



Fuzzy Logic Based Speed Control of Electric Vehicle Driven by PMSM

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Abstract: The Permanent Magnetic Synchronous Motor (PMSM) has become increasingly popular in high-performance applications, especially in electric vehicles, due to its excellent power density, high power factor, and superior efficiency. This research presents a novel approach to speed control for PMSM drives utilizing fuzzy logic control techniques. While Field Oriented Control (FOC) has been the conventional method for regulating torque and speed in PMSM systems, advancements in vector control have broadened the usage of PMSMs to sectors traditionally dominated by DC motors. The proposed fuzzy logic-based speed controller undergoes extensive testing using MATLAB/SIMULINK across various scenarios, including sudden changes in load and quick fluctuations in speed, even encompassing abrupt reversals. Through thorough analysis and simulation, this research aims to validate the effectiveness of this method in achieving precise speed control and robust performance in dynamic conditions. By integrating the advantages of PMSM technology with the flexibility and strength of fuzzy logic control, this study aims to enhance high-performance electric drive systems, particularly in applications that demand rapid and responsive motor control. Ultimately, this work aspires to advance the current state of electric drive technology, establishing new benchmarks for efficiency and performance in challenging environments.

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

I. INTRODUCTION

The rising interest in eco-friendly vehicles is being influenced by both consumer choices and governmental initiatives. However, the limitations associated with electric vehicles (EVs) have led to the emergence of hybrid electric vehicles (HEVs). HEVs integrate an internal combustion engine with electric drive systems, presenting various advantages despite their greater complexity. These advantages include an extended range for driving, the capacity to optimize the internal combustion engine for improved fuel efficiency or lower emissions, and the implementation of regenerative braking. Regenerative braking harnesses the energy typically lost during deceleration, converting it into electrical energy to recharge the battery instead of dissipating it as heat [1-4].

The Permanent Magnet Synchronous Motor (PMSM) is highly regarded for variable speed drives due to its excellent torque-to-weight and power-to-weight ratios, along with its high efficiency and power factor. However, controlling the speed of PMSMs presents challenges stemming from the nonlinear relationship between winding currents and rotor speed. For high-performance applications, it is essential to achieve a rapid and precise speed response that remains stable even when loads fluctuate. In recent years, PMSMs have attracted interest due to their relatively simple design compared to other motor types. Nevertheless, effective operation in PMSM-driven electrical systems necessitates accurate rotor position information for the application of field-oriented control (FOC). While mechanical sensors can supply this data, they can introduce additional costs and may be less reliable in demanding environments [5-8].

Field-oriented control (FOC) is a flexible technique utilized to regulate both synchronous and induction motors, enabling independent control of torque and speed akin to that of separately excited DC motors. In DC motors, the armature and field currents in the rotor can be managed separately through components such as brushes and commutators. In contrast, AC motors—whether synchronous or induction—experience variations in the spatial relationship between the rotating stator field and rotor flux with changes in load, resulting in oscillatory responses. FOC mimics the operating conditions of DC motors within AC motor configurations by continuously monitoring the position of the rotor field and adjusting the stator field accordingly to maintain a 90-degree phase difference between the two. This technique guarantees maximum torque while allowing for independent regulation of rotor speed. To implement FOC effectively, a position sensor is necessary to track the rotor and rotor flux positions, which facilitates the adjustment of the phase and magnitude of the three-phase AC quantities. This is why it is often referred to as "vector control" [9-17].

II. MODELLING OF PMSM

The Permanent Magnet Synchronous Motor (PMSM) is an essential type of electric machine characterized by the use of permanent magnets on the rotor, which provide the necessary magnetization. Over the years, various mathematical models have been developed for different applications, including the abc-model and the two-axis dq-model. Among these, the two-axis dq-model has gained prominence in the design of PMSM controllers due to its simplicity and effectiveness. This model enables the design of control systems by transforming stationary symmetrical AC variables into DC variables within a rotating reference frame, leveraging the principles of the d-q reference frame theory [5-12].

When developing the mathematical model for a PMSM, several assumptions are made. Firstly, it is assumed that the stator windings have an equal number of turns per phase. Additionally, it is presumed that the rotor flux is concentrated along the d-axis, with no flux present along the q-axis, mirroring the assumptions applied in indirect vector-controlled induction motor drives. The model also assumes that the rotor flux remains constant at a specified operating point, negating the need to incorporate the rotor voltage equation. This is justified by the fact that there is no external power source linked to the rotor magnet, and any time-related changes in rotor flux are considered negligible. The PMSM model is derived from the stator equations of an induction machine in the rotor reference frame. This approach is adopted because the position of the rotor magnet independently influences the instantaneous induced electromotive forces (emfs), stator currents, and torque of the machine, irrespective of the stator voltages and currents. By elaborating on these stator equations, they can be articulated in terms of flux linkages, which leads to the formulation of the PMSM model. The rotor reference frame is utilized since it governs the instantaneous induced emfs, stator currents, and machine torque without dependence on stator voltages and currents [15-18].

