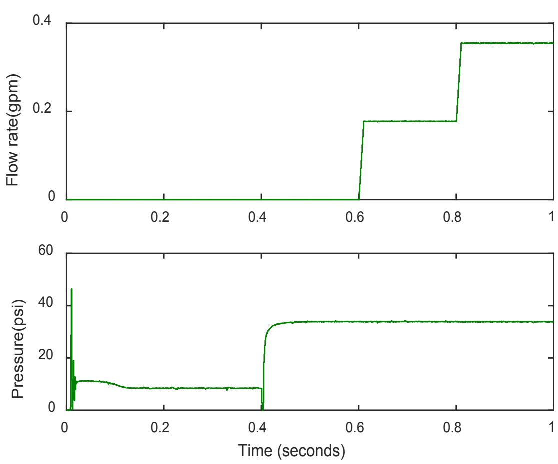

(b)

Figure 11. Pump output at 2 KHz (a) and 5 KHz (b) switching frequency.

6. Comparison of Control Techniques

6.1 Motor Output Comparison

All simulated results at 5 KHz switching frequency has been given in section (5). As it is shown by increasing the switching frequency the ripple in the stator current, torque and stator flux is decreasing with a proportion. Fuzzy logic control gives better transient results. The graphical representation of ripple content in torque and flux at different frequencies is shown in Figure 12 and 13.

Table 2. PMSM Specifications

Pole pairs	2
Armature resistance[ohm]	0.81
Armature inductance[mH]	0.086
Moment of inertia[Kg-m^2]	0.0009
Flux linkage[Wb]	0.176
Torque constant	0.524

The calculated torque and flux ripple from proposed control techniques has been compared with the other three existing DTC control techniques mentioned in. The calculated data is being shown in below charts as well as tabular form.

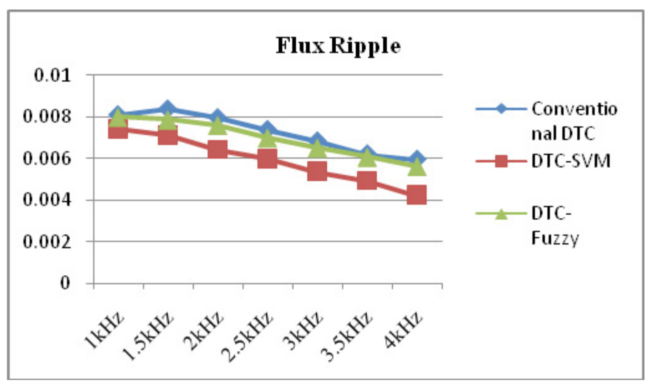

Figure 12. Analysis of Stator flux ripple at 500 r/min of three control techniques at different frequencies.

From Figure 12, it is revealed that the stator flux ripple is remarkably less in DTC with SVM. With the increase in switching frequency beyond 2 KHz, a sharp reduction in flux ripple has occurred in Conventional DTC and DTC

Table 3. Flux ripple at 3khz frequency at 500 and 1000 r/min for all control strategies

speed (RPM)	CONV. DTC	DTC-SVM	DTC-FLC	DTC[12]	MPDTC[12]	DDTC[12]	FOC[12]
500	0.00683	0.00536	0.00651	0.005	0.0055	0.0034	0.0026
1000	0.00694	0.00571	0.006774	0.0056	0.0054	0.0042	0.004

with FLC, and after 4 KHz frequency, there is no such effect of frequency on flux ripple. At 2KHzswitching frequency the flux ripple in DTC-SVM is 40% and 35% lesser than DTC-FLC and Conventional DTC correspondingly. In Table 3 we can see that speed variation from 500 to 1000 r/min is not having much effect on flux ripple.

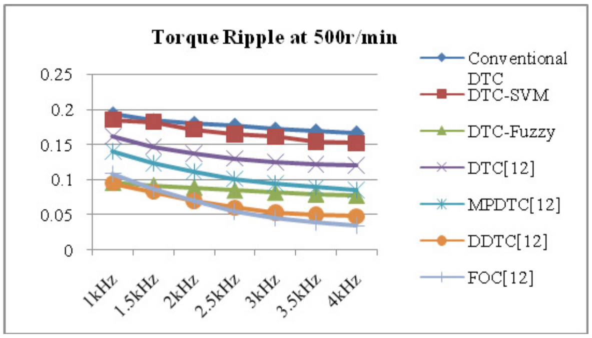

Figure 13. Analysis of Electromagnetic torque ripple at 500 r/min for proposed and existing control technique implemented in[12] at different frequencies.

From Figure 13 of torque ripple, at the speed of 500rpm proposed fuzzy control employed is having fewer ripples then proposed other two strategies, in addition to that it is giving better result than existing DTC and MPDTC.

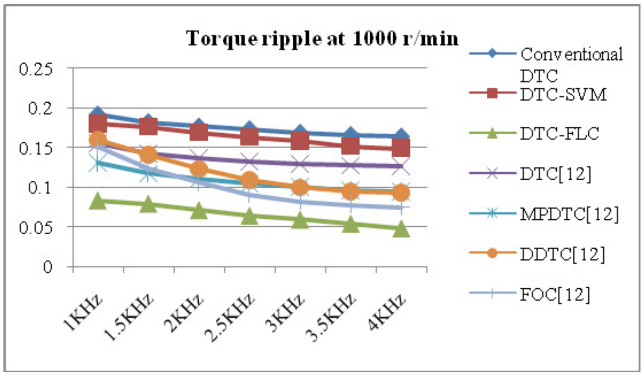

Figure 14. Analysis of Electromagnetic torque ripple at 1000 r/min for the proposed and existing control techniques implemented in[12] at different frequencies.

Table 4. Torque ripple(500/1000 rpm)

Freq (KHz)	Proposed control strategies			Existing control strategies			
	Conv.DTC	DTC-SVM	DTC-FLC	DTC	MPDTC	DDTC	FOC
1	0.1931/0.1913	0.185/0.1798	0.096/0.083	0.162/0.15	0.14/0.131	0.095/0.16	0.108/0.15
1.5	0.1834/0.1819	0.1824/0.176	0.092/0.079	0.147/0.14	0.123/0.117	0.083/0.141	0.087/0.12
2	0.1793/0.1764	0.1713/0.1687	0.08/0.071	0.137/0.13	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	0.13/0.132	0.101/0.104	0.06/0.109	0.055/0.09
3	0.1709/0.1687	0.1608/0.1581	0.082/0.059	0.125/0.12	0.094/0.1	0.053/0.1	0.0454/0.0819
3.5	0.1682/0.166	0.154/0.1511	0.0795/0.05	0.122/0.12	0.089/0.096	0.05/0.095	0.04/0.078
4	0.1655/0.1640	0.1519/0.1489	0.0778/0.04	0.12/0.126	0.085/0.094	0.048/0.094	0.035/0.07

Table 5. Control comparison

Characteristics	At low frequency			At high frequency		
	Conv. DTC	DTC-SVM	DTC-FLC	Conv.DTC	DTC-SVM	DTC-FLC
Stator current ripple	High	< Both	< conv. DTC	Less	Least	<conv. DTC
Torque ripple	High	> conv .DTC	< conv. DTC	Less	<con DTC	Least
Flux ripple	High	Less	> conv. DTC	Less	Least	>conv. DTC
Control complexity	Less	High	Less	Less	More	Less
Steady state response	Good	< conv .DTC	> conv. DTC	Good	Better	>conv. DTC
Transient response	Good	Poor	> conv .DTC	Good	Poor	>conv. DTC

At 1000rpm proposed DTC-FLC is having least ripple among all control strategies.

Tabulated form of torque ripple is being given in Table 4.

The torque and flux ripple have been calculated with the following expressions.

$$T_{ripple} = \sqrt{\left(\frac{1}{N_m}\sum_{i=1}^{N_m}(T_e(i) - T_e^*)^2\right)} \tag{15}$$

$$\varphi_{ripple} = \sqrt{\left(\frac{1}{N_m}\sum_{i=1}^{N_m}(\varphi_s(i) - \varphi_s^*)^2\right)} \tag{16}$$

Where, m is the number of samples taken for ripple calculation.

The summary of comparison among proposed three DTC control techniques is being mention in Table 5.

For better comparison of control strategies, it has been done at low as well as high frequencies. It must be noted that, above comparison has been done at particular values of various parameters. Results may vary if the values of the control parameters will vary or if the evaluation will be done with different kind of machine.

6.1 Pump Output Comparison

The centrifugal pump has two outputs specifically flow rate and pressure. Both of these parameters have been calculated for all the three above mentioned control techniques at different frequencies as shown in result section. The flow rate and pressure of the centrifugal pump are directly proportional to the motor speed .At different speed and torque, flow rate and pressure have been calculated and tabulated in Table 6. Smoothness of the pump output is increasing with increase in the switching frequency.

The Table 6 shows, at the same speed DTC-SVM is giving increased amount of flow rate and pressure compared to other but the drawback with this technique is, while increasing torque from low value (0.5N-m) to high value (5N-m) reduction in the flow rate and pressure occurred. This is the negative point with DTC-SVM; other two strategies will give positive results while switching torque from low value to high value.

7. Conclusion

Three control strategies based on direct torque control (DTC) have been carefully analyzed with PMSM coupled with centrifugal pump in Matlab Simulink. Various control parameters are compared i.e.; electromagnetic torque ripple, stator current , stator flux, control complexity, steady state and transient response as control performance. Two pump parameters flow rate and pressure are also reviewed. With the obtained results, it is proved that among the three strategies; each one has some specific advantage with some negative aspects. Comparison has been done by taking Conventional DTC as reference.

In terms of stator current ripple and stator flux ripple, DTC with Space vector modulation gave better result, while torque ripple is very much reduced with fuzzy logic controller. Since DTC-SVM uses PI controllers to transform reference parameters to control parameters, complexity of control and designing the values for controller will be a bit hard. The transient response with DTC-SVM is poor and having heavy ripples in stator current, torque and speed, while with other two equivalents gave satisfactory transient response. At low frequency,

Table 6. Pump output comparison

Ref. speed (rpm)	Ref. torque (N-m)	Conventional DTC		DTC-SVM		DTC-FLC	
		Flow rate (gpm)	Pressure (psi)	Flow rate (gpm)	Pressure (psi)	Flow rate (gpm)	Pressure **(psi)**
200	0.5	0.3491	32.7	0.409	45.06	0.351	33.2
300	0.5	0.5181	72.01	0.614	101.3	0.531	75.35
500	0.5	0.8760	205.9	1.024	281.3	0.892	213.6
1000	0.5	1.4840	590.7	2.045	1122	1.492	596.9
200	5	0.3499	32.89	0.409	44.96	0.353	33.57
300	5	0.5237	73.58	0.613	100.9	0.532	76.01
500	5	0.8781	207.5	1.023	280.8	0.893	214.3
1000	5	1.4916	596.3	2.020	1108	1.498	602.5

steady state response with fuzzy logic is worthy but at high frequency DTC-SVM overtaken to DTC-FLC.

In terms of pump concern the flow rate and pressure have been calculate at different speed and torque as mention in Table 6. Among all three, DTC-SVM is giving improved flow rate and pressure at same speed. Increase in torque, results in reduced flow rate and pressure in DTC-SVM, but with Conventional DTC and DTC-FLC it is increasing with the increase in torque.

Comparison also has been done with already implemented four control strategies in in terms of torque and flux ripple at various frequencies and speed .It has been concluded that at 500 r/min proposed DTC with FLC is having less torque ripple then existing DTC and MPDTC, while at 1000 r/min it is having least ripple than all existing as well as proposed strategies.

8. Acknowledgment

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