TORQUE RIPPLE MINIMIZATION FOR SPM AND IPM DRIVE USING FUZZY AND PI CONTROLLERS WITH AN ONLINE STATOR REFERENCE FLUX

N. KRISHNA KUMARI[1], R. GESHMA KUMARI[2], K. SRAVANI[3].
[123]Department of Electrical and Electrical Engineering, VNR Vignana Jyothi Institute of Technology, Hyderabad, India, krishnakumari_n@vnrvjiet.in, geshmakumari_r@vnrvjiet.in, sravani_k@vnrvjiet.in

ABSTRACT

The torque ripples are crucial to the drive's ability to operate dynamically well. The torque ripples cause speed fluctuations that impair the drive's performance. The performance of PMSM drives is deteriorated, especially at low speeds, by these torque pulsations, which fluctuate periodically with rotor position and manifest as speed ripples. Therefore, a drive's successful dynamic functioning depends on the torque's smooth change. Direct Torque Control (DTC)'s primary characteristic is its lack of accurate mathematical models. Even though DTC's decoupling feature allows it to manage torque and flux independently, it can be challenging to choose the precise voltage space vector, which leads to substantial torque and flux ripples. However, with the aid of an appropriate voltage space vector, it is crucial to maintain torque and flux within certain bounds. Three sets of DTC space vectors are used to investigate the drive's transient and steady state performance using the "Maximum Torque per unit Current/Ampere (MTPA)" operation. Instead of using stator flux linkage, the online stator reference flux is determined using the "A Maximum Torque per Ampere (MTPA)" approach, which uses quadrature stator flux, direct stator flux, and torque reference. The performance of the three control parameters is assessed in terms of flux ripple, torque ripple and transient responsiveness to step variations in torque and speed control instructions. Three sets of DTC space vectors are taken into consideration with MTPA operation for analytical purposes. By selecting the appropriate membership functions and rule base in a fuzzy logic controller (FLC), torque and flux ripples can be significantly reduced, resulting in an accurate voltage space vector with a smaller hysteresis band. An attempt has been made to simulate and analyse DTC on PMSMs with both SPM and IPM rotor configurations. The performance of IPM and SPM are compared using DTC Strategy, by simulation with MATLAB/Simulink Tools. This paper's goal is to use DTC-SVM to reduce torque ripples of a PMSM drive on both IPM and SPM rotor designs. A drive's dynamic performance can be examined offline with the use of simulation software, which lowers costs and time and enables real-time system design.

Keyword: *MTPA, FOC, DTC, PI Controller, Fuzzy Logic Control*

1.INTRODUCTION

Exhaustive literature survey is carried out on the following factors: Selection of Motor in Adjustable-Speed Drives; Control Strategy; Problem Identification; Speed Controllers; Hardware Implementation; Solution to the Problem. Over the past 20 years, PMSM drives have gained attention. Various researchers have modelled, simulated, and implemented such drives experimentally. These motors are the ideal option for drive applications, such as servo drives, where the drive needs to respond to torque quickly and precisely [1] [2] [3].

Selection of motor is carried out based on the following features from literature survey: Enhancement of magnet materials and manufacturing techniques- high-precision and low-cost positioning systems [4]; High efficiency, high torque/weight ratio, and less cooling arrangements are the outcomes of eliminating the rotor winding and the associated losses [5]; Miniature size of PMSMs are very much essential for robotics, servo drives, automotive, aerospace, low-cost and high precision positioning systems [6][4][7]; These applications need motors with low inertia, higher torque to volume, and higher torque to current ratios [8]. Wind generators and spindle drives use SPM's flux weakening function and sufficient torque capability to achieve a broad range of speed control [9][10][11]. For

the dynamic performance of AC drives, two key principal approaches are suggested. The 1960s saw the introduction of the first technique, vector control. This technique uses the direction of rotating rotor flux as a reference vector to split the

stator current into components that produce torque and flux [12].M. Depenbrock and I. Takahashi and T. Noguchi first proposed the second technique, Direct Torque Control, in 1984 and 1986, respectively. Also, the comparison between DTC and Field Orientated Control (FOC) [12].
The following are the specifics of the control strategies found in the literature survey: Scalar Control, Vector Control such as FOC, DTC and DSC [13][14]. FOC is preferred in steady state and DTC is preferred in transient state of operation of a drive [15][16]. Also coordinate transformation is not required in DTC [19] and it has less parameter dependency compared to FOC [17][18].In steady state, a PI controller is thought to be
the best option for improving a drive's dynamic performance, whereas FLC is thought to be the best option for transient operations. Therefore, to improve drive operation, a hybrid fuzzy-PI controller is preferred. [20] [21] [22] [23] [24] [25].

The right motor control technique must be chosen to minimize the torque ripples so that the resources are effectively utilized, thereby increasing the overall efficiency of the drive. Various speed control techniques are available for AC drives. Compared to Scalar control, Vector control techniques minimize the oscillating flux and torque responses in inverter fed AC drives resulting in efficient control of the drive. One of the most important features of vector control (Direct Torque Control-DTC) is that it does not require coordinate transformations, but the major problem associated with DTC is the large torque and flux ripples because of the presence of flux hysteresis controller, torque hysteresis controller and not having exact mathematical model [26].

The torque ripples can be removed by the inertia of the system at high speeds. On the contrary, torque ripple happens to be undesirable ripples at low speeds and could not be acceptable especially in position control applications [27]. Along with the ripples mentioned above, DTC gives slow transient response to the step changes in torque during start-up. In this work MTPA is implemented. In MTPA or id=0 control can enhance the torque output capability, minimize the stator current and there by copper loss and hence increase the overall operational efficiency of motor drive system [28] and is suitable for below base speed ranges. At the end PID and Fuzzy Controllers are used to estimate the flux and torque so that the expected speed is achieved with less ripples in torque. To achieve a better dynamic performance of a drive, PI controller is the best choice during steady state whereas FLC in transient operations.

Based on a literature survey it was found that torque ripple is the one of the main factors which deteriorates the drive's performance. In this paper, the following methods are proposed to minimize the torque ripples of a PMSM drive:

- DTC-SVM with different sets of sector divisions
- Online Stator Flux Estimator using MTPA Principle with PI and Fuzzy Speed regulators

The proposed Fuzzy logic controller with only 15 rules are implemented i.e controller with simple design approach and smaller rule base to achieve better performance.

2. DTC WITH SPACE VECTOR DIVISION

Like an independently excited DC motor, a DTC regulates a motor's torque and speed according to the electromagnetic torque's condition. Using the appropriate stator voltage vector, it guarantees optimal switching losses in addition to controlling the motor's torque and flux. Table 1 shows the suggested three space vectors division.

Table 1: Space Vector Division [29]

Sector No.	DTC I MDTC (proposed DTC)	DTC II	DTC III (CDTC)
1	$0^0 \rightarrow 60^0$	$-45^0 \rightarrow 15^0$ Little Torque ambiguity	$-30^0 \rightarrow +30^0$ Torque ambiguity
2	$60^0 \rightarrow 120^0$	$15^0 \rightarrow 75^0$	$+30^0 \rightarrow 90^0$
3	$120^0 \rightarrow 180^0$ Flux ambiguity	$75^0 \rightarrow 135^0$ Little Flux ambiguity	$90^0 \rightarrow 150^0$
4	$180^0 \rightarrow 240^0$	$135^0 \rightarrow 195^0$ Little Torque ambiguity	$150^0 \rightarrow 2\ 10^0$ Torque ambiguity
5	$240^0 \rightarrow 300^0$ Flux ambiguity	$195^0 \rightarrow 255^0$ Little Flux ambiguity	$210^0 \rightarrow 270^0$
6	$300^0 \rightarrow 360^0$	$255^0 \rightarrow 315^0$	$270^0 \rightarrow 330^0$

3. ESTIMATION OF ONLINE STATOR FLUX

Based on the necessary speed, torque ripple, and flux ripples, the reference torque and flux of IPM and SPM
are calculated. Proper applied voltage is necessary to obtain reference torque and flux. Hence to choose an appropriate switching voltage vector, torque error and flux errors are to be computed. The "Maximum Torque per unit Current/Ampere (MTPA)" principle is used in the proposed DTC with three sets of space vectors to determine the reference stator flux, which is calculated from the reference torque up to the drive's rated speed.

This maximises efficiency by minimising stator ohmic losses [27]. The reference flux for the drive's above-rated speed is determined using the "Maximum Torque per unit Flux (MTPF)" principle. An ideal switching method that guarantees minimal stator ohmic losses and maximises efficiency is crucial when using MTPA. Otherwise, the least amount of stator current should be required to achieve the required electromagnetic torque.

Therefore, the proper switching vectors are required to force i_d to zero. The following is how the reference flow is determined [29]:

$$\lambda = \sqrt{(L_d i_d + \lambda_f)^2 + (L_q i_q)^2}$$
(1)

With i_d=0

$$\lambda = \sqrt{\lambda_f^2 + L_q^2 i_q^2}$$
(2)

then electromagnetic torque is given by

$$T_e = \frac{3}{2} p[\lambda_f i_q]$$
(3)

From Eqn. (3), i_q is given by

$$i_q = \frac{2T_e}{(3p\lambda_f)}$$
(4)

Substituting i_q in Eqn. (2) yields

$$\lambda = \sqrt{\left[\lambda_f^2 + L_q^2\left[\frac{2T_e}{(3p\lambda_f)}\right]^2\right]}$$
(5)

$$\lambda_{ref} = \sqrt{\left[\lambda_f^2 + L_q^2\left[\frac{2T_{e\,ref}}{(3p\lambda_f)}\right]^2\right]}$$
(6)

Here, the instantaneous reference torque from Equation (6) is taken into consideration to find the reference flux online.
Next, as illustrated in Figure. 1, the reference torque is produced by converting the rotor speed error into instantaneous torque using a PI controller and FLC [30].

4. ANALYSIS AND INTERPRETATION

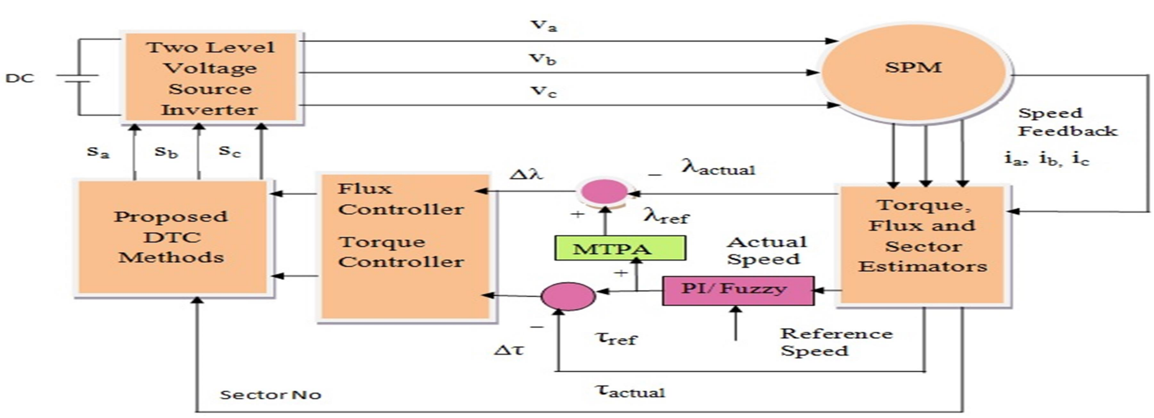


Figure 1: Online Stator Reference Flux Generation For PMSM Drive [29]

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

4. DTC PERFORMANCE FOR SPM USING FUZZY LOGIC CONTROLLER AND PI CONTROLLER

The dynamic performance of the SPM drive is assessed for three different space vectors using PI and FLCs, accounting for online stator flux estimate. The percentage of torque ripples, flux ripples, and phase current and voltage THDs, respectively, are all thoroughly examined in Table 2. When the SPM drive is started at 1500 rpm (half of the rated speed) without any load, as shown in Figure. 2, the FLC obeys the command speed in 0.08 seconds.

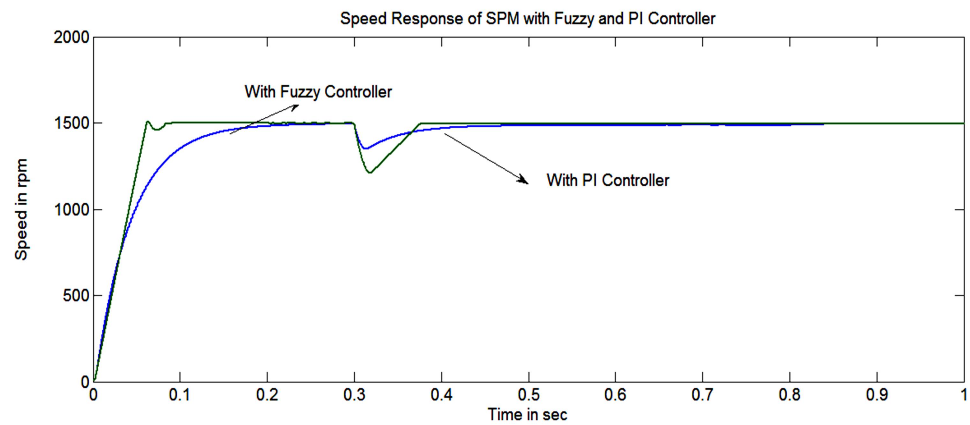


Figure 2: SPM's Speed Response With And Without A Load At T=0.3 Seconds Using DTC I

When T_L=2.3 Nm is given to SPM at t=0.3 sec, it is discovered that, using a fuzzy controller, the torque response approaches the steady state value at 0.31 sec, and the speed briefly follows load disturbances before reaching the reference value at 0.4 sec, as illustrated in Figure 3.

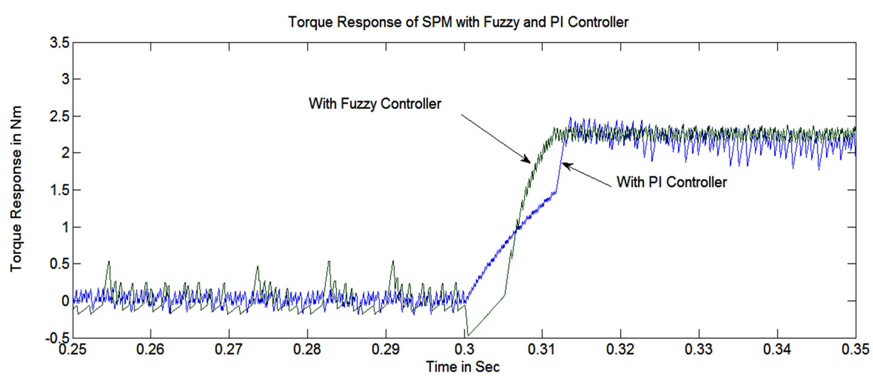


Figure 3: SPM's Torque Response With And Without A Load At T=0.3 Seconds Using DTC I

With a constant set speed of 1500 rpm, the dynamic analysis of the SPM drive is performed for a range of load torques provided at different times. Using a PI controller, it is seen that the torque response reaches a steady state with no time and minimal overshoot. However, the steady state response, as seen in Figure. 4, exhibits fewer ripples than the fuzzy controller.

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

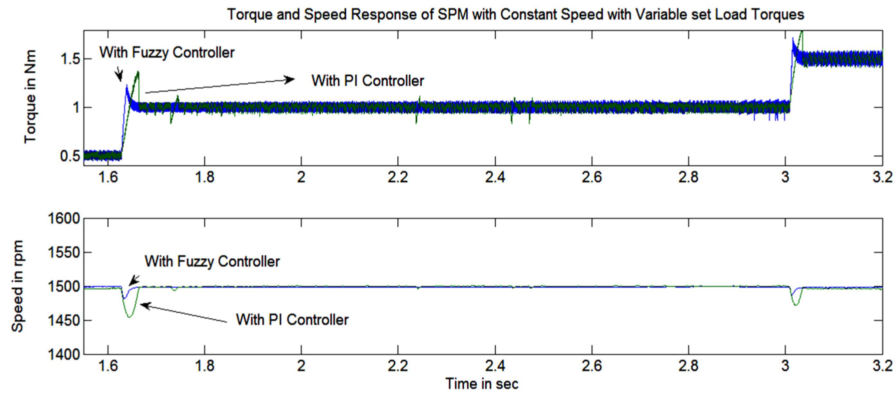


Figure 4: SPM's Torque And Speed Responses With DTC I At Constant Speed And Varying Loads

When the speed is increased from 500 rpm to 1000 rpm at t=1.59 sec, the torque response is slower and the speed response is faster with the fuzzy controller shown in Figure 5.

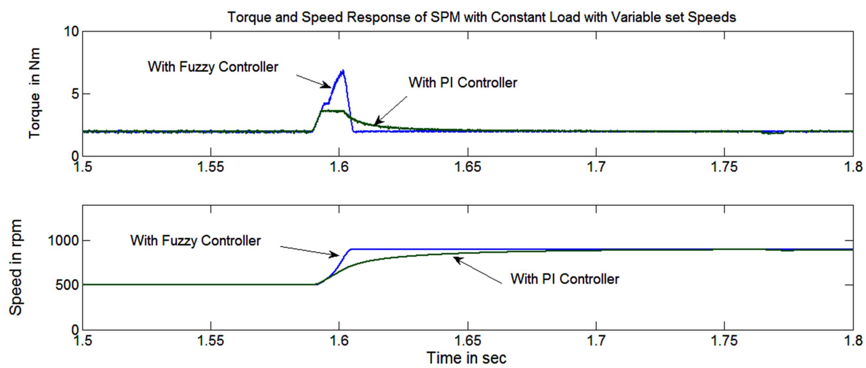


Figure 5: SPM's Torque And Speed Responses With Varied Set Speeds And Constant Load Torque Using DTC I

The torque ripple analysis for SPM with two controllers is seen in Figure. 6. With a PI controller, the torque ripples are larger and more noticeable. In contrast, FLC flattened the torque ripples. The flux ripple analysis of the SPM drive is shown in Figure 7.

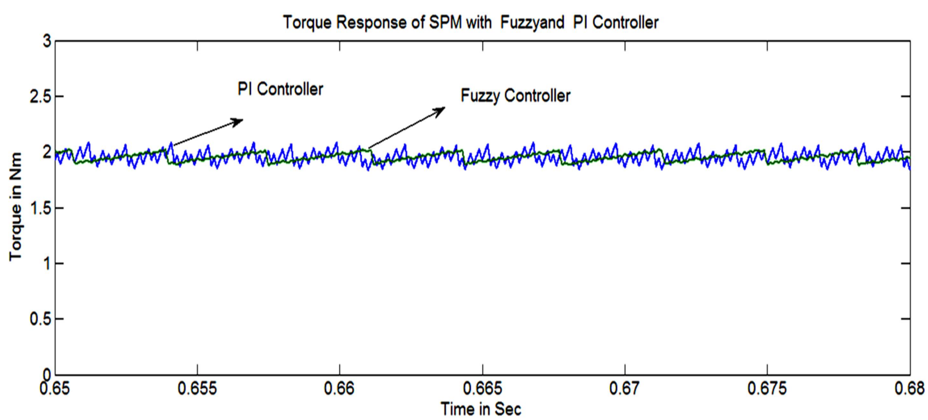


Figure 6: Torque Ripple Analysis Comparison Of SPM And DTC I

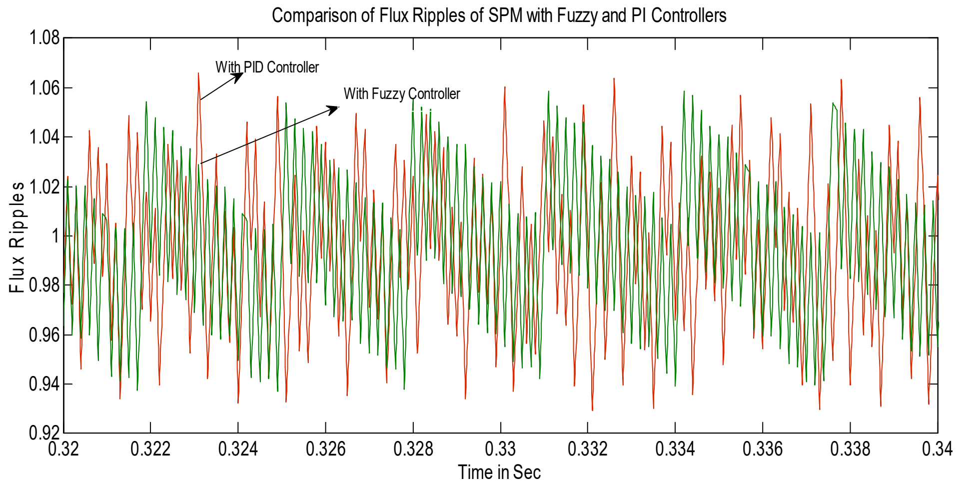


Figure 7: Flux Ripple Analysis Comparison Of SPM And DTC I

Table 2 provides a full examination of torque ripples, flux ripples, and THD of phase current and voltages for the following two cases for SPM:

(i). T_L= 1.5 Nm at 3000 rpm and 1500 rpm
(ii). T_L= 2.0 Nm at 3000 rpm and 1500 rpm.

Table 2: SPM With DTCI Using PIC And FLC

T_L (Nm)	N (rpm)	TR (%)		FR (%)		I_{ph} (THD) %		V_{ph} (THD) %	
		PIC	FLC	PIC	FLC	PIC	FLC	PIC	FLC
	1500	11.38	10.29	13.29	9.12	2.09	1.98	20.18	18.72
1.5	3000	16.46	12.40	11.57	7.98	2.52	2.52	22.92	22.92
	1500	11.68	9.12	12.81	9.78	1.32	1.21	20.89	20.14
2.0	3000	15.59	10.20	11.52	6.81	1.49	2.49	21.29	24.12

The dynamic performance of the SPM drive is tested utilising three space vectors while taking into account the on-line stator reference flux estimation using PI and FLCs. It is found that DTC III has reduced flux ripple (not substantially different from DTC II), but DTC I has lower torque ripple and phase current THD. Tables 3 through 8 make it clear that DTC I performs better in terms of SPM drive performance than CDTC and DCT II. Consequently, DTC I is considered when analysing the performance of the IPM drive.

Table 3: SPM With DTCI Using PIC At 3000 Rpm

t (sec)	T_L (Nm)	TR (%)	FR (%)	I_{ph} (THD) %	V_{ph} (THD) %
0.7	0.5	38.46	12.37	2.63	25.78
1.5	1.0	18.18	11.45	3.82	23.10
2.5	1.5	16.46	11.57	2.52	22.92
3.5	2.0	15.59	11.52	2.49	21.29
4.5	2.5	12.21	10.41	1.52	21.13

Table 4: SPM With DTCII Using PIC At 3000 Rpm

t (sec)	T_L (Nm)	TR (%)	FR (%)	I_{ph} (THD) %	V_{ph} (THD) %
0.7	0.5	53	10.02	4.3	34.71
1.5	1.0	26	9.56	3.97	32.82
2.5	1.5	20.5	8.5	3.33	33.21
3.5	2.0	18	7.12	3.06	33.90
4.5	2.5	16	5.55	2.4	31.21

Table 5: SPM With DTCIII Using PIC At 3000 Rpm

t (sec)	T_L (Nm)	TR (%)	FR (%)	I_{ph} (THD) %	V_{ph}(THD) %
0.7	0.5	33.33	12.45	5.1	35.21
1.5	1.0	25	11.52	4.79	32.18
2.5	1.5	22	12.20	3.71	31.25
3.5	2.0	21	12.04	3.63	32.18
4.5	2.5	14.81	10.63	3.26	32.92

Table 6: SPM With DTCI Using FLC At 3000 Rpm

t (sec)	T_L (Nm)	TR (%)	FR (%)	I_{ph} (THD) %	V_{ph} (THD) %
0.7	0.5	35.3	10.4	2.63	22.29
1.5	1.0	14.2	8.2	3.82	23.10
2.5	1.5	12.4	7.98	2.52	22.92
3.5	2.0	10.2	6.81	2.49	24.12
4.5	2.5	9.3	6.2	1.52	22.81

Table 7: SPM With DTCII Using FLC At 3000 Rpm

t (sec)	T_L (Nm)	TR (%)	FR (%)	I_{ph} (THD) %	V_{ph} (THD) %
0.7	0.5	48.2	9.21	3.12	26.89
1.5	1.0	22.13	8.08	4.23	26.21
2.5	1.5	16.38	7.68	2.81	24.29
3.5	2.0	13.45	7.1	2.54	25.18
4.5	2.5	13.18	5.02	1.98	24.72

Table 8: SPM With DTCIII Using FLC At 3000 Rpm

t (sec)	T_L (Nm)	TR (%)	FR (%)	I_{ph} (THD) %	V_{ph} (THD) %
0.7	0.5	31.5	11.42	4.8	28.21
1.5	1.0	24.7	9.1	4.12	29.18
2.5	1.5	19.2	10.02	3.12	27.64
3.5	2.0	18.8	9.21	3.21	28.35
4.5	2.5	12	8.12	2.9	26.31

Journal of Theoretical and Applied Information Technology
31st August 2025. Vol.103. No.16

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

5. DTC PERFORMANCE FOR IPM USING FUZZY LOGIC CONTROLLER AND PI CONTROLLER

Figures 8 to 13 display the simulated responses of IPM with PI and fuzzy controllers using the suggested DTC (DTC I). The IPM drive's dynamic reaction is depicted in this graph.

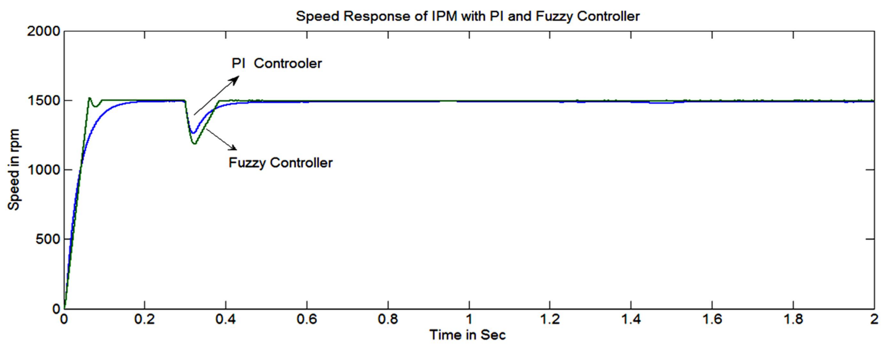


Figure 8: IPM's Speed Response With And Without A Load At T=0.3 Seconds Using DTC I

As seen in Figure 8, the drive is started at 1500 rpm with no load. Figure 8 shows that there is no overshoot, undershoot, or steady state error and that the IPM drive with FLC matches the instruction speed within 0.08 seconds. On the other hand, it takes a long time for the PI controller to reach the steady state. The IPM drive is subjected to T_L = 1.95 N-m at t = 0.3 sec. When there are load disturbances in either controller, the speed briefly follows and then quickly reaches the reference value. But compared to a PI controller, a fuzzy controller allows the drive to achieve the reference value more quickly.

The torque responses of IPM with no load and with a load imposed at state t = 0.3 sec are shown in Figure. 9. The drive with FLC has a lower stable error than the one with PI Controller. It is evident from 0.6 seconds onwards.

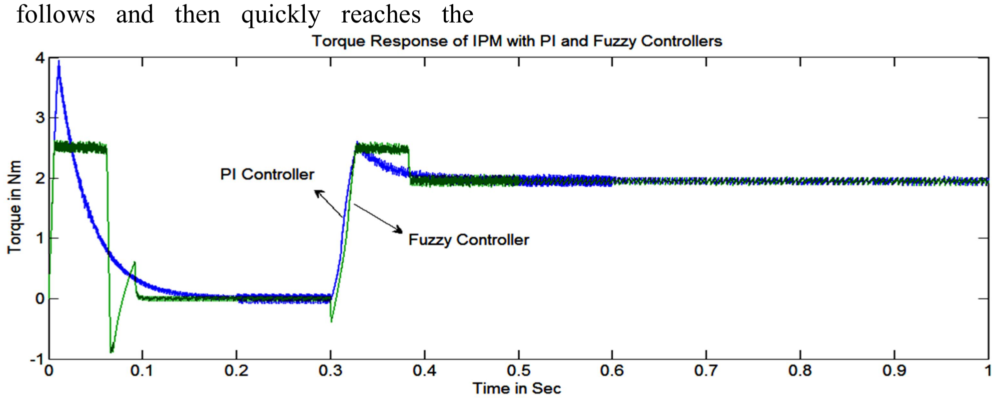


Figure 9: IPM's Torque Response With And Without A Load At T=0.3 Seconds Using DTC I

The torque and speed responses of IPM with a constant load and various set speeds are shown in Figure. 10. The dynamic reaction of speed is smoother and faster with FLC while the speed is changing from 500 rpm to 1000 rpm at t=1 sec. Additionally, FLC has a lower steady state speed error than PI controllers. Additionally, there are more variations in the torque response when using a PI controller.

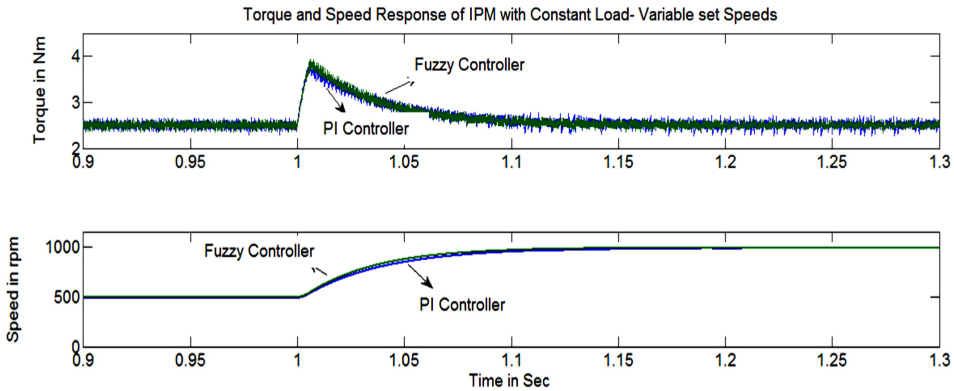


Figure 10: IPM's Torque And Speed Responses With Varied Set Speeds And Constant Load Torque Using DTCI

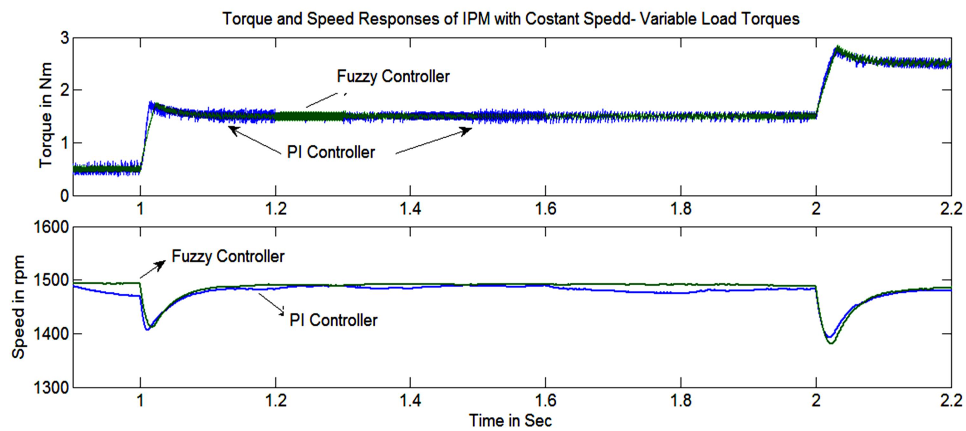


Figure 11: IPM's Torque And Speed Responses With DTC I At Constant Speed And Varying Loads

The torque and speed responses of IPM with varying load torques and constant speed are shown in Figure. 11. The speed response is smooth with FLC when the load varies from 0.5 Nm to 1.95 Nm at t=1sec and 1.95 Nm to 2.5 Nm at t=2sec. With a PI controller, the torque response's steady state inaccuracy varies considerably.

The torque ripple analysis for IPM with two controllers is seen in Figure. 12. With a PI controller, the torque ripples are larger and more noticeable. In contrast, FLC flattened the torque ripples. The flux ripple analysis of the IPM drive is shown in Figure. 13

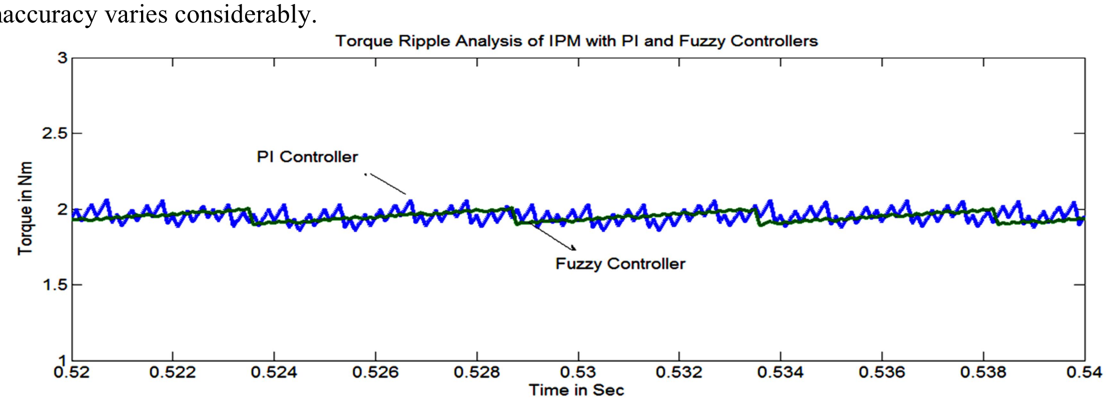


Figure 12: Torque Ripple Analysis Comparison Of IPM And DTC I

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

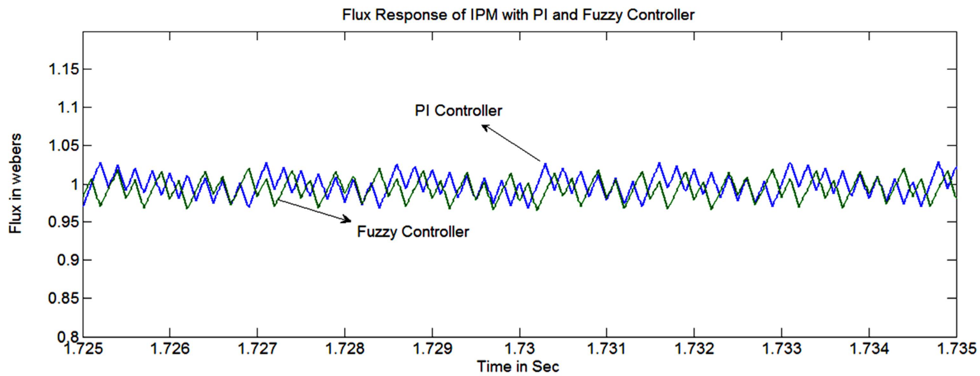


Figure 13: Flux Ripple Analysis Comparison Of IPM And DTC I

Table 3 provides a full examination of torque ripples, flux ripples, and THD of phase current and voltages for the following two cases for IPM

(i). T_L= 1.5 Nm at 3000 rpm and 1500 rpm

(ii). T_L= 2.0 Nm at 3000 rpm and 1500 rpm

Table 3: Dynamic Performance Of DTC For IPM Using PI And Fuzzy Controller

T_L (Nm))	N (rpm)	TR (%)		FR (%)		I_{ph} (THD) %		V_{ph} (THD) %	
		PI Controller	Fuzzy Logic Controller	PI Controller	Fuzzy Logic Controller	PI Controller	Fuzzy Logic Controller	PI Controller	Fuzzy Logic Controller
	1500	16.21	8.86	15.71	11.63	3.43	1.58	24.29	22.78
1.5	3000	21.49	15.0	9.82	6.45	5.78	2.63	23.18	23.46
	1500	12.38	5.43	13.59	4.3	3.21	1.22	25.62	24.67
2.0	3000	15.74	11.32	12.79	10.33	4.62	2.63	23.77	24.51

6. COMPARISON OF THE PROPOSED WORK WITH EXISTING

Case I: [31] [32][33]

The torque and phase current THD using a three-level inverter [31][32][33],
It is found that with a two-level inverter using DTC I-FLC, the values obtained are 9.3 % and 1.52 % respectively.

Method	Torque Ripple (%)	Phase Current (THD)%
Y, Zhang et al.[Jan-2011]	12.22	5.85
Y.Zhanget al.[Oct.2011]	11.10	4.67
DTCI Method I [3 Level Inverter][SivaPrakasam-JPE-2013]	19.56	6.97
DTC Method II [3 Level Inverter][SivaPrakasam-JPE-2013]	15.63	5.70
DTC Method III [3 Level Inverter][SivaPrakasam-JPE-2013]	**10.92**	4.40
DTC Method IV [3 Level Inverter][SivaPrakasam-JPE-2013]	11.07	5.28
Two-Level Inverter		
DTC 1	12.21(PI)	1.52
	9.3(Fuzzy)	1.52

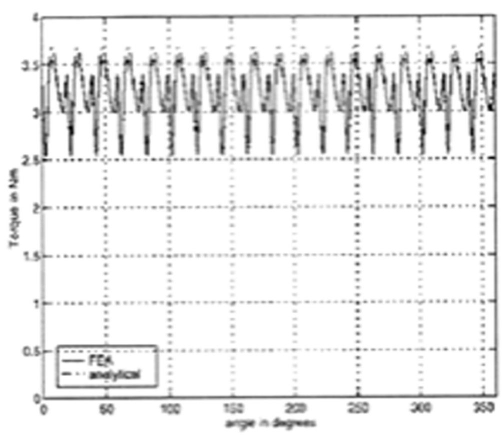
DTC II	1.6(PI)	2.54
	13.18(Fuzzy)	1.98
DTC III	14.81(PI)	3.26
	12(Fuzzy)	2.9
FPGA (DTC I)	18.23(PI)	4.02
	19.54(Fuzzy)	4.02

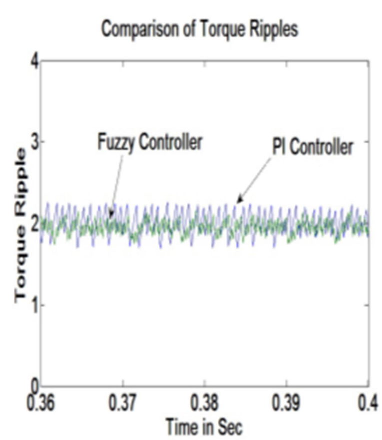
Case II: [31]

The torque and phase current THD are compared with [31], it is found that the torque and phase current THD are 9.8% and 2.53% respectively for a three-level inverter with DTC I using PI. Whereas in [31] the values obtained are 10.92 % and 4.40 %

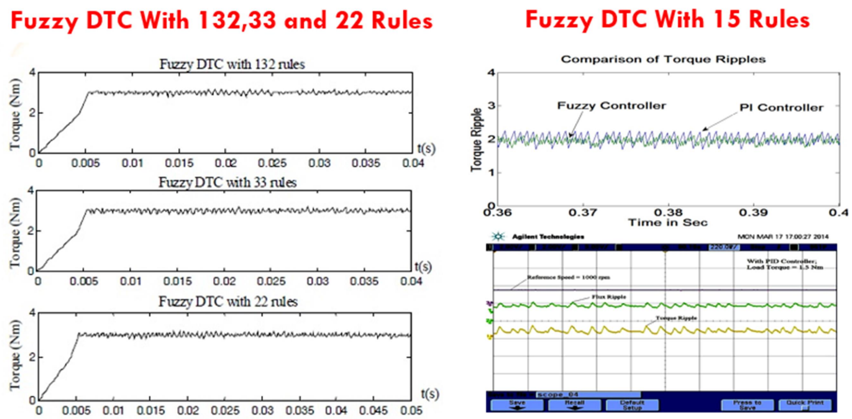
Method	Torque Ripple (%)	Phase Current (THD)%
Three-Level Inverter		
DTCI Method I [SivaPrakasam-JPE-2013]	19.56	6.97%
DTCI Method II [SivaPrakasam-JPE-2013]	15.63	5.70%
DTCI Method III [SivaPrakasam-JPE-2013]	10.92	4.40%
DTCI Method IV [SivaPrakasam-JPE-2013]	11.07	5.28%
Three-Level Inverter		
SVM	50%	3.03%
DTC-SVM	9.8%	2.53%
Five-Level Inverter		
SVM	38.4%	3.03%
DTC-SVM	7.2%	2.11%

Case III: [34]
The torque ripple are obtained in this work is found to be less with PI and Fuzzy control for SPM as compared to the torque ripples presented in [34]





Case IV: [35]
In this work by using 15 rules the magnitude of the torque ripples is found to be less when compared with [35].



7. CONCLUSION

Using PI and FLCs with a two-level inverter, the simulation is run for both DTC-SVM fed SPM and IPM drives while taking the online reference stator flux into account. This work uses MATLAB/Simulink to model IPM and SPM utilising PI and FLCs and three sets of space vectors of DTC. The comparison results obtained demonstrate that the torque, flux ripple reduction, and reduced THD for phase currents of the PMSM drive are all improved by the vectors associated with DTC I.

To achieve precise control of torque and flux linkages in DTC, a suitable voltage space vector with a smaller hysteresis band is essential. FLC is required since DTC does not provide accurate mathematical results with standard controllers like PI. A proper voltage space vector with a lower hysteresis range is necessary to accomplish accurate control of torque and flux linkages in DTC. Since DTC does not yield precise mathematical answers when using typical controllers like PI, FLC is necessary. When using FLC instead of PI controllers, the torque and flux ripples are reduced. The suggested FLC with a straightforward design methodology and fewer rules provides better dynamic response than the PI controller, according to the results.

The system's performance indexes provide strong evidence for this. Further research is done for SPM drives just because the torque flux and speed wave patterns are smoother in SPM cases than in IPM cases. Engineers are increasingly recommending permanent magnet synchronous motors (PMSMs) due to the need for increased energy efficiency and precise operation. The PMSM is highly effective in an appliance because it uses a permanent magnet on the rotor to provide a steady rotor magnetic field. Because of these motors' various benefits, industry and researchers are interested in using them in a variety of applications.

For a drive to have strong dynamic performance, torque ripples are crucial. The drive's performance is harmed by the torque ripples that follow and the ensuing speed fluctuations. The performance of the PMSM drive is deteriorated, especially at low speeds, by these torque pulsations, which fluctuate periodically with rotor position and manifest as speed ripple. For machine cutting tools, for instance, steady torque is crucial to the successful dynamic operation of a drive.

In vector control of AC drives DTC is a simple method, as coordinate transformation is not required hence it does not need current controllers. The prime drawback of DTC is high torque and flux pulsations, by minimizing torque and flux pulsations the performance of PMSM drive can be better using DTC. Therefore, a multi level torque controller and flux controller must be designed to replace instead of two/three level hysteresis controllers in order to minimize the torque.

The scope of the work may be carried out further in reduction of torque ripple, flux ripple, voltage and current THD waveforms by incorporating Multi Level SVM of DTC algorithm using Genetic Algorithm along with Model Reference Adaptive Controller.

In the present work, FLC implementation of torque hysteresis controller for PMSM drive is designed and discussed. Further the same logic using FLC can also be extended to flux controller. Torque and flux ripples can be minimized to a great extent with FLC implementation for both torque and flux controllers. This is very much essential especially to have a smooth control of a drive in many applications like electric power steering.

REFERENCES

[1] C.French and P acarnley, " Direct torque control of permanent magnet drives", IEEE Trans on Industrial Applications", vol 32, Issue:5, Sep-Oct 1996, pp 1080-1088

[2] S. Wang, H. Gan, Y. Luo, X. Wang and Y. Chen, "A Fractional-Order Reset ADRC Scheme for PMSM Speed Servo System," 2024 20th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA), Genova, Italy, 2024, pp. 1-6, doi: 10.1109/MESA61532.2024.10704835.

[3] F. F. M. El-Sousy, M. M. Amin, A. S. Soliman and O. A. Mohammed, "Optimal Adaptive Ultra-Local Model-Free Control Based-Extended State Observer for PMSM Driven Single-Axis Servo Mechanism System," in IEEE Transactions on Industry Applications, vol. 60, no. 5, pp. 7728-7745, Sept.-Oct. 2024, doi: 10.1109/TIA.2024.3401097

[4] Shih-Chin Yang, Takahiro Suzuki, Robert D. Lorenz, Thomas M. Jahns, " Surface-Permanent-Magnet Synchronous Machine Design for Saliency-Tracking Self-Sensing Position Estimation at Zero and Low Speeds", IEEE Transactions on Industry Applications, Vol. 47, No. 5, September/October 2011, pp no :2103-2116

[5] Marco Tursini, Enzo Chiricozzi, and Roberto Petrella," Feed forward Flux-Weakening Control of Surface-Mounted Permanent-Magnet Synchronous Motors Accounting for Resistive Voltage Drop" IEEE Transactions on industrial electronics, vol. 57, No 1, January 2010 pp no 440-448

[6] Luís Romeral, Julio César Urresty, Jordi-Roger Riba Ruiz and Antonio Garcia Espinosa, "Modeling of Surface-Mounted Permanent Magnet Synchronous Motors With Stator Winding Interturn Faults", IEEE Transactions on Industrial Electronics, Vol. 58, No. 5, May 2011, pp no : 1576-1585

[7] Ronghai Qu, and Thomas A. Lipo, "Analysis and Modeling of Air-Gap and Zigzag Leakage Fluxes in a Surface-Mounted Permanent-Magnet Machine", IEEE Transactions on Industry Applications, Vol. 40, No. 1, January/February 2004, pp no: 121-127

[8] K. Boughrara, D. Zarko, R. Ibtiouen, O. Touhami and A. Rezzoug, "Magnetic Field Analysis of Inset and Surface-Mounted Permanent-Magnet Synchronous Motors Using Schwarz–Christoffel Transformation", IEEE Transactions on Magnetics, Vol. 45, No. 8, August 2009, pp no: 3166-3178

[9] Tae-Suk Kwon,Seung-Ki Sul, "Novel Antiwindup of a Current Regulator of a Surface-Mounted Permanent-Magnet Motor for Flux-Weakening Control" IEEE Transactions on industry applications, vol 42, No. 5, pp no: 1293 – 1300, September/October 2006.

[10] Jiunn-Jiang Chen and Kan-Ping Chin, "Minimum Copper Loss Flux-Weakening Control of Surface Mounted Permanent Magnet Synchronous Motors", IEEE Transactions on Power Electronics, Vol. 18, No. 4, July 2003, pp No: 929-936

[11] Ping-Yi Lin and Yen-Shin Lai, "Voltage Control Technique for the Extension of DC-Link Voltage Utilization of Finite-Speed SPMSM Drives", IEEE Transactions on Industrial Electronics, Vol. 59, No. 9, September 2012,pp no: 3392- 3402

[12] Xavier del Toro Garcia, Branislav Zigmund, Angela A. Terlizzi, Rastislav Pavlanin, Ligui Salvatore, "Comparison between FOC and DTC Strategies for Permanent Magnet Synchronous Motors", Advances in Electrical and Electronic Engineering, 2006,Vol 5, No 1,pp No:76-81.