The stator flux linkage vector ψ_s and the rotor flux linkage ψ_f 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. Figure 1 illustrates the rotor flux (dq) frame, showing the correlation between rotor flux and the d-q axes, where the rotor flux is primarily aligned along the d-axis, with zero flux along the q-axis. Meanwhile, Figure 2 presents the stator flux (xy) and stationary (DQ) frames, highlighting the relationship between stator and rotor flux linkages in both contexts. These reference frames are essential for understanding the behavior of the PMSM under varying operational conditions and for formulating effective control strategies. Grasping the dynamics of the PMSM within these reference frames is crucial for developing high-performance control systems. The dq-model's capability to simplify intricate AC variables into manageable DC equivalents facilitates easier control and analysis, resulting in more efficient and effective PMSM operations. This methodology not only improves the performance of PMSM drives but also broadens the scope of their application across various advanced engineering disciplines.

When employing rotor reference frames, the stator windings of the q and d axes are transformed into frames that rotate in sync with the rotor. This transformation eliminates any speed differential between the rotor and stator magnetic fields, preserving a constant phase relationship between the stator q and d axis windings and the rotor magnet axis, which aligns with the d axis in the model. The angle between the stator and rotor flux linkages, denoted as δ , represents the load angle when stator resistance is ignored. During steady-state operation, δ remains unchanged, reflecting the load torque, with both stator and rotor fluxes rotating at synchronous speed. In the stator flux reference frame, the D axis is aligned with the stator flux linkage space vector ψ_s . The Q axis, known as the stator reference frame (SRF), is positioned 90 degrees ahead of the D axis in a counter-clockwise orientation. This configuration offers a clear view of the interactions between the stator and rotor fluxes, which is vital for designing effective control strategies.

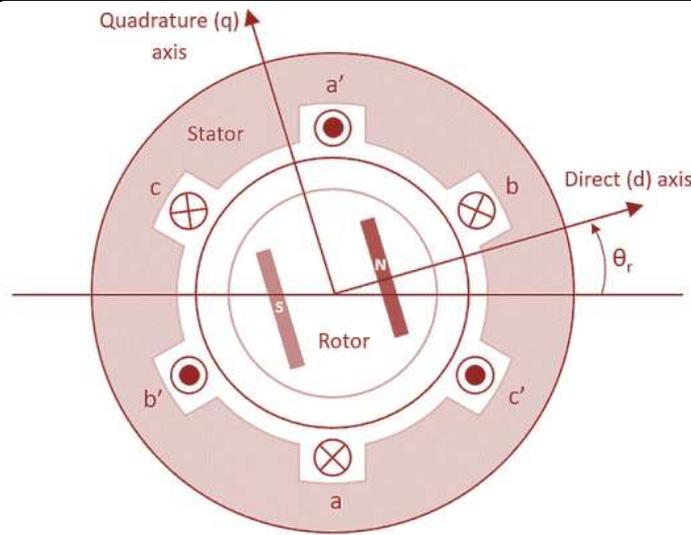


Fig.1. Two pole three phase surface mounted PMSM.

By ensuring that there is no speed differential between the rotor and stator magnetic fields, the rotor reference frame method establishes a stable phase relationship, simplifying the analysis and control of the PMSM. The angle δ plays a crucial role in illustrating the connection between load torque and flux linkages, as it remains steady in a balanced state, facilitating synchronous rotation of both the stator and rotor flux. In this setup, the D axis, aligned with the stator flux linkage vector ψ_s , and the Q axis, which leads by 90 degrees, aid in visualizing and managing the dynamics of flux. This alignment is instrumental in developing effective control algorithms that enhance the performance of PMSM drives, especially under varying load conditions. A comprehensive understanding of the dynamics in both rotor and stator reference frames is essential for optimizing control and performance of PMSM drives. This methodology not only streamlines the analysis of PMSM behavior but also supports the formulation of advanced control strategies capable of addressing complex operating conditions, thereby improving the motor's overall efficiency and reliability across diverse applications [22-29].

θ_s = rotational angle of stator flux vector,

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

θ_r = rotational electric angle of rotor,

$$\theta_s = \theta_r + \delta$$

Stator flux linkage is given by

$$\Psi_s = L_s I_s + \Psi_{af} e^{j\theta_r} \quad (1)$$

Where L_s is stator self inductance and Ψ_{af} is the rotor permanent magnet flux linkage. The stator voltage equation in rotor reference frame (dq reference frame) are given as

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

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

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 i_f . The q axis current in the rotor is zero, assuming no flux along this axis. Then, the flux linkages can be expressed as follows:

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

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

Ψ_f is the flux through stator winding due to permanent magnets

$$\Psi_f = L_m i_f$$

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.

$$T_e = 3/2P(\Psi_d I_d + (L_d - L_q) I_q I_d) \tag{4}$$

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

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

$$V_d = R_s I_d + \omega_r L_q I_q + \rho R_d (L_d I_d + \Psi_f) + L_d \dot{i}_d \tag{6}$$

