Performance Analysis of PMSM Using a DTC-based ANFIS Controller for Electric Vehicle

Marulasiddappa H B[1], Pushparajesh Viswanathan[2]

[1]*Research Scholar, JAIN - A Deemed to be University, Bengaluru, Karnataka, India*
Email*: marul.bethu@gmail.com
ORCID: 0000-0001-7558-3579
[2]*Associate Professor, JAIN - A Deemed to be University, Bengaluru, Karnataka, India*
v.pushparajesh@jainuniversity.ac.in

Abstract: Now a day's environment pollution is the major concern in designing vehicles. Until now internal combustion engine (ICE) vehicles takes a major part in vehicle manufacturing. Day by day, the use of ICE are deteriorating because of pollution and less fuel availability. In the present scenario, the electric vehicle (EV) plays a major role in the place of an ICE vehicle. The performance of EVs can be improved by the proper selection of electric motors. Initially, EV preferred induction motors for traction purposes, but due to complexity in controlling the induction motor, the permanent magnet synchronous motor (PMSM) is replacing the induction motor in EV due to its advantages. Direct torque control (DTC) is one of the known techniques for PMSM drive in EV to control the torque and speed. However, the presence of torque ripple is the main drawback of this technique. Many control strategies are followed to reduce the torque ripples in PMSM. Adaptive neuro-fuzzy inference system (ANFIS) controller strategy is explained to reduce torque ripples and settling time. Here, the performance parameters like torque, speed and settling time are compared between the conventional proportional-integral (PI) controller and the ANFIS controller.
Keywords: Direct torque control **(**DTC), Electric vehicle (EV), Torque ripple, PMSM

1. Introduction

In the early days, the DC motor was the better choice for electric vehicles because of their simpler control method and its characteristics and hence is most preferable for EV motor. The presence of a commutator and brushes makes the motor more complex for an electric vehicle. To overcome complexity in the structure of the DC motor, induction motors (IM) are used in EV applications [1]. The absence of a commutator and brushes makes it simple in construction. Analysis of IM becomes complex due to its nonlinear characteristics [2]. To overcome IM drawbacks, permanent magnet synchronous motor (PMSM) finds development in EV. PMSM has a higher current density and is more efficient than an induction motor. Hence, it is very much suitable for EV applications. Comparison is made in Table 1 on electric motors with respect to different parameters.

Table 1 Comparison of different motors for electric vehicle [3]

Parameter/motor	**PMSM**	**SRM**	**IM**	**DC**
Efficiency	High	Low	Low	Low
Power density	High	Low	Low	Low
Controllability	Medium	Low	High	High
Reliability	Medium	High	High	Low

It is better to choose a suitable motor for an electric vehicle depending on its requirements. Brushless DC motors are a better choice for 2-wheelers. PMSM or induction motors are a good choice for four-wheeler vehicles. However, when considering the efficiency and power density, PMSM is a better choice for an electric vehicle. For EV applications, controlling torque over a wide range is necessary. Complexity in controlling a PMSM drive is one of the drawbacks. Scalar and vector controls are the basic control methods for AC drives. Scalar control gives a good steady-state performance. To get highly accurate and good dynamic performance vector control methods are used. The proportional-integral (PI) controller is a commonly applied controller rather than a PID controller, but it leads to instability in the system. Field Oriented Control (FOC) is used to improve steady-state performance and to reduce torque ripples. FOC improves the dynamic response [4], [5] and increases its performance. However, this method is sensitive to small changes in the parameter when temperature changes. Many control strategies are proposed to improve the performance of PMSM motor. These authors [6] established a new technique called direct torque control (DTC) in place of FOC drawbacks. DTC has the capability to control torque and flux directly by increasing the efficiency of the PMSM drive. The simplicity of DTC has one of the major advantages. The conventional DTC produces more torque and flux ripples and parameters like torque and flux are measurable efficiently [7], [8]. This paper [9] uses to look up table-based vector control for switched reluctance motor to improve the torque response. This paper [10] explains a new strategy called a combination of PI and iterative learning control (PI-ILC) for a repetitive task in a control system. This control technique is used to reduce the speed signal ripples if this motor has repetitive tasks.

This paper [11] establishes a hybrid intelligent controller, which reduces the torque, ripples and improves performance. The author [12] delivered new hybrid technique for dual phase PMSM where he achieved good dynamic response. In this proposed technique [13], inter turn fault produces ripple in the torque, hence torque injection is applied to minimize it. Section II explains the modeling of the PMSM drive. Section III describes the ANFIS controller, section IV explains the results, and finally, section V gives the conclusion.

2. PMSM Mathematical modeling

PMSM modeling is explained by taking rotor as reference. The following equations [9], [10] are expressed for PMSM with respect to rotor reference.

$$\begin{bmatrix} v_{qs}^r \\ v_{ds}^r \end{bmatrix} = \begin{bmatrix} R_s + L_q p & \omega_r L_q \\ -\omega_r L_q & R_s + L_d p \end{bmatrix} \begin{bmatrix} i_{qs}^r \\ i_{ds}^r \end{bmatrix} + \begin{bmatrix} \omega_r \Psi_{af} \\ 0 \end{bmatrix} \quad (1)$$

$$\Psi_{af} = L_q * i_{fr} \quad (2)$$

Where, superscript 'r' represents rotor reference frame, v_{ds}^r = d-axis voltage , i_{ds}^r = d-axis current, v_{qs}^r = q-axis voltage, i_{qs}^r= q-axis current, P = is number of poles, Ψ_{af} = permanent magnet flux linkage, L_m = mutual inductance, L_d = d-axis inductance, R_s = stator resistance, ω_r = rotor speed, L_q = q-axis inductance.

The torque equation of a PMSM is given as:

$$T_e = \frac{3}{2} * \frac{P}{2} (\Psi_{af} * i_{qs}^r + \left(L_d - L_q\right) * i_{qs}^r * i_{ds}^r \quad (3)$$

The resultant flux linkage is:

$$\Psi_{res} = \sqrt{(\left(\Psi_{af} + L_d * i_{ds}^r\right)2 + \left(L_d * i_{qs}^r 2\right)} \quad (4)$$

Proposed methodology

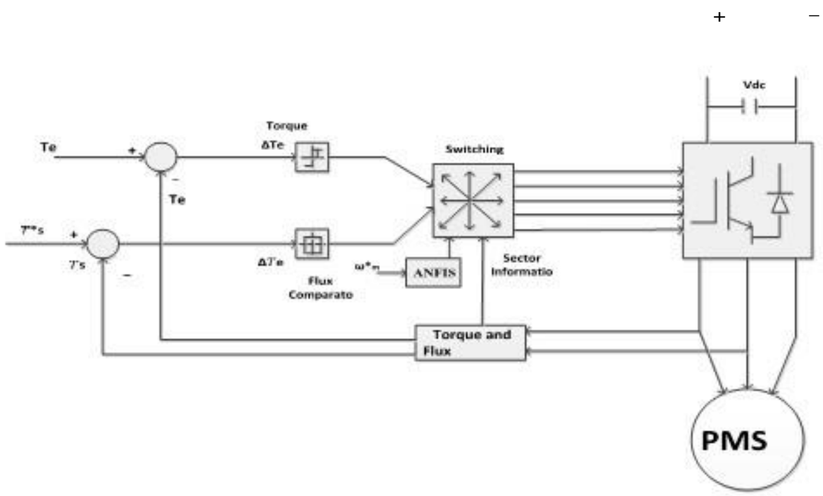


Figure. 1 Block diagram of proposed controller

Figure 1 shows the block diagram of proposed controller. Generally, flux estimation is done by using current modeling, voltage modeling, or by using both. Proper control of the drive system is necessary to determine the proper flux in direct torque control based PMSM. For low-frequency operations, the determination of flux is based on current modeling. To understand this stator current and rotor mechanical position is necessary. Rotor parameters cause more errors in the speed estimation of PMSM. To avoid these errors DTC proposes voltage model to calculate torque and flux by using equations (5)-(7). In the DTC position,sensors are absent and only stator resistance is considered.

$$\Psi_{s\alpha} = \int (V_{s\alpha} - Rs\, i_{s\alpha})dt \tag{5}$$

$$\Psi_{s\beta} = \int (V_{s\beta} - Rs\, i_{s\beta})dt \tag{6}$$

The torque is given by:

$$T_e = \frac{3}{2} * p(\Psi_{s\alpha}\, i_{s\beta} - \Psi_{s\beta}\, i_{s\alpha}) \tag{7}$$

The torque has an input -1, 0, +1 corresponding to flux values 1 and 0. The vectors are selected appropriately whether errors are outside or inside the hysteresis bands. The selected vectors should not make flux and torque errors leave the hysteresis bands. There are six switches and eight voltage vectors. The selection of an appropriate voltage vector improves the overall performance and reduces ripples in the torque and flux.
The following Table 2 gives the lookup table for the PMSM drive.

Table 2 Look-Up Table

Flux error	Torque error	Q1	Q2	Q3	Q4	Q5	Q6
1	1	V2(110)	V3(010)	V4(011)	V5(001)	V6(100)	V1(100)
	0	V0(000)	V7(111)	V0(000)	V7(111)	V0(000)	V7(111)
	-1	V6(100)	V1(100)	V2(110)	V3(010)	V4(011)	V5(001)
0	1	V3(010)	V4(011)	V5(001)	V6(100)	V1(100)	V2(110)
	0	V7(111)	V0(000)	V7(111)	V0(000)	V7(111)	V0(000)
	-1	V5(001)	V6(100)	V1(100)	V2(110)	V3(010)	V4(011)

3. Results

There are two cases studied. Case 1 is a PI controller-based speed control and the second case is an ANFIS-based speed control. The following Figure. 2 gives the characteristic curve of speed in PI controller in DTC where the speed settles at 0.25 secs. The following Figure 3 gives the torque characteristics of PI controller in DTC; here, the maximum peak of the torque goes to 67 Nm. Then, the voltage curve is shown in Figure 4 and the current characteristics are in Figure.5.

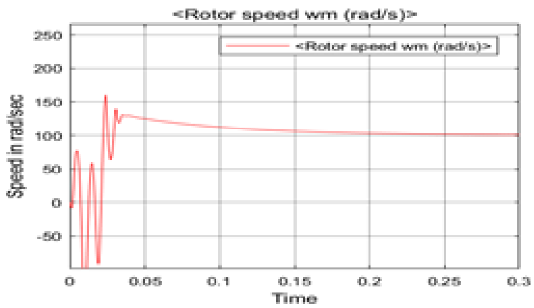


Figure. 2 Speed waveform of PI control method

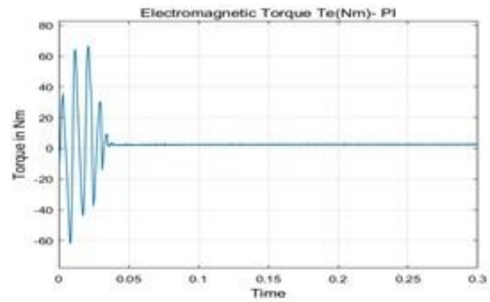


Figure. 3 Torque waveform of PI control method

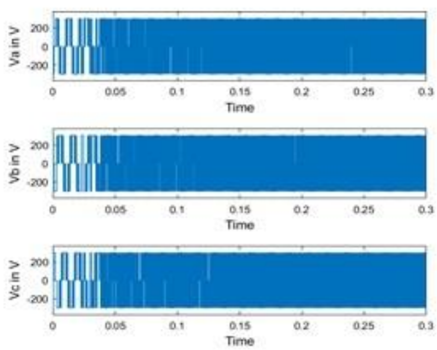


Figure. 4 Voltage curve of PI control method

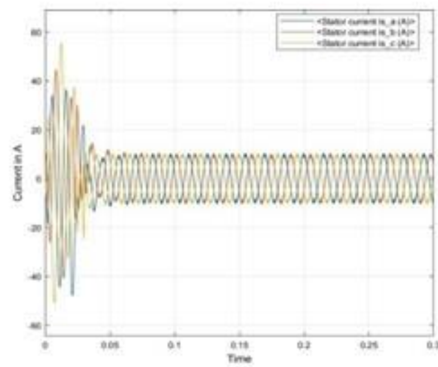


Figure. 5 Current curve of PI control method

Speed behavior of the ANFIS is shown in Figure 6. Using DTC. It shows that the settling time of speed is 0.07 secs, which is faster than the PI controller. The torque behavior of the ANFIS controller is shown in Figure 7 using DTC, here the maximum torque goes to 39 Nm. Figure. 8 shows the current characteristics of the DTC based ANFIS controller. Figure 9 shows the comparison of the speed curve between PI and ANFIS controller in DTC. Then Figure 10 shows the comparison of torque curve between PI and ANFIS controller in DTC. In this comparison, the speed settling is faster in ANFIS andthe torque ripple minimization is happening in ANFIS.

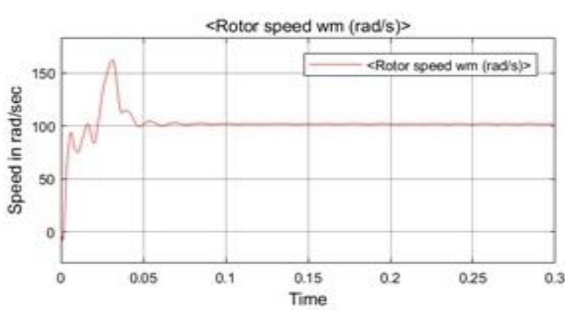


Figure 6 Speed characteristics of ANFIS controller in DTC

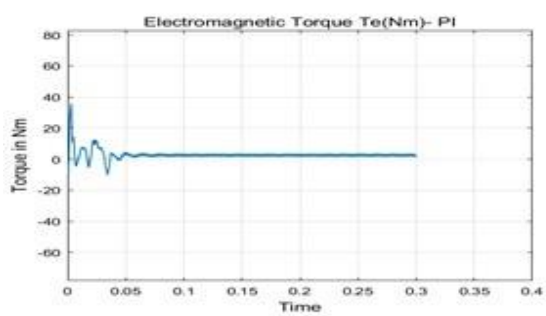
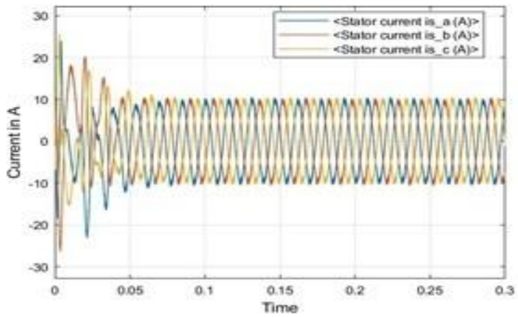


Figure 7 Torque characteristics of ANFIS controller in . DTC



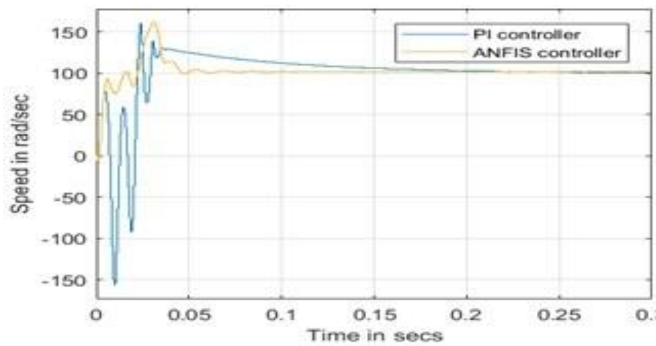


Figure 8 Current characteristics of ANFIS controller in DTC

Figure 9 Speed waveforms comparison between two controller in DTC

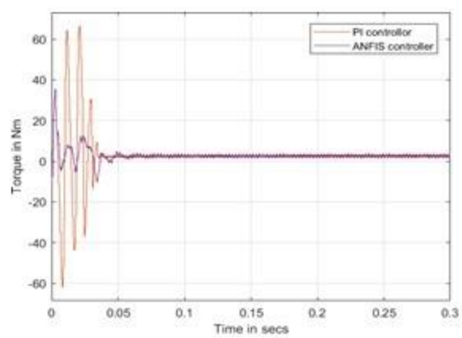


Figure 10 Torque curve comparison between PI and ANFIS controller DTC

Table 3 Comparison of torque values of PI controller and ANFIScontroller

Technique	**Torque In N-M**			**Parameters**		
	Maximum value	**Minimum value**	**MEAN**	**σ_T**	**T_r**	t_s sec
PI Controller	65.2	28.570	42.410	8.130	0.720	0.0720
ANFIS	65.64	40.17	54.48	6.53	0.47	0.048

Where, σ_T = total torque, t_s = Settling time, T_r = torque ripple co-efficient, Max = torque max value, Min = minimum value of torque, Mean = mean value of total torque.

4. Conclusion

This work illustrates the ANFIS-based direct torque controlled PMSM drive system and simulation results are shown for both controllers. With the use of a proper lookup table, torque error is minimized within the described hysteresis band. Table 3 compares the ANFIS controller with the PI controller for different parameters. The torque ripple coefficient of the ANFIS controller is 0.47 which is low compared to 0.72 of the PI controller. Settling time is low in the ANFIS controller than PI controller and hence torque ripples are considerably low in comparison to the PI control method. It can be concluded from the results that, operational parameters of the ANFIS is better than conventional PI control method.