[13] Isao Takahashi and Toshihiko Noguchi, "A New Quick- Response and High-Efficiency Control Strategy of an Induction Motor", IEEE Trans. Ind. Appl., Vol.IA.22, No.5, pp. 820-827, Sep/Oct, 1986

[14] Pavel BRANDSTETTER, Petr CHLEBIS, Petr PALACKY , "Direct Torque Control of Induction Motor with Direct Calculation of Voltage Vector", Advances in Electrical and Computer Engineering, Volume 10, Number 4, 2010, pp No:17-22.

[15] M. S. Merzoug, and F. Naceri, "Comparison of Field-Oriented Control and Direct Torque Control for Permanent Magnet Synchronous Motor (PMSM)", World Academy of Science, Engineering and Technology 45, 2008 ppNo: 299-304

[16] R. G. Shriwastava, D. R. Bhise and P. Nagrale, "Comparative Analysis of FOC Based Three Level DCMLI Driven PMSM

Drive," 2019 International Conference on Innovative Trends and Advances in Engineering and Technology (ICITAET), Shegoaon, India, 2019, pp. 26-31, doi: 10.1109/ICITAET47105.2019.9170242.

[17] Zhong, M.F. rahman, w.Y.Hu and K.W. Lim, " Analysis of direct torque control in permanent magnet synchronous motor drives", IEEE Trans. On power Electronics, vol 12 Issue: 3, may 1997, pp No: 528- 536.

[18] Fatiha Zidani, Rachid Nait Said, "Direct Torque Control of Induction Motor With Fuzzy Minimization Torque Ripple", Journal of Electrical Engineering, Vol. 56, No. 7-8, 2005, pp No:183–188

[19] Dan SUN, Yikang HE, Jian Guo ZHU, "Fuzzy Logic Direct Torque Control for Permanent Magnet Synchronous Motors", Proceedings of the 5Ih World Congress on Intelligent Control and Automation, June 15-19, 2004, Hangzhou. P.R. China

[20] Amit Vilas Sant and K. R. Rajagopal, " PM Synchronous Motor Speed Control Using Hybrid Fuzzy-PI With Novel Switching Functions", IEEE Transactions on Magnetics, Vol. 45, No. 10, October 2009, pp no: 4672-4675.

[21] Junzhi Yu, Xiaolei Hu, Rui Ding, "Fuzzy Logic PID Based Control Design for Permanent Magnet Synchronous Motor Servo System",Second International Conference on Intelligent Computation Technology and Automation, 2009,pp no: 728- 731.

[22] Kein Huat Chua, Yun Seng Lim, Stella Morris and Jianhui Wong, "Improved Performance of PMSM Speed Responses Using a Hybrid Fuzzy/ PI Controller", 2010 IEEE International Conference on Power and Energy (PEcon2010) Nov 29- Dec 1, 2010 Kuala Lumpur, Malaysia pp no: 474-479

[23] Amir Mehdi Yazdani, Ahmadreza Ahmadi, Salinda Buyamin, Mohd Fua'ad Rahmat, Farshad Davoudifar And Herlina Abd Rahim, "Imperialist Competitive Algorithm-Based Fuzzy PID Control Methodology For Speed Tracking Enhancement Of Stepper Motor", International Journal On Smart Sensing And Intelligent Systems, Vol. 5, No. 3, September 2012, Pp No: 717-741

[24] Feng Yang, Qingwang Song, Lei Wang,"Fuzzy-Logic-Based Direct Torque Control Research on Permanent Magnet Synchronous Motor", Proceedings of 2012 International Conference on Mechanical Engineering and Material Science (MEMS 2012),pp No: 283-286

[25] Z. Tang, L. Wang, J. Han, D. Wang and X. Li, "Multi-Objective Optimal Tuning Framework of the Entire PMSM-Driven Servo System Considering High-Frequency Disturbance Suppression," in IEEE Access, vol. 13, pp. 11957-11968, 2025, doi: 10.1109/ACCESS.2025.3529983

[26] Dan SUN, Yikang HE, Jian Guo ZHU, "Fuzzy Logic Direct Torque Control for Permanent Magnet Synchronous Motors", Proceedings of the 5Ih World Congress on Intelligent Control and Automation, June 15-19, 2004, Hangzhou. P.R. China

[27] Kamel Boughrara, Brahim Ladghem Chikouche, Rachid Ibtiouen, Damir Zarko, and Omar Touhami, "Analytical Model of Slotted Air-Gap Surface Mounted Permanent-Magnet Synchronous MotorWith Magnet Bars Magnetized in the Shifting Direction", IEEE Transactions on Magnetics, Vol. 45, No. 2, February, 2009, pp.No: 747-758.

[28] Sukanta Halder,Pramod Agarwal,S.P. Srivastava,"Comparative analysis of MTPA and ZDAC control in PMSM drive", 2015 Annual IEEE India Conference (INDICON),17-20 Dec.2015

[29] N. Krishna Kumari, G. Tulasi Ram Das, and M.P.Soni, Online Stator Reference Flux Approach to Torque Ripple Minimization for SPM Drive using Fuzzy and PI Controllers, ICGST-ACSE Journal, ISSN: 1687-4811, Volume 15, Issue 1, Delaware, USA, June 2015 , pp Nos: 31-38

[30] Lixin Tang, Limin Zhong, Muhammed Fazlur Rahman and Yuwen Hu, "A Novel Direct Torque Control for Interior Permanent-Magnet Synchronous Machine Drive With Low Ripple in Torque and Flux—A Speed-Sensorless Approach", IEEE Transactions on Industry Applications, Vol. 39, No. 6, November/December 2003, pp.No: 1748-1756.

[31] Sivaprakasam Arumugam, Manigandan Thathan "Novel Switching Table for Direct Torque Controlled Permanent Magnet Synchronous Motors to Reduce Torque Ripple", Journal of Power Electronics, Vol. 13, No. 6, pp. 939-954, November 2013

[32] Y. Zhang and J. Zhu, "Direct torque control of permanent magnet synchronous motor with reduced torque ripple and commutation frequency," IEEE Trans. Power Electron., Vol. 26, No. 1, pp. 235–248, Jan. 2011.

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

[33] Y. Zhang and J. Zhu, "A Novel Duty Cycle Control Strategy to Reduce Both Torque and Flux Ripples for DTC of Permanent Magnet Synchronous Motor Drives with Switching Frequency Reduction," IEEE Trans. Power Electronics., Vol. 26, No. 10, Oct. 2011, pp. 3055-3067

[34] Amuliu Bogdan Proca, Ali Keyhani, Ahmed EL-Antably,Wenzhe Lu, and Min Dai, "Analytical Model for Permanent Magnet Motors With Surface Mounted Magnets", IEEE Transactions on Energy Conversion, Vol. 18, No. 3, September 2003, , pp no: 386-391.

[35] A. Tlemcani, O. Bouchhida, K. Benmansour, D. Boudana and M. S. Boucherit, "Direct Torque Control Strategy (DTC) Based on Fuzzy Logic Controller for a Permanent Magnet Synchronous Machine Drive",Journal of Electrical Engineering & Technology, Vol. 4, No.1, 2009, pp. 66-78.