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

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

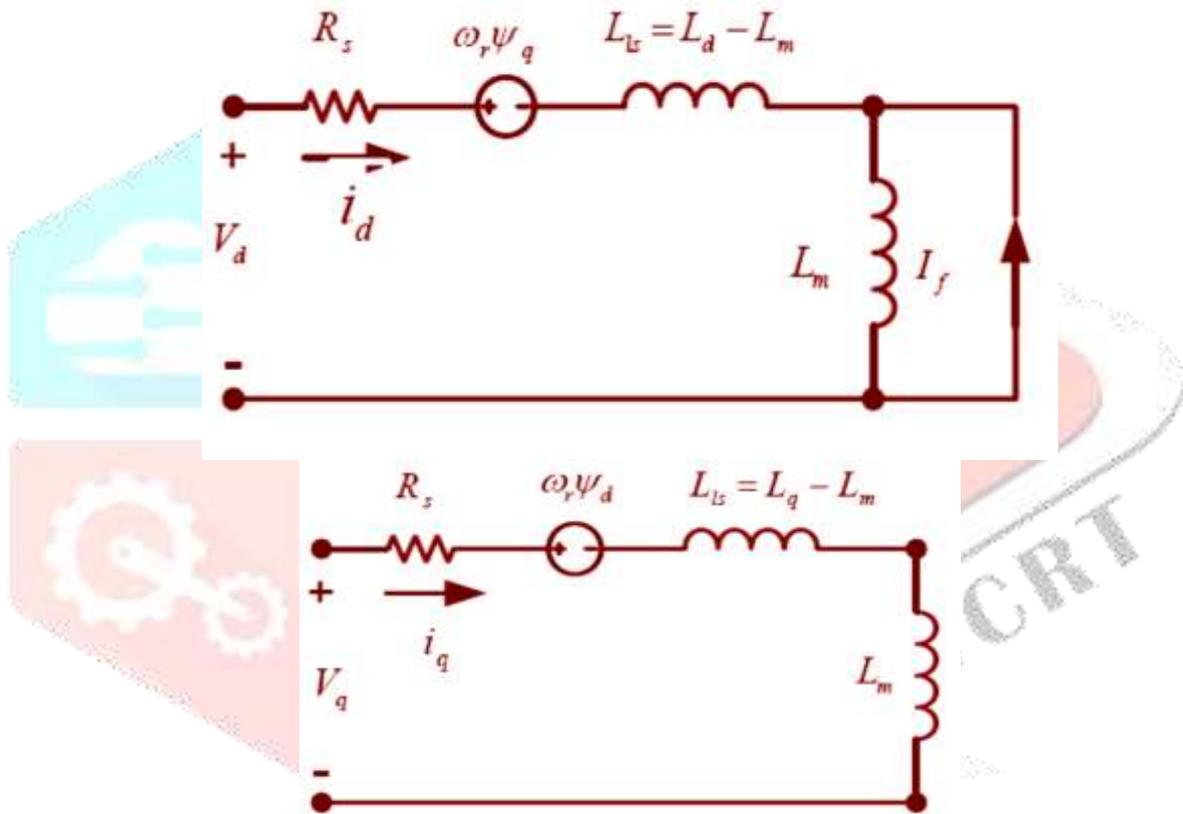


Fig.2 Equivalent Circuit of PMSM.

The developed torque motor is being given by (8)

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

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

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

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

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

Where T_L is load torque, J is moment of inertia, B (viscous friction) is damping coefficient.

The developed electromagnetic torque is given by

$$T_e = \frac{3}{2} P [\Psi_d i_q - \Psi_q i_d] \tag{11}$$

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

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

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

III. SPEED CONTROL OF PMSM FED ELECTRIC VEHICLE

Field Oriented Control (FOC) is an advanced technique for regulating stator currents through vector representation. This approach utilizes projections to transform a three-phase, time-varying, and speed-dependent system into a two-coordinate framework (d and q axes) that remains constant over time. These projections establish a control architecture similar to that used in DC machines. FOC operates based on two fixed input references: the torque component, which is aligned with the q axis, and the flux component, aligned with the d axis. By leveraging these projections, FOC effectively manages instantaneous electrical quantities, enabling precise control during both steady-state and transient conditions. This attribute makes it particularly powerful, as it is not constrained by the bandwidth limitations associated with traditional mathematical models, allowing for accurate control across various operating scenarios [17-19].

To improve dynamic performance, particularly in Permanent Magnet (PM) motors, more sophisticated control methods are required. The advancements in computational power of modern microcontrollers facilitate the implementation of these enhanced strategies. These methods utilize mathematical transformations to decouple torque generation from magnetization functions in PM motors. This decoupling process, often referred to as rotor flux-oriented control or simply Field Oriented Control (FOC), enables independent management of torque and magnetization.

In this control strategy, three-phase currents are measured and then transformed into a stationary reference frame (α - β) using the Clarke transformation, resulting in the currents $I_{s\alpha}$ and $I_{s\beta}$. These stationary frame currents are subsequently converted into a rotating reference frame (d-q), producing I_{sd} and I_{sq} . Proportional-Integral (PI) controllers are employed to compare the reference values with the actual measured values, assessing the operational state of the system. The outputs from these controllers are then transformed back from the rotating frame to the stationary frame using the Park transformation. The resