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Performance Analysis of Electric Vehicle Using Fuzzy Logic

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Abstract: The Permanent Magnetic Synchronous Motor (PMSM) has garnered increasing attention in various high-performance applications such as electric vehicles, owing to its advantageous features including high power density, power factor, and efficiency. This paper introduces a novel approach for speed control of Permanent Magnet Synchronous Machines (PMSM) drives, utilizing fuzzy logic-based control techniques. PMSM torque and speed control has relied on Field Oriented Control (FOC). However, advancements in vector control techniques have expanded the application of PMSM motors into domains where previously only DC drives were feasible. The proposed fuzzy logic-based speed controller is meticulously examined with MATLAB/SIMULINK under various operating conditions, including sudden changes in load demand and frequent alterations in speed, such as sudden speed reversals. Through rigorous analysis and simulation, this approach aims to demonstrate its effectiveness in maintaining precise speed control and robust performance in dynamic operating environments. By combining the advantages of PMSM technology with the adaptability and robustness of fuzzy logic control, this research seeks to contribute to the advancement of high-performance electric drive systems, particularly in applications requiring agile and responsive motor control.

***Index Terms* - PMSM, PWM, Fuzzy Logic Controller, Vector Control.**

1. INTRODUCTION

The demand for environmentally friendly vehicles is on the rise, spurred by both individual consumers and government initiatives. However, the limitations of electric vehicles (EVs) have led to the emergence of hybrid electric vehicles (HEVs). In HEVs, the combination of an internal combustion engine with electric propulsion offers numerous advantages, despite the increased complexity involved. These benefits include extended range, the potential for optimizing the internal combustion engine's operation for fuel economy or emissions, and the utilization of regenerative braking. During regenerative braking, the energy used to slow or stop the vehicle is converted into electricity, recharging the battery instead of dissipating it as heat. The Permanent Magnet Synchronous Motor (PMSM) has gained significant traction in variable speed drives due to its high torque-to-weight ratio, power-to-weight ratio, power factor, and efficiency. However, controlling the speed of PMSM presents challenges due to the nonlinear coupling of winding currents and rotor speed. Achieving fast and accurate speed response, unaffected by load disturbances, is crucial for high-performance drives. Recent years have seen growing interest in PMSMs due to their simpler structure compared to other types of motors. Yet, achieving high performance in electrical drives using PMSM necessitates knowledge of the rotor position to implement field-oriented control. While mechanical sensors can provide this information, they come with increased costs and reduced reliability, particularly in harsh environments.

Field-oriented control (FOC) is a flexible mechanism used to drive synchronous and induction motors. It enables independent control of torque and speed, akin to separately excited DC motors. In DC motors, armature current and field current in the rotor can be controlled independently through mechanisms like brushes and commutators. However, in AC motors (synchronous and induction), the spatial angle between the rotating stator field and rotor flux varies with the load, resulting in oscillatory responses. FOC mimics DC conditions in AC motor structures by continuously monitoring the rotor field position and orienting the stator field accordingly to maintain a 90-degree angle between them. This achieves maximum torque condition while independently controlling rotor speed. FOC necessitates a position sensor to monitor the rotor position and, consequently, the rotor flux position. The stator field is oriented by varying the phase and magnitude of three-phase AC quantities, hence its reference as 'vector control'. [4-7]

2. MODELLING OF PMSM

The Permanent Magnet Synchronous Motor (PMSM) is a crucial category of electric machines, notable for the use of permanent magnets attached to the rotor for magnetization. Over time, various mathematical models have been proposed to address different applications, such as the abc-model and the two-axis dq-model. Among these models, the two-axis dq-model has emerged as the most widely used in PMSM engineering controller design, owing to its simplicity and practicality. The dq-model simplifies control system design by transforming stationary symmetrical AC variables into DC ones in a rotating reference frame, leveraging the d-q reference frame theory. To develop the mathematical model of the PMSM, several assumptions are made: The stator windings of the PMSM are assumed to have an equal number of turns per phase. The rotor flux is assumed to be concentrated along the d-axis, while there is zero flux along the q-axis, similar to the assumptions made in the derivation of indirect vector-controlled induction motor drives. The rotor flux is considered constant at a given operating point, eliminating the need to include the rotor voltage equation. This assumption stems from the fact that there is no external source connected to the rotor magnet, and any variation in the rotor flux over time is negligible. The model of the PMSM is derived from the stator equations of the induction machine in the rotor reference frame, as the position of the rotor magnets independently determines the instantaneous induced electromotive forces (emfs), stator currents, and torque of the machine, regardless of the stator voltages and currents. Expanding on the stator equations, they are expressed using flux linkages to derive the model of the PMSM. The rotor reference frame is chosen because the position of the rotor magnets determines the instantaneous induced emfs and subsequently the stator currents and torque of the machine independently of the stator voltages and currents.

The stator flux linkage vector ψs and rotor flux linkage ψf of the PMSM can be illustrated in the rotor flux (dq), stator flux (xy), and stationary (DQ) frames, as depicted in figures 1 and 2. In Figure 1, the rotor flux (dq) frame illustrates the relationship between the rotor flux and the d-q axes. Here, the rotor flux is primarily along the d-axis, while the q-axis experiences zero flux. Figure 2 showcases the stator flux (xy) and stationary (DQ) frames, highlighting the relationship between the stator and rotor flux linkages in both frames. These frames are essential for understanding the behavior of the PMSM under different operating conditions and for designing effective control strategies.