5. References

[1] Tabbache, B., Kheloui, A., & Benbouzid, M. E. H. (2010, September). Design and control of the induction motor propulsion of an electric vehicle. In *2010 IEEE Vehicle Power and Propulsion Conference* (pp. 1-6). IEEE.

[2] Gdaim S, Mtibaa A and Mimouni M “Design and experimental implementation of DTC of an induction machine based on fuzzy logic control on FPGA” IEEE Trans. Fuzzy Sys., vol. 23, no. 3, pp. 644-655, Jun. 2015.

[3] Hashemnia, N., & Asaei, B. (2008, September). Comparative study of using different electric motors in the electric vehicles. In *2008 18th International Conference on Electrical Machines* (pp. 1-5). IEEE.

[4] El Ouanjli, N., Derouich, A., El Ghzizal, A., Chebabhi, A., & Taoussi, M. (2017, November). A comparative study between FOC and DTC control of the Doubly Fed Induction Motor (DFIM). In *2017 International Conference on Electrical and Information Technologies (ICEIT)* (pp. 1-6). IEEE.

[5] Mehazzem, F., Nemmour, A. L., & Reama, A. (2017). Real time implementation of backstepping-multiscalar control to induction motor fed by voltage source inverter. *International Journal of Hydrogen Energy*, *42*(28), 17965-17975.

[6] Takahashi, I., & Noguchi, T. (1986). A new quick-response and high-efficiency control strategy of an induction motor. *IEEE Transactions on Industry applications*, (5), 820-827.

[7] Reza, C. M. F. S., Islam, M. D., & Mekhilef, S. (2014). A review of reliable and energy efficient direct torquecontrolled induction motor drives. *Renewable and Sustainable Energy Reviews*, *37*, 919-932.

[8] Naik, N. V., Panda, A., & Singh, S. P. (2015). A three-level fuzzy-2 DTC of induction motor drive using SVPWM. *IEEE Transactions on Industrial Electronics*, *63*(3), 1467-1479.

[9] Pushparajesh, V., Balamurugan, M., & Ramaiah, N. S. (2019). Artificial Neural Network Based Direct Torque Control of Four Phase Switched Reluctance Motor. *Available at SSRN 3371369*.

[10] Nicola, M., Nicola, C. I., & SacerdoŢIanu, D. (2020, May). Sensorless Control of PMSM using DTC Strategy Based on PI-ILC Law and MRAS Observer. In *2020 International Conference on Development and Application Systems (DAS)* (pp. 38-43). IEEE.

[11] Pushparajesh, V., Nandish, B. M., & Marulasiddappa, H. B. (2021). Hybrid intelligent controller based torque ripple minimization in switched reluctance motor drive. *Bulletin of Electrical Engineering and Informatics*, *10*(3), 1193-1203.

[12] Wang, X., Wang, Z., & Xu, Z. (2018). A hybrid direct torque control scheme for dual three-phase PMSM drives with improved operation performance. *IEEE Transactions on Power Electronics*, *34*(2), 1622-1634

[13] Hang, J., Ding, S., Ren, X., Hu, Q., Huang, Y., Hua, W., & Wang, Q. (2021). Integration of Inter-Turn Fault Diagnosis and Torque Ripple Minimization Control for Direct-Torque-Controlled SPMSM Drive System. *IEEE Transactions on Power Electronics*.

BIOGRAPHIES OF AUTHORS

V. Pushparajesh has been serving as Associate Professor in the in the Department of Electrical and Electronics Engineering ,School of Engineering and Technology ,Jain Deemed to be University since 2017.He has completed his Ph.D from Anna University in Electrical Engineering specialized in Power Electronics and Special Electrical Drives. He has received the International Best Research Award for the year 2018- 2019 instituted by SDF International, London, UK. Adding to his credit he also received national award like Best Academic Researcher, Outstanding faculty award, Best faculty award and Best Placement coordinator from various Research Organization. He has Many National and Internationals journals in his research account.

Marulasiddappa H B is a research scholar from Jain Deemed to be university, Bengaluru Karnataka, India. Research scholar completed his under graduation from Kuvempu university in 2005 in the stream Electrical and Electronics Engineering, and post-graduation in power electronics from VTU in 2011, Belagavi, Karnataka, India. He has 15 years of teaching experience. He published many papers in international conferences and journals.

.