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Fuzzy Logic Controller Based Performance of SPMSM Fed With Improved Direct Torque Control

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Abstract- The main objective of this research paper is to improve the performance characteristics of Surface Mounted Permanent Magnet Synchronous Motor fed with modified Direct Torque Control using Fuzzy Logic Controller. The proposed control algorithm is developed with a torque hysteresis controller and stator voltage sectors whereas flux controller is abandoned. The overall drive configuration is implemented in SIMULINK/MATLAB. The focus of this investigation is to compare the performance of the motor with the proposed scheme using Fuzzy Logic Controller and Traditional PI Controller. In fact, the effectiveness of proposed drive is validated with various speeds and load disturbances. The obtained results are described the efficacy of the proposed control of SPMSM with speed loop of fuzzy controller than PI controller.

Keywords Fuzzy Logic Controller (FLC), Direct Torque Control (DTC), PI Controller, Ripples, Surface Mounted PMSM (SPMSM).

1. Introduction

Over the last two decades, the demand for Surface Mounted Permanent Magnet Synchronous Machines (SPMSM) increased drastically in industrial applications like National defense, Surgical and Aerospace, Wind energy conversion system due to its better performance characteristics such as small size, high torque density, high efficiency and small inertia [1,2,3]. The Conventional Direct Torque Control (DTC) was widely popular as high-performance control algorithm in the era of AC drives. Although, the DTC is made up of simple structure that is using the torque, flux modulus and vectors of stator voltage. Moreover, DTC furnish the fast and dynamic characteristics [4]. Consequently, it despite more disadvantages that are high torque ripples and slows transient response due to usage of hysteresis controllers and selection of stator voltage vectors [5]. Further, the control scheme deteriorated the output responses of the SPMSM. However, the DTC algorithm with duty cycle suffered with motor parameter uncertainties during parameter variations and sliding mode technique based control of drive despite with chattering operation [6,7].

In order to overcome aforesaid drawbacks, the research is carried out with the modified/improved Direct Torque Control (MDTC). The MDTC of SPMSM using different speed controllers to improve the performance characteristics of the system under steady and dynamic state. The proposed method is implemented with a torque controller and sector selection of stator voltage. The proposed method avoids the flux linkage hysteresis controller for regulating the stator magnetic flux linkage. Whereas, the flux linkage is used to estimate torque error. The impact of the control technique is to maintain the speed response of the system efficiently even the load is changed. The quantity of ripples in flux linkage caused due to flux hysteresis is suppressed [8].

The focus of this research is to analyze the performance of SPMSM for applying proposed topology with different speed controllers. The speed control designing of SPMSM is complicit with variation of torque load and parameters. However, the speed control of the system is considered as the aim for achieving healthy conditions to motor such as high accuracy and fast transient state. In high performance variable speed controlled drives like SPMSM, the traditional PI and PID Controllers are widely used for controlling the speed of the plant [9]. However, these controllers are yielded certain unsatisfied performances of SPMSM for non-linearity of the parameters. Furthermore, to enhance the performance characteristics of the system are used the Fuzzy Logic Controller (FLC). The Fuzzy Controllers are invoked with various control rules. Therefore, the Fuzzy Logic Controller is to overcome the draw backs of the conventional controller [10,11].

This research paper describes, the effectiveness of proposed algorithm based SPMSM validated with PI and FLC. However, the proposed drives are implemented a model in MATLAB/Simulink. Further, the obtained results demonstrated that the speed torque characteristics of SPMSM significantly are improved for employing the Fuzzy Controller in place of PI Controller. This paper is organized as: the mathematical modeling of SPMSM is described in section 2. In section 3, the implementation of the proposed control scheme, the design of control with FLC is presented in section 4 and finally the discussion of results is illustrated in section 5 followed by conclusions.

2. Mathematical Modeling of SPMSM in Rotor Reference Frame

The machine modeling is to be achieved by the understanding of the physics of machine which is key requirement for any electrical machine control. In this investigation, focused on Surface Mounted Permanent Magnet Synchronous Motor are modeled and valid mathematical equations. The stator and rotor flux linkages in different reference frames. Depending on rotor reference frame theory (d-q reference frame) that is shown in Fig.1, the stator voltages expressions of PMSM [12,13] are represented as follows.

$$U_q = R_q i_q + L_q \frac{d\,i_q}{dt} + (\omega_r) L_q i_d + (\omega_r)\lambda_f \tag{1}$$

$$U_d = R_d i_d + L_d \frac{di_d}{dt} - (\omega_r)\, L_q i_q \tag{2}$$

$$\lambda_q = L_q i_q \tag{3}$$

$$\lambda_d = L_d i_d + \lambda_f \tag{4}$$

A surface Mounted (SPMSM), there is uniform air gap [14] $L_d = L_q = L_s$
The electromagnetic torque developed by the motor [15,16] is given as Eq. (5).

$$T_e = \frac{3P}{2}\{L_d i_q i_d + \lambda_f i_q - L_q i_q i_d\} \tag{5}$$

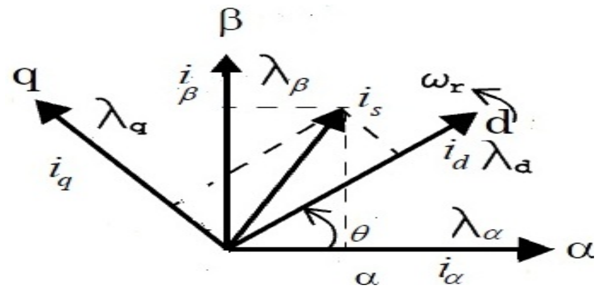

Fig. 1. Flux linkages in different reference frames

Further, the mechanical torque equation is expressed as flows in Eq. (6).

$$T_e - T_L = B\omega_m + J\,\frac{\omega_m}{dt} \tag{6}$$

The torque is to be achieved as stable [17], if

$$\lambda_s \leq \frac{L_q}{L_q - L_d}\lambda_f \tag{7}$$

The estimated stator flux is to be obtained from the α-β axis of SPMSM [18] are given as Eq. (8) to (10).

$$\lambda_\alpha = \int (V_\alpha - R_s i_\alpha)dt \tag{8}$$

$$\lambda_\beta = \int (V_\beta - R_s i_\beta)dt \tag{9}$$

$$\theta_s = \tan^{-1}\left(\frac{\lambda_\beta}{\lambda_\alpha}\right) \tag{10}$$

3. Implementation of Modified Direct Torque Control for SPMSM

The Conventional Direct Torque Control controls the inverter switches directly with ON or OFF state based on estimated values of stator magnetic flux linkage and torque [19] from the Eq. (11). However, the state of inverter changes if the output of hysteresis controller and sector changes and the hysterisis output will not change until the error reaches neigther lower band nor upper band. Further, the ripples are generated in flux linkage and torque of the drive due to both hysteresis controllers. The fluctautions is deteriorate the performance of SPMSM. In addition, the speed response describes with overshoot and delay for settling to command speed of the motor.

$$\lambda_s(n+1) = \lambda_s(n) + U_s T_e \rightarrow \Delta\lambda_s = U_s T_e \tag{11}$$

In order to rectify the drawbacks of Conventional DTC, the modified DTC is proposed to control the stator voltage vectors selection directly with a torque hysteresis controller and sector in which the stator magnetic flux controller is eliminated as shown in Fig. 2. However, the flux is controlled indirectly in this control algorithm. Moreover, the stator flux is used to estimate the error that is from the command torque and flux linkage. In order to design this proposed method, the ripples caused by the flux hysteresis controller are significantly prevented. Consequently, the speed control of SPMSM is improved although, the load torque is applied. Therefore, it impacts to enhance the performance of drive.

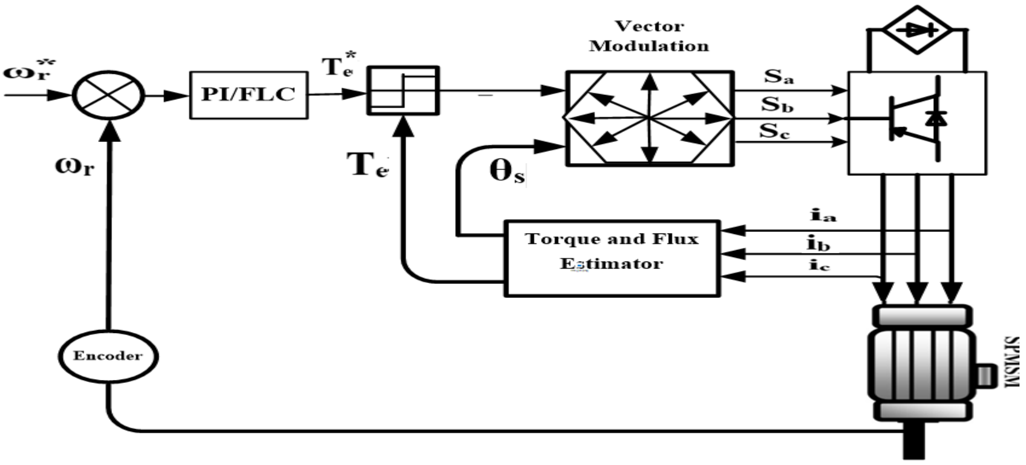

Fig. 2. Block diagram of proposed control fed SPMSM

4. Reduction of Torque and Flux Ripples using Fuzzy Controller

The scope of this investigation is to analyze the steady state and dynamic performance of SPMSM, PI controller and FLC are used in the speed loop circuit. However, the speed control of motor with PI is a challenging task because of parameter variations. Moreover, the control method like PI is not strongly suggested to achieve the best performance of SPMSM. Fortunately, Fuzzy Logic controller is used efficiently to control the motor which is shown in Fig. 3. This intelligent controller is to handle the difficulties for nonlinear systems which comprises of uncertainty. However, it is very suitable for incomplete drive system control [20].

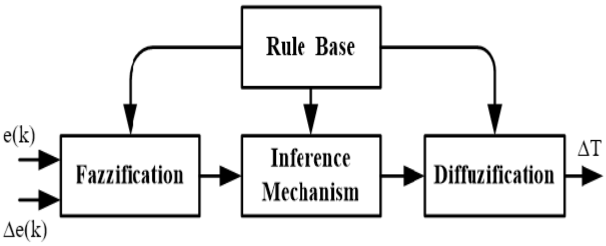

Fig. 3. Block diagram of Fuzzy Logic Controller

The main objective in this research paper is to develop the FLC to identify position direction by giving instruction speed and also considering the operation conditions. Further, to improve the performance and obtain more refined output, the membership functions are chosen that is modeled in Eq. (12) and (13) respectively.

$$e(k) = \omega_{ref} - \omega_r \tag{12}$$

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

Where ω_{ref} and ω_r are the reference speed and actual speed, e(k) and Δe(k) are the speed error and change in error respectively.

Whereas e(k) is an input variable that is error between commanding speed and actaul speed, and its derivative. The other input Δe(k) is the change in error whose input is integral. For the input parameter e(k), there are five fuzzy sets and another input parameter Δe(k) is also defined as five sets. The membership functions of two inputs and surface viewer of FLC are as shown in Fig.4, Fig. 5 and Fig.6 respectively. Therefore, FLC is processed by interface engine with a set of control rules contained (5×5) rule base. Table 1 describes the rule base for decision making unit and defined as an algorithm as follows:

a. If e(k) is NB and Δe(k) is NB, then the output is NB.

b. If e(k) is NS and Δe(k) is PB, then the output is ZE.

c. If e(k) is ZE and Δe(k) is PS, then the output is NS.

d. If e(k) is NS and Δe(k) is ZE, then the output is NB.

e. If e(k) is NB and Δe(k) is PS, then the output is ZE.

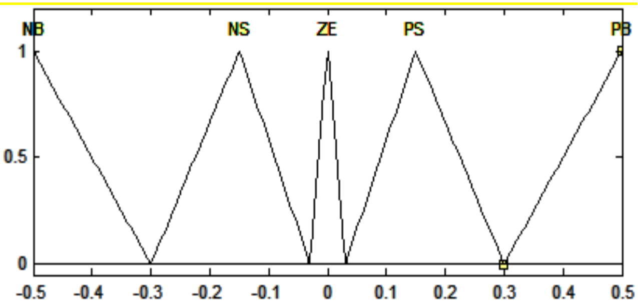

Fig. 4. Membership functions for speed error

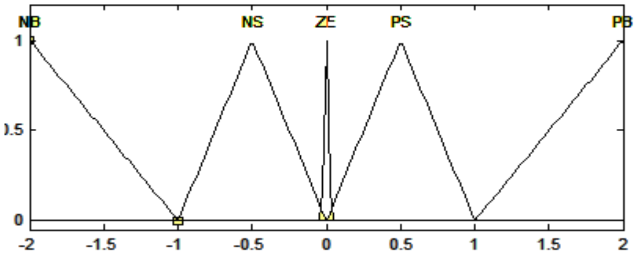

Fig. 5. Membership functions for change in speed error

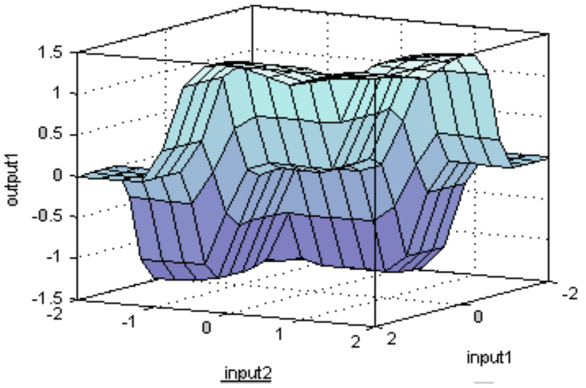

Fig. 6. Surface Control viewer of Fuzzy Controller

Table 1. Rule base unit for speed control

Δe(k)↓/e(k)→	PB	PS	ZE	NS	NB
PB	PB	PB	PB	ZE	PS
PS	PB	PB	PS	NS	ZE
ZE	PB	PS	ZE	NB	NS
NS	ZE	NS	NB	NB	NB
NB	PS	ZE	NS	NB	NB

5. System Simulation and Interpretation of Results

The simulation block diagram of MDTC of SPMSM as shown in Fig. 7 with FLC using three phase two level VSI comprises the estimation of stator flux and torque block, stator flux sector, torque comparator, Vector modulation and three phase two level inverter which are modeled based on mathematical equations using Eq. (1) to (9).

5.1. Simulation of SPMSM Drive

To validate the effectiveness of SPMSM with MDTC using different speed controllers such as PI and FLC drive was implemented in MATLAB/SIMULINK environment. The results of speed, torque flux and current are observed and presented here. The performance of PI and Fuzzy Logic speed controller of proposed control for SPMSM is validated under various cases that are the motor is operated with constant speed with fixed torque, variable speed with constant torque and variable speed with variable load. The values of motor parameters that considered [8,21] in analysis are shown in Table 2.

Table 2. Specifications of SPMSM

Motor Parameters	Symbol	Values
Stator Resistance	Rs	2.875Ω
Direct Axis Inductance	L_d	0.0085H
Quadrateaxis Inductance	L_q	0.0085H
Induced Flux	λ_f	0.175 wb
Momentum of Inertia	J	0.0008 Kg-m^2
Friction Factor	B	0.0001
No. of Poles	P	4

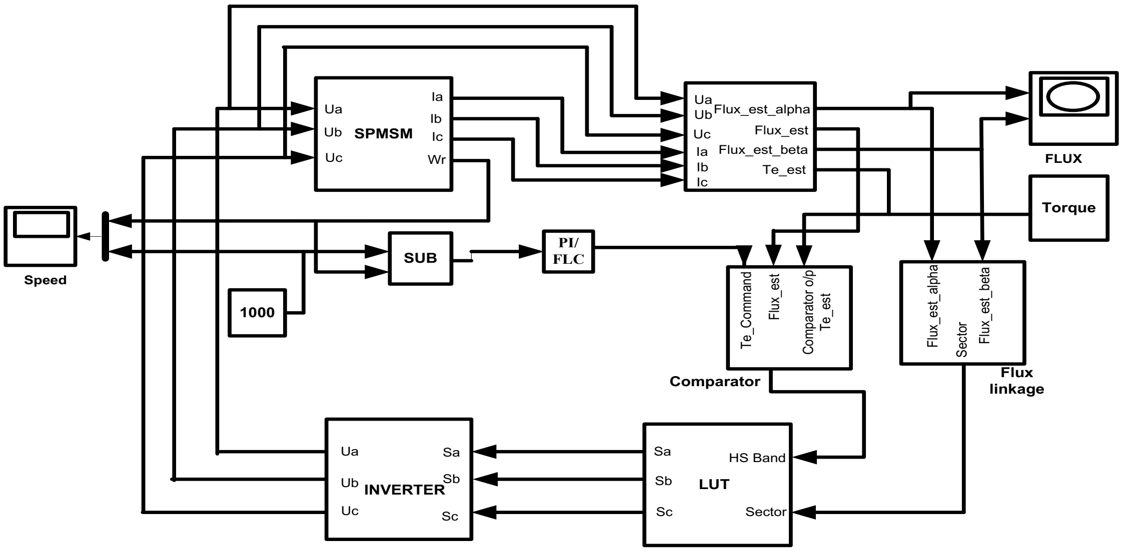

Fig. 7. Simulation block diagram of MDTC of SPMSM using PI and FLC

5.2. Comparative analysis of Results

The effectiveness of SPMSM with MDTC is evaluated in view of steady state and transient operations. However, the proposed drive is subjected to various performance operations and a comparison is made between the performance of motor with traditional PI and fuzzy controller under different speed and load test conditions that summarized the performances indices as in table 3. Additionally, the quantitate indices of the proposed drives are revealed graphically.

Test Case.1 Constant Speed with Constant Load

The first comparative analysis of the proposed drive is performed with constant speed and constant load (CSCL) disturbance in view of steady state and transient responses. The responses of speed and electromagnetic torque of proposed control approach for SPMSM are demonstrated in Fig. 8 to Fig. 11 respectively. In which, the motor is started from rest to 250 rad/sec without load toque. It is observed that the steady state speed response of FLC based proposed control fed SPMSM is reached to command speed at 0.0471 sec. without overshoots. Consequently, the fixed torque load of 1.9 N-m is applied at different instants of time. Further, it is founded that the transient response of the drive is stabilized to the instructed speed at various time with small delays. Whereas, the speed response of the system using PI is settled to the reference speed at 0.049 sec with oscillations. Additionally, it is evident that the torque ripples are considerably reduced during dynamic control state with fuzzy controlled drive than PI based drive system.

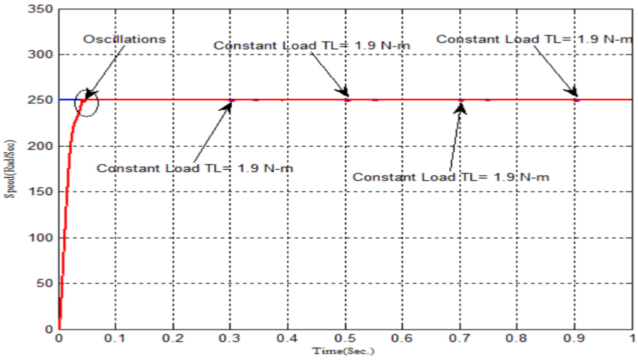

Fig. 8. Speed of SPMSM with PI under CSCL

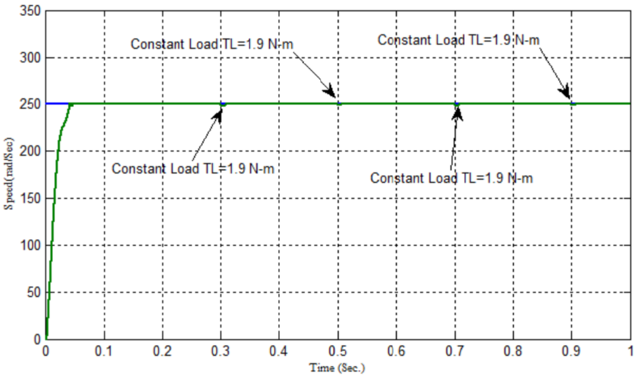

Fig. 9. Speed of SPMSM with FLC under CSCL

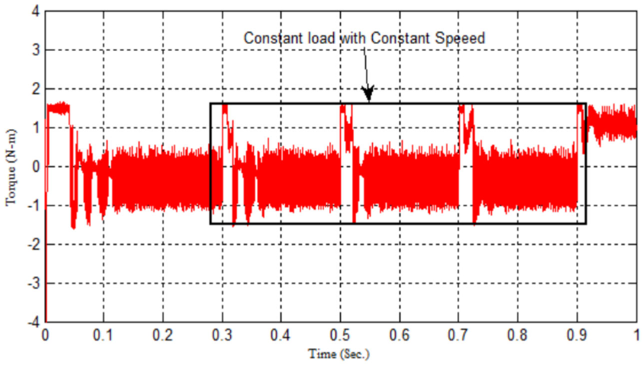

Fig. 10. Torque of SPMSM with PI under CSCL

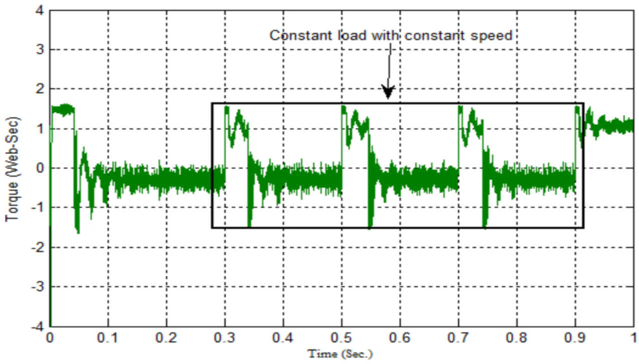

Fig. 11. Torque of SPMSM with FLC under CSCL

Test Case.2 Variable Speed with Constant Load

The performance of SPMSM is tested for forward and backward speed regions for which the command speed is set at 250 rads/sec to 300 rads/sec. and 300 rads/sec. to 250 rads/sec. respectively. Subsequently, the constant torque load of T_L=1.9N-m is applied at different instant of time. The responses of speed and electromagnetic torque of proposed system at fixed load disturbance is illustrated in Fig.12 to Fig.15.From the Figures, it is evident that the PI controlled drive has reached the command speed with overshoot. Whereas the FLC based drive, the overshoots are eliminated in the actual rotor speed. Furthermore, the constant load is applied at various instants of time such as 0.3sec., 0.5 sec., 0.7sec. and 0. 9sec. The FLC drive is exhibited closed dip after constant load applied at different times during forward and reversal speed changes from 250 rad/sec to 300 rad/sec.

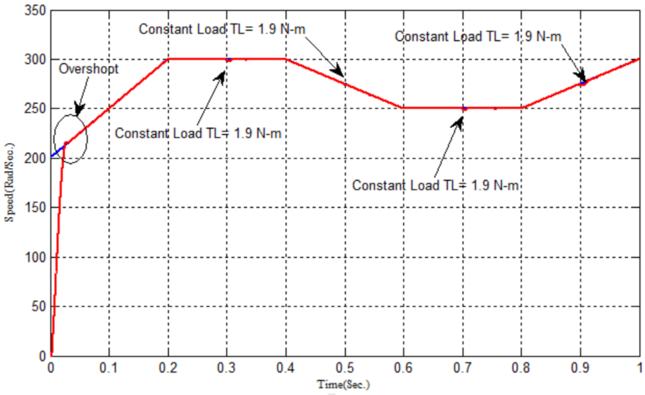

Fig. 12. Speed of SPMSM with PI under VSCL

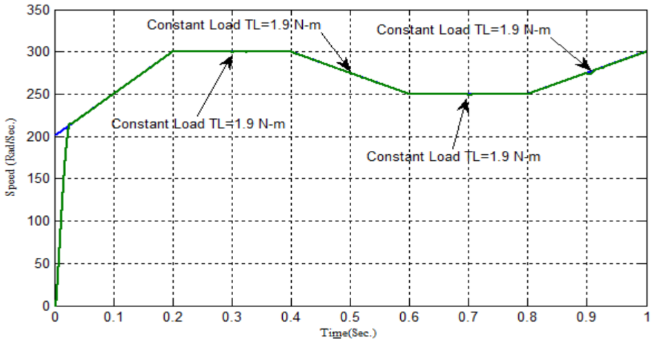

Fig. 13. Speed of SPMSM with FLC under VSCL

Under transient response of drive, the amplitude of pulse fluctuations is reduced significantly in the electromagnet torque of FLC drive. In fact, the proposed control technique fed SPMSM is yielded smooth steady state and transient responses under variation of speed with fixed load. However, the effectiveness of the proposed drive is illustrated from the comparative analysis of the performance indices under VSCL test that are presented as in Fig. 16 and Fig. 17 respectively.

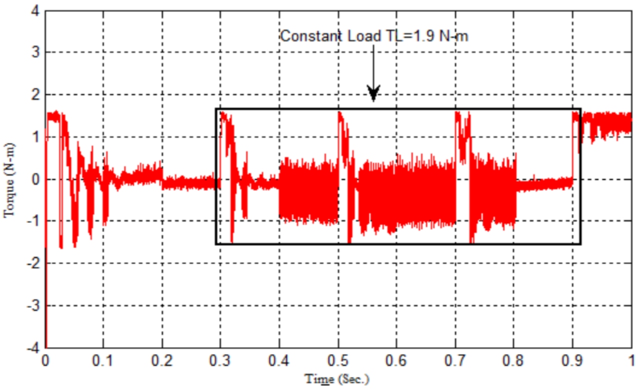

Fig. 14. Torque of SPMSM with PI under VSCL

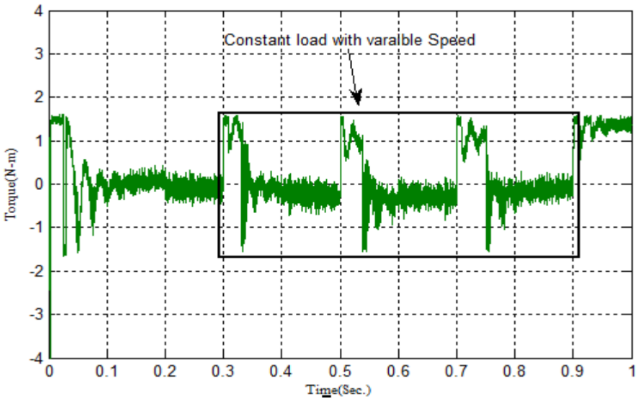

Fig. 15. Torque of SPMSM with FLC under VSCL

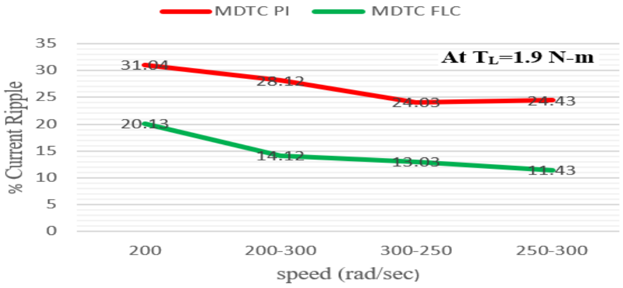

Fig. 16. Comparison of current ripples under VSCL

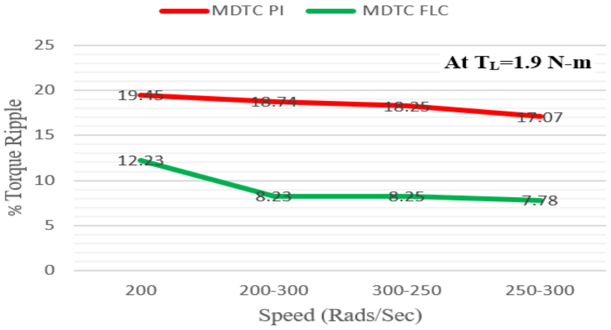

Fig. 17. Comparison of torque ripples under VSCL

Test Case.3 Variable Speed with Variable Load

In order to achieve the smooth and fast dynamic torque responses of the system, the proposed drive is viable and tested under variable speed with variable load (VSVL) conditions. The drives are operated under forward and reversal speed during variation in the load torque such as 1.7 N-m to 1.9 N-m. This is demonstrated as shown in Fig. 18 to Fig.23. It is observed that the response of actual speed, torque, and the three phase stator currents of proposed control FLC drive is performed with smooth steady state operation during the load changes from 1.7 N-m to 1.9 N-m. Further it is found that the magnitude of ripple in the torque and flux is reduced effectively with FLC speed controller than PI. Subsequently, the comparative description of the performance quantitative indices of current and torque ripples for the proposed control approach of SPMSM under VSVL are represented in Fig.24 and Fig. 25 respectively. Additionally, the stator winding flux is maintained constant during entire speed range of system that described as in Fig.26 and Fig.27 respectively. Therefore, the MDTC based drive system with FLC is yielded best performance characteristics in steady state and transient state conditions.

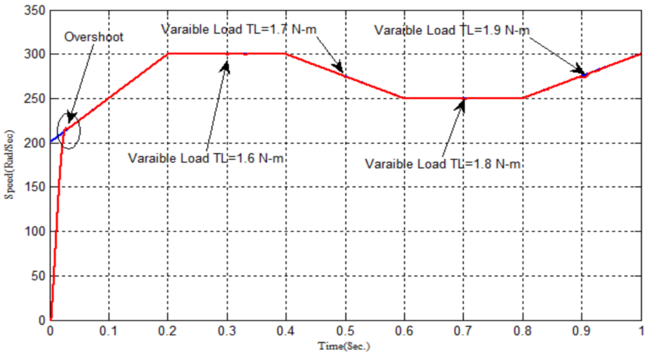

Fig. 18. Speed of SPMSM with PI under VSVL

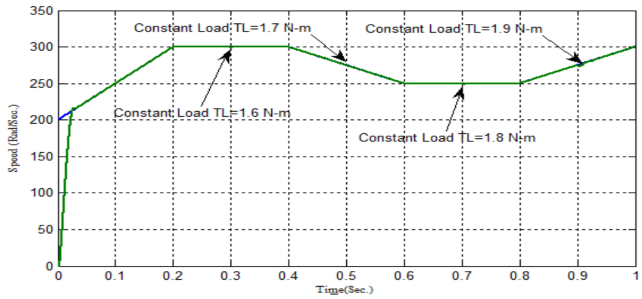

Fig. 19. Torque of SPMSM with FLC under VSVL

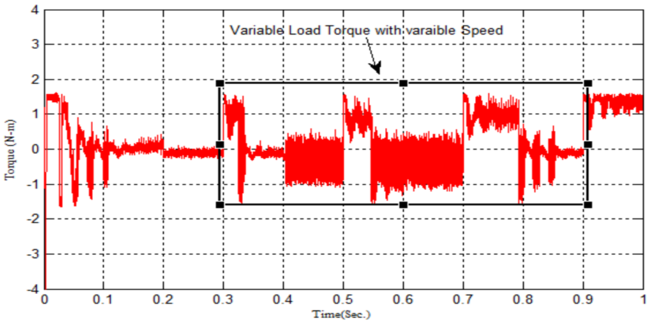

Fig. 20. Torque of SPMSM with PI under VSVL

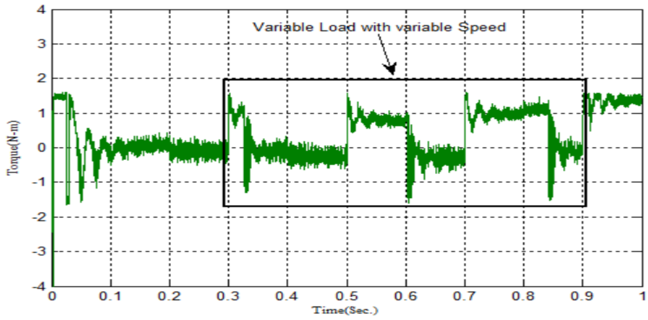

Fig. 21. Torque of SPMSM with FLC under VSVL

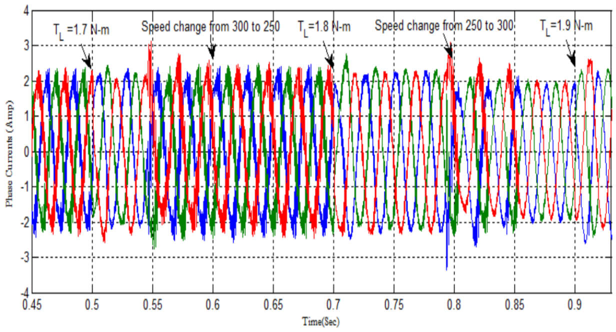

Fig. 22. Stator currents of SPMSM with PI under VSVL

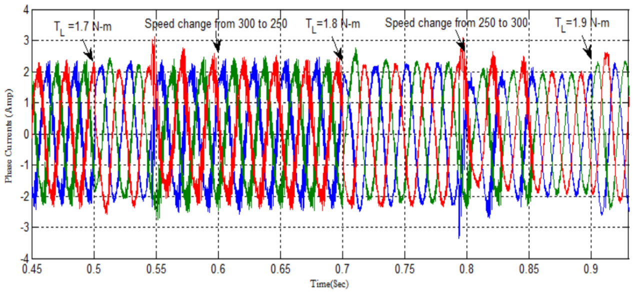

Fig. 23.Stator currents of SPMSM with FLC under VSVL

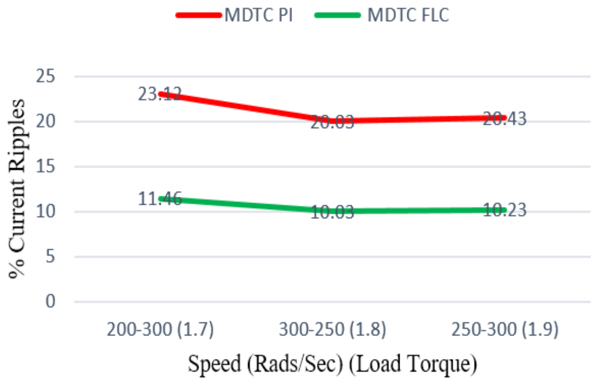

Fig. 24. Comparison of current ripples under VSVL

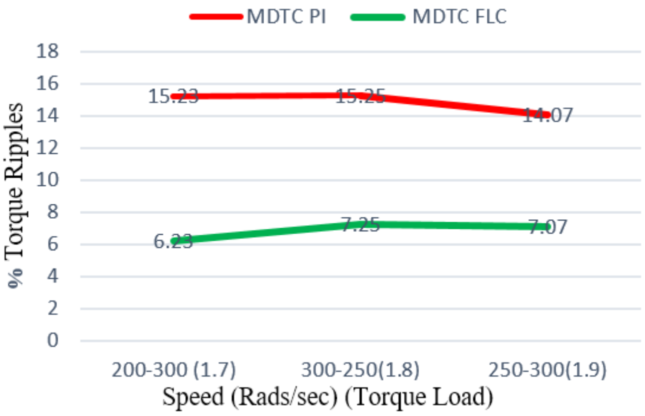

Fig. 25. Comparison of torque ripples under VSVL

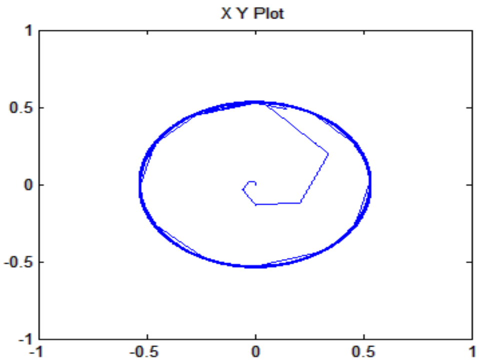

Fig. 26. Flux trajectory of SPMSM with PI

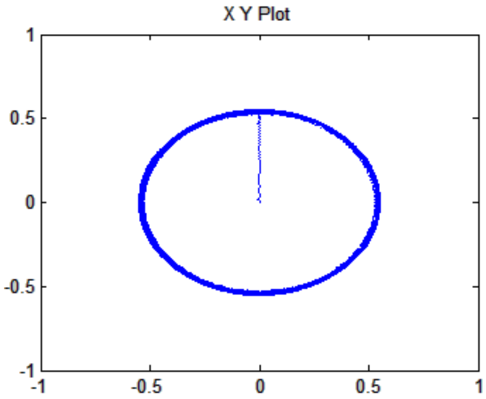

Fig. 27. Flux trajectory of SPMSM with FLC

Table 3.Summarisation of performance indices of SPMSM fed with MDTC using PI and FLC

	Speed change (RPS)	Applied torque load (Nm)	Current ripples (%)	Torque ripples (%)
PI	200	1.9	31.04	19.45
	200-300	1.9	28.12	18.74
	300-250	1.9	24.03	18.25
	250-300	1.9	24.43	17.07
	200-300	1.7	23.12	15.23
	300-250	1.8	20.03	15.25
	250-300	1.9	20.43	14.07
FLC	200	1.9	20.13	12.23
	200-300	1.9	14.12	8.23
	300-250	1.9	13.03	8.25
	250-300	1.9	11.43	7.78
	200-300	1.7	11.46	6.23
	300-250	1.8	10.03	7.25
	250-300	1.9	10.23	7.07

6. Conclusion

In this research paper, the modified direct torque control of SPMSM is presented.However, the control peformances of SPMSM is investigated and comparative analysis is peformaned between the FLC connected SPMSM and the drive with PI controller in speed feedback loop.The significance of modified DTC of SPMSM is validated with various speed and load conditions. In fact, the proposed control technique based FLC drive is eliminates the overshoot under steady state. Further, the proposed technique of the system with FLC is affirmed that the significantly reduction in the torque ripples at transient state of the SPMSM.Therefore,the performances of system with improved DTC are demonstrated that the fuzzy logic speed controlled drive is explored the superior characteristics than the PI based controlled system.

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