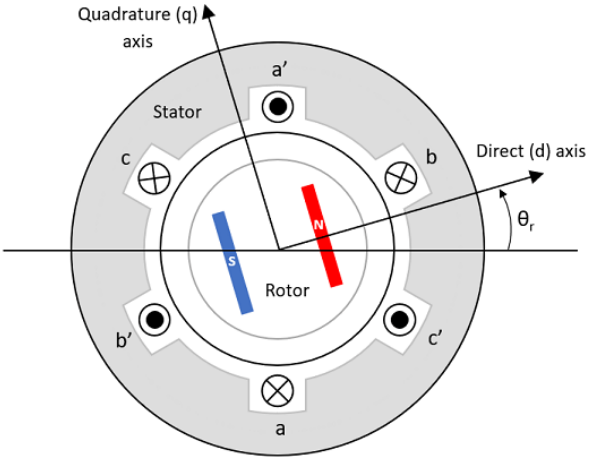

Fig.1. Two pole three phase surface mounted PMSM.

When considering rotor reference frames, it entails transforming the equivalent q and d axis stator windings to frames that revolve at rotor speed. This ensures there's zero speed differential between the rotor and stator magnetic fields, establishing a fixed phase relationship between the stator q and d axis windings and the rotor magnet axis (the d axis in modeling). The angle between the stator and rotor flux linkage, denoted by δ, represents the load angle when neglecting stator resistance. In a steady state, δ remains constant, corresponding to a load torque, with both stator and rotor flux rotating at synchronous speed. In the stator flux reference frame, the D axis aligns with the stator flux linkage space vector ψs. The Q axis (of SRF) leads 90 degrees to the D axis in the counter-clockwise direction. This arrangement facilitates a comprehensive understanding of the interplay between stator and rotor fluxes, aiding in the development of effective control strategies.

θs = rotational angle of stator flux vector,

$\theta_s = \frac{d\theta_r}{dt}$

θr = rotational electric angle of rotor,

$\theta_s = \theta_r + \delta$

Stator flux linkage is given by

$$\Psi_s = L_s I_s + \Psi_{af} e^{j\theta r} \qquad (1)$$

Where Ls is stator self inductance and ψaf ix the rotor permanent magnet flux linkage. The stator voltage equation in rotor reference frame (dq reference frame) are given as

$$V_d = R_d I_d + \frac{d\Psi_d}{dt} - \omega_r \Psi_q \qquad (1a)$$

$$V_q = R_q I_q + \frac{d\Psi_q}{dt} + \omega_r \Psi_d \qquad (1b)$$

Where R_d & R_q are the direct and quadrature axis winding resistances which are equal & be referred to as R_s in the stator resistance.

To compute the stator flux linkage in q and d axes, the current in the stator and rotor is required. The permanent magnet excitation can be modelled as a constant current source if the rotor flux is along the d axis. Thus, the rotor current along the d axis is denoted as if. The q axis current in the rotor is zero, assuming no flux along this axis. Then, the flux linkages can be expressed as follows:

$$\Psi_q = L_q i_q \qquad (2)$$

$$\Psi_d = L_d i_d + \Psi_f \qquad (3)$$

Ψ_f is the flux through stator winding due to permanent magnets

$$\Psi_f = L_m i_f$$

3. EQUIVALENT CIRCUIT OF PMSM

The d-q modeling of the motor, utilizing the stator voltage equations, enables the derivation of the equivalent circuit of the motor, as depicted in Figure 2. Assuming the rotor d-axis flux from the permanent magnet is represented by a constant current source, described by the equation $\Psi_f = L_m I_f$, the figure illustrates the equivalent circuit derived from equation 4.

$$Te = 3/2P(\Psi_d I_d + (L_d - L_q) I_q I_d) \qquad (4)$$

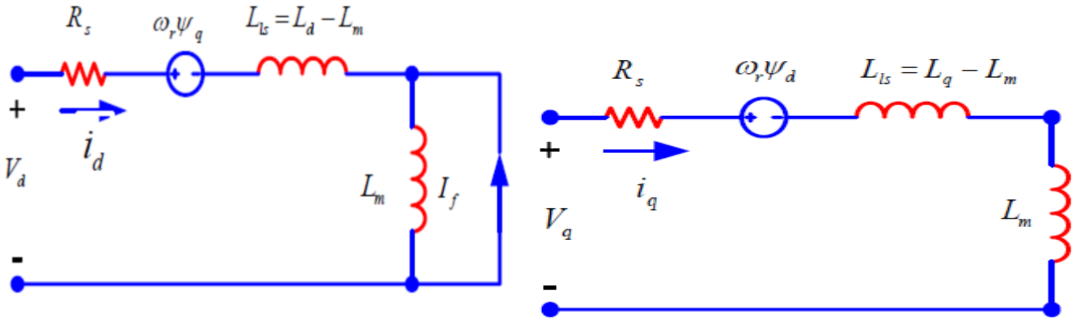

Fig.2 Equivalent Circuit of PMSM.

Where Lm is the mutual inductance between the stator winding and rotor magnets. Substituting these flux linkages into the stator voltage equations gives the stator equations.

$$V_q = R_s I_q + \omega_r (L_d I_d + \Psi_f) + \rho L_q I_q \qquad (5)$$

$$V_d = R_s I_d + \omega_r L_q I_q + \rho R_d (L_d I_d + \Psi_f) + L_d i_d \qquad (6)$$

Where V_d and V_q are d-q axis stator voltages, id and iq are d-q axis stator currents, L_d and L_q are d-q axis inductances. R_s is stator winding resistance per phase, Ψd, Ψq are stator flux linkage in d-q axis & ωr is rotor speed in (rad/sec) electrical. Arranging the above equation in matrix form

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_q + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_d + \rho L_d \end{bmatrix} + \begin{bmatrix} \omega_r L_m i_f \\ \rho \Psi_f \end{bmatrix} \qquad (7)$$

The developed torque motor is being given by (8)

$$Te = \frac{3}{2} P (\Psi_d I_d - \Psi_q I_q) \qquad (8)$$

which upon substitution of the flux linkages in terms of the inductances and current yields

$$T_e = 3/2P(\Psi_d I_d + (L_d - L_q) I_q I_d) \qquad (9)$$

Where P= No. of pole pair = p/2, and p= Total No. of poles Based on theory of dynamics the motion equation of PMSM is *given by*

$$T_e = T_L + B\omega_r + J\frac{d\omega_m}{dt} \qquad (10)$$

Where T_L is load torque, J is moment of inertia, B (viscous friction) is damping coefficient.
The developed electromagnetic torque is given by

$$T_e = \frac{3}{2} P \left[\Psi_d i_q - \Psi_q i_d\right] \quad (11)$$

ω_m is the motor mechanical speed. Solving for the rotor mechanical speed from the above equation

$$\omega_m = \int \frac{(T_e + T_L + B\omega_r)dt}{\tau}$$

And $\omega_m = \omega_r \frac{2}{p}$ Where ω_r is the rotor electrical speed.

4. SPEED CONTROL OF PMSM FED ELECTRIC VEHICLE

Field Oriented Control (FOC) is a method of controlling the stator currents represented by a vector. This control strategy involves projections that transform a three-phase time and speed-dependent system into a two-coordinate (d and q coordinates) time-invariant system. These projections create a structure similar to that of DC machine control. FOC requires two constant input references: the torque component (aligned with the q coordinate) and the flux component (aligned with the d coordinate). Since FOC is based on projections, the control structure handles instantaneous electrical quantities, ensuring accuracy in both steady-state and transient operations. This independence from the limited bandwidth of mathematical models allows for precise control in various working conditions. To achieve better dynamic performance, more complex control schemes are required for controlling Permanent Magnet (PM) motors. With the computational power offered by microcontrollers, advanced control strategies can be implemented. These strategies utilize mathematical transformations to decouple the torque generation and magnetization functions in PM motors. Such decoupled torque and magnetization control is commonly known as rotor flux-oriented control, or simply Field Oriented Control (FOC). In this control scheme, three-phase currents are measured and transformed using the Clarke transformation into a stationary frame (α-β) $I_{s\alpha}$ and $I_{s\beta}$. These currents are then transformed into a rotating frame (d-q) I_{sd} and I_{sq}. PI controllers compare the command values with the measured values to assess the operational condition. The outputs of the controllers are then transformed from a rotating frame to a stationary frame using the Park transformation. The commanded signals of the vector are sent to the pulse width modulation (PWM) block for implementation. This comprehensive control strategy ensures precise and efficient operation of PM motors in various applications. The performance of the FOC block diagram can be summarized in the following steps:

1. Stator currents and rotor angle are measured.
2. Stator currents are transformed into a two-axis reference frame using the Clarke Transformation.
3. The αβ currents are converted into a rotor reference frame using the Park Transformation. These dq values remain invariant in steady-state conditions.
4. The speed regulator generates a quadrature-axis current reference (the direct-axis reference is zero for operation below rated speed). The d-current controls the air gap flux, and the q-current controls torque production.
5. Current error signals are used in controllers to generate reference voltages for the inverter.
6. The voltage references are transformed back into the abc domain.
7. PWM signals required for driving the inverter are computed based on these values.

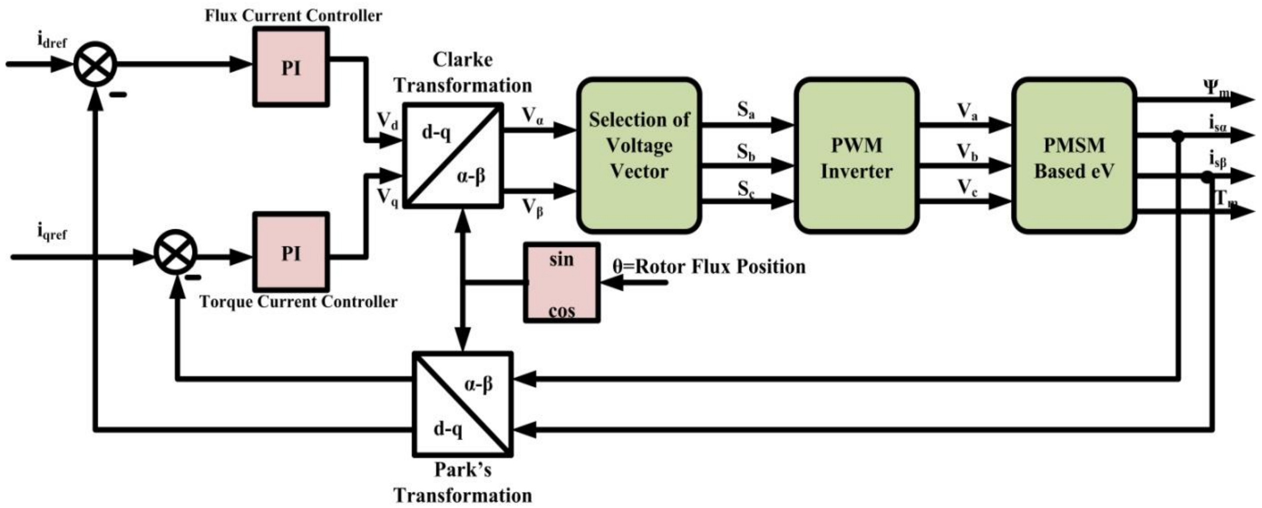

Fig. 3 Field oriented control of Electric vehicle.

5. FUZZY LOGIC CONTROL

While the Proportional-Integral (PI) controller is commonly used as the speed controller for Electric Vehicles, it is susceptible to the effects of load disturbances, speed changes, and parameter variations if its gains are not continuously tuned. The emergence of artificial intelligence techniques, such as Fuzzy Logic Controllers (FLC), has provided improved speed control performance for drives. FLC, among various intelligent controllers, stands out as a simpler option with faster response and insensitivity towards load variation. To address the limitations of the PI controller, an FLC with 49 rules is designed for speed control of PMSM drives. The dynamic performance of the drive is significantly improved by the Fuzzy Logic controller compared to the PI controller. The incorporation of linguistic variables and a user-defined rule base allows for the integration of human intelligence into the controllers. The general control scheme of an Electric Vehicle using a Fuzzy Logic controller is depicted in Figure 5. The control scheme involves closed-loop control of speed and current. The three-phase currents i, i_b, and i_c are measured by the rotor circuit and transformed into DC components i_d and i_q through Park's transformation. These currents are then fed into the current feedback loop. The deviation between the speed reference and actual speed is regulated by FLC, generating the current reference of d and q axis, i.e., i_{dref} and i_{qref}. The current is regulated by individual FLC controllers for DC components, i_d and i_q. The regulated DC currents produce three-phase stator currents and voltages, which are fed to the voltage source inverter, producing the required torque and speed.

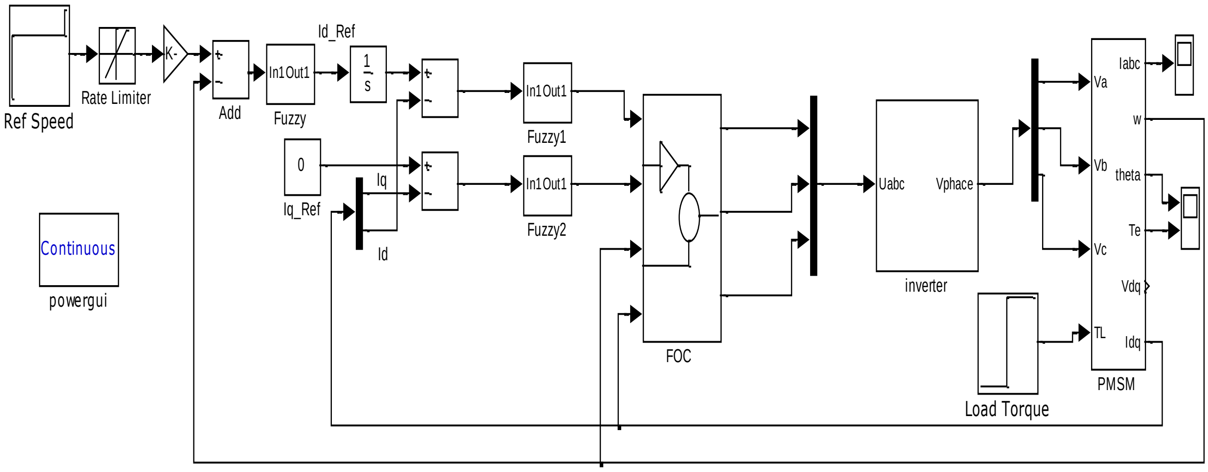

Fig.4. Basic control scheme of Electric Vehicle using FLC

In the Fuzzy Logic Controller (FLC), two fuzzy input variables are utilized: speed error (ω) and change in speed error ($d_{\omega e}/dt$). These inputs are then processed to produce an output, ΔI, which is summed or integrated to generate the actual output, I_f . Each input variable is represented by a set of five membership functions: large negative (LN), small negative (SN), zero (Z), small positive (SP), and large positive (LP). These membership functions are symmetrical about their advantageous and disadvantageous values. The change in output variable (ΔI) is also represented by a set of five membership functions, ranging from negative (N) to positive (P). Triangular functions are used due to their robustness. The formulation of fuzzy rules or knowledge base is crucial in this system. The IF-THEN weighted 25 rules are illustrated in Table 1. Sample the speed w and 'w_{reff}' and compute the speed error

$w_e(y) = w_{reff}(y) - w(y)$

$cw_e = w_e(y) - w_e(y\text{-}1)$

These w_e and cw_e are divided by scaling factor SF and SQ respectively to convert the signal in per unit values The amplitude of output of FLC is given as: $I_w(y) = I_w(y\text{-}1) + \Delta I_w$

Table I Fuzzy Control Rules

ERROR ⇩	CHANGE IN ERROR ⟹				
	LN	SN	Z	SP	LP
LN	LN	LN	SN	Z	SP
SN	SN	SN	SN	Z	SP
Z	SN	SN	Z	SP	LP
SP	SN	Z	SP	SP	LP
LP	LN	SN	Z	SP	LP

6. SIMULATION RESULTS & DISCUSSION

To assess the proposed topology and modulation techniques, a model is developed and simulated. Permanent Magnet Synchronous Motors (PMSM) find wide application in low and medium power systems such as computer peripherals, robotics, adjustable speed drives, and electric vehicles. The increasing demand for PMSM motor drives in the market necessitates simulation tools capable of handling motor drive simulations. Simulations play a crucial role in the development of new systems, including motor drives, by reducing both cost and time. Simulation tools offer dynamic simulations of motor drives in a visual environment, facilitating the development of new systems. The speed control model of the PMSM drive is developed in the MATLAB environment with Simulink and PSB toolboxes to simulate the behavior of the drive with a PI controller. In this test system, the reference speed is increased from ω_r=0 to 1500 rpm at 0.5 seconds, then from 1500 to 1650 rpm at t=1 second, followed by sudden speed reversals at t=2 and again at t=2.5 seconds. The torque also increases from T_L=5 Nm to 10 Nm at t=2.5 seconds. The torque is kept constant while the electric vehicle experiences a step increase in speed reference.

Figure 6 illustrates that the motor oscillates for a few cycles during speed reversal. Additionally, there is a slight dip in the speed of the machine when the load torque changes from 5 Nm to 10 Nm. At this instant, the d-axis and q-axis currents of the machine also increase to match the increase in load torque demand.

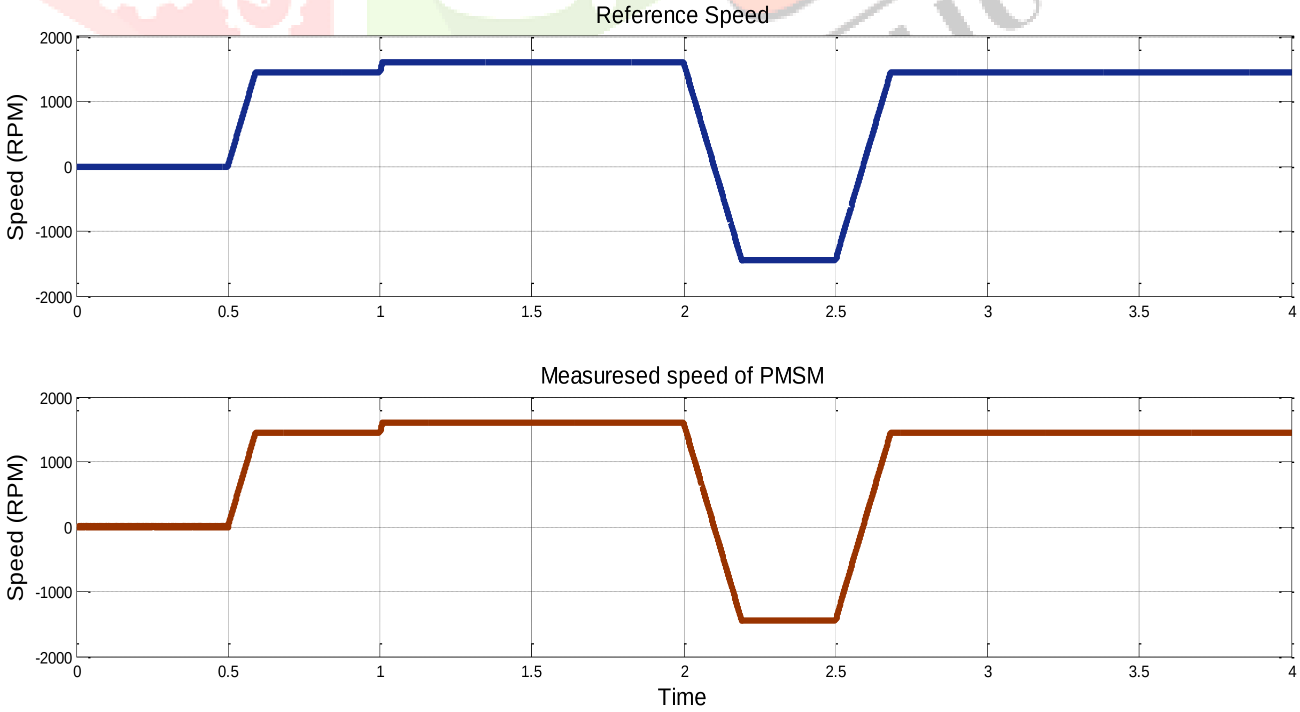

Fig. 5 Measured speed of PMSM drive

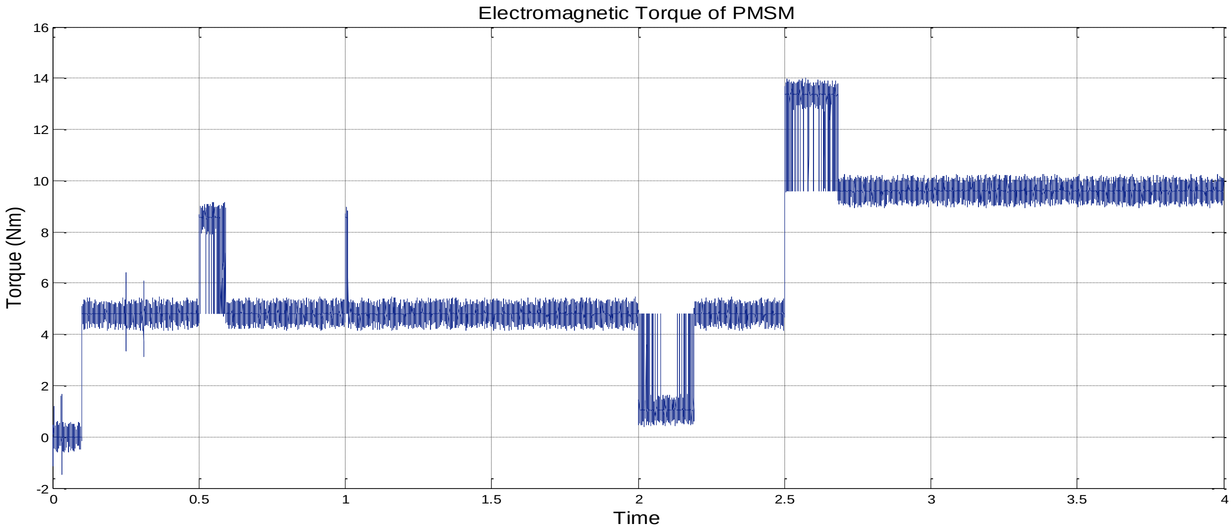

Fig. 6. Electromagnetic torque of PMSM drive

The motor torque ripple is more pronounced when the electric vehicle is started or when there is a change in reference speed, as shown in Figure 5. This is because the electromechanical time constant is much larger than the electromagnetic time constant, resulting in a larger instantaneous rate of change of stator flux linkage compared to the rotor flux linkage. During perturbations in speed, the system fails to reach equilibrium. When the actual motor torque is less than the given value, the angle between the stator and rotor flux linkages increases, leading to a rapid growth in torque, and vice versa. This explains why the motor torque ripple is larger when the motor experiences a change in speed reference or during the starting of the PMSM-eV drive. Figure 7 displays the three-phase stator current of the PMSM-eV. The machine current varies with changes in speed and load torque. It increases with an increase in load torque to generate more electromagnetic torque to counter the load torque demand.

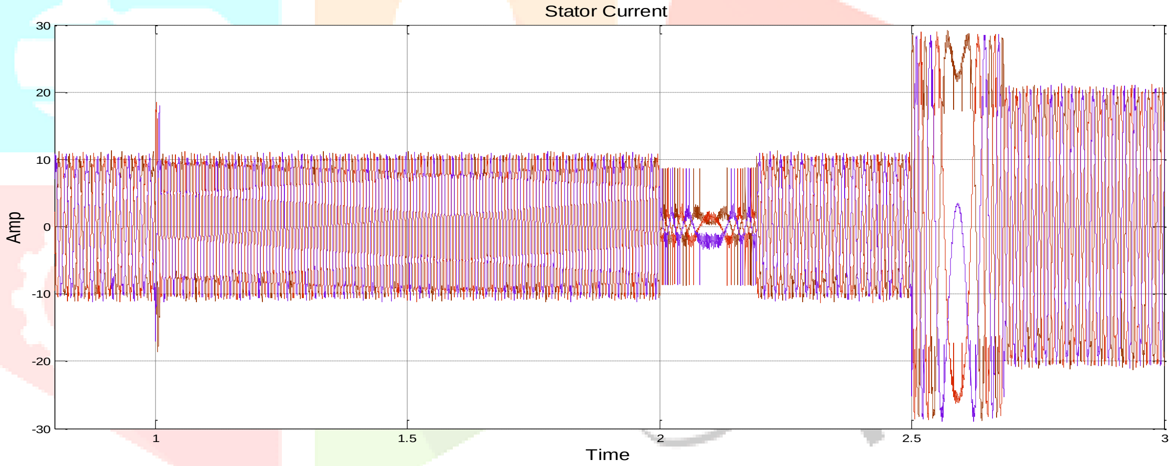

Fig. 7 Stator current of PMSM for change in speed

Fig. 8 shows the zoomed view of stator current during increase in speed above rated speed and during sudden speed reversal.

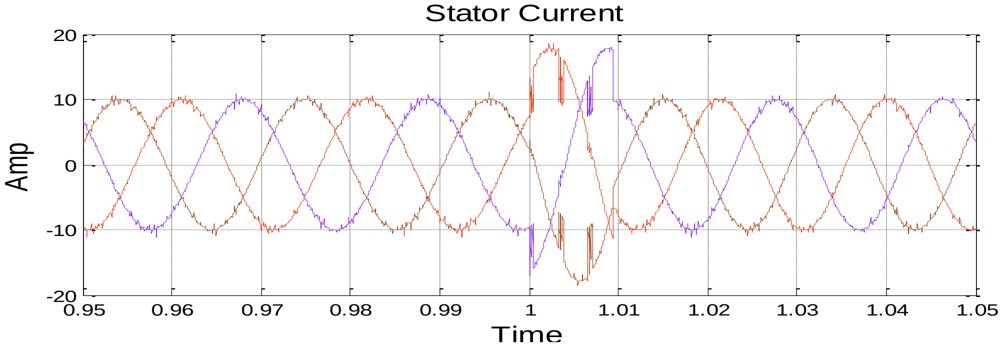

Fig. 8 Stator current above rated speed

Fig. 9 and Fig. 10 shows the THD of stator current during sudden speed changes with PI controller.

Figure 11 illustrates the torque response of the Electric vehicle with fuzzy control. It is evident that the torque ripples during sudden speed changes with the fuzzy logic controller are significantly smaller compared to those with the PI controller.

Fig.12 and Fig.13 shows the THD of stator current during sudden speed changes with Fuzzy logic controller based PMSM-eV.

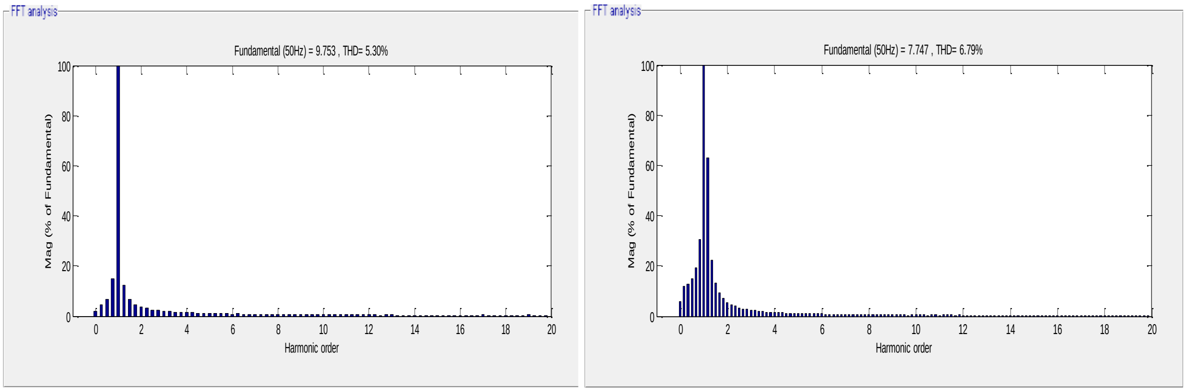

Fig. 9 THD of stator current for starting of Electric vehicle at rated speed, above rated speed

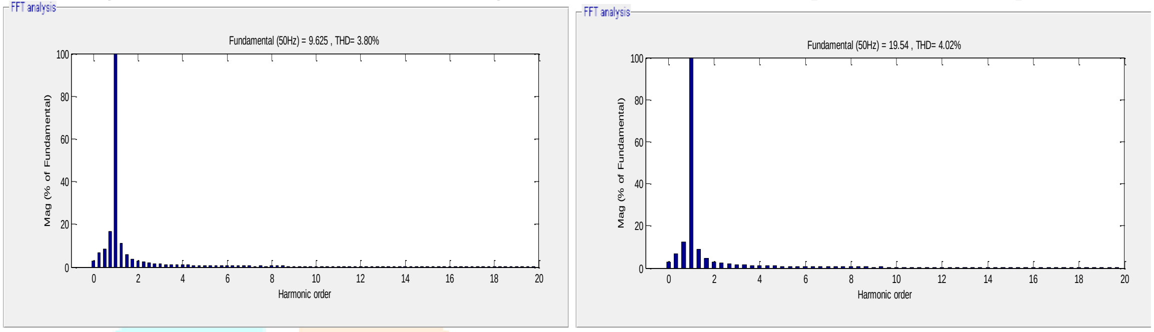

Fig.10 THD of stator current for starting of Electric vehicle under speed reversal, increase in torque

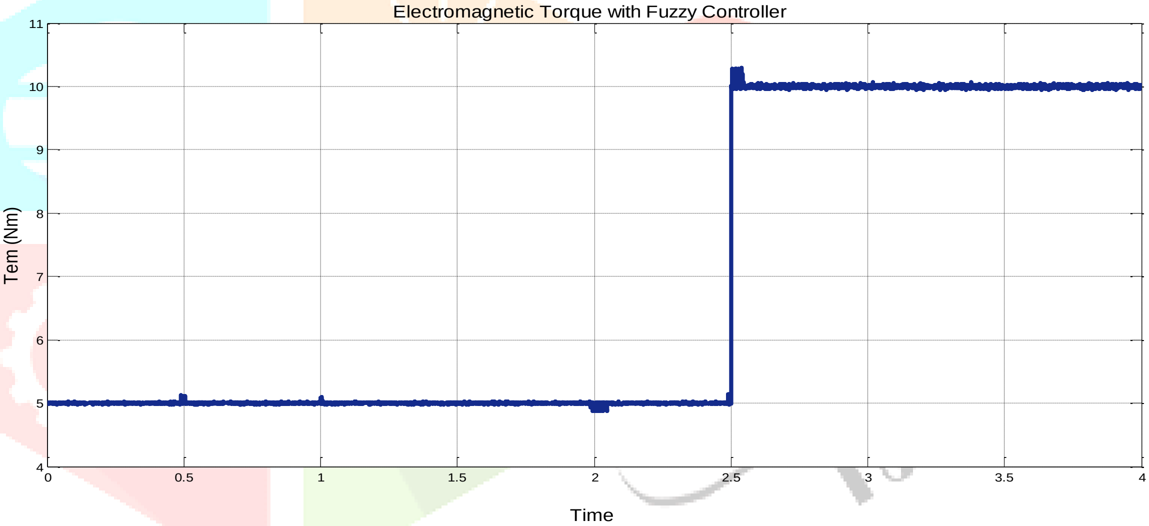

Fig. 11 Electromagnetic torque of Electric vehicle with fuzzy logic controller based PMSM-eV

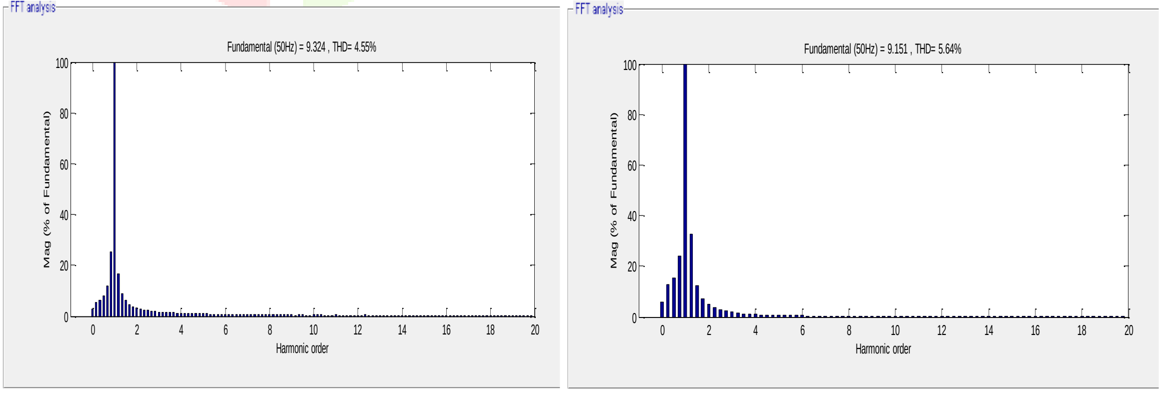

Fig. 12 THD of stator current for rated & above rated speed with FLC based PMSM-eV.

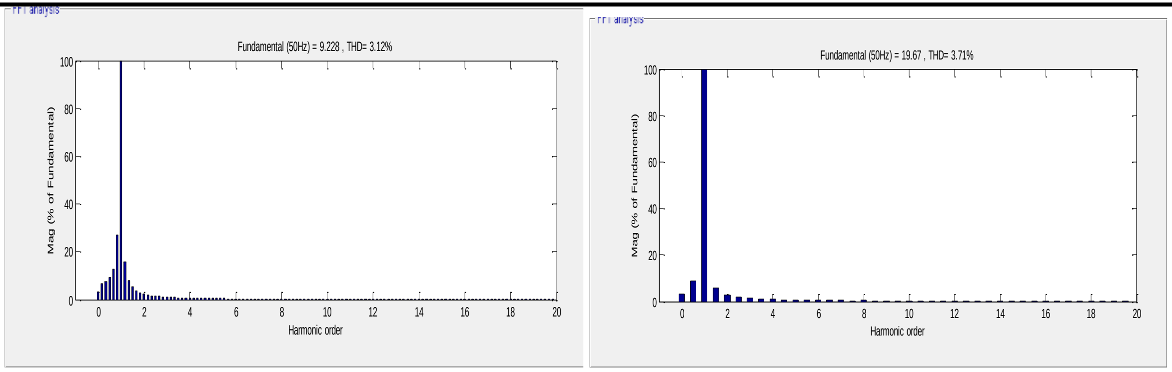

Fig. 13 THD of stator current for speed reversal, increase in torque with Fuzzy logic controller based PMSM-eV.

Table 1-summarizes the THD for PI and Fuzzy controlled PMSM drive. It is clear that by using fuzzy logic controller performance of the system is improved.

TABLE-1 Comparison of THD for PI and Fuzzy controlled PMSM-Electric vehicle

THD of stator current	Fuzzy Based PMSM-eV	PI Based PMSM-eV
Rated speed	4.56	5.30
Above rated speed	5.64	6.79
Speed reversal	3.12	3.80
Increase in torque	3.71	4.02

CONCLUSION

This paper proposes a closed-loop vector control system for Electric vehicles using a fuzzy logic speed controller. The integration of the fuzzy logic speed controller in the speed loop significantly enhances system performance. A comprehensive performance comparison between the fuzzy control-based Electric vehicle system and a conventional PI controller-based drive system is conducted through simulation. Results demonstrate the superior efficiency and enhanced dynamic response of the proposed method across a wide range of load variations compared to traditional methods. The simulation results highlight the high efficiency and dynamic performance of the fuzzy control-based Electric vehicle system. The proposed fuzzy logic speed controller proves to be a promising approach for improving the overall performance of Electric vehicle systems, offering higher efficiency and better dynamic response.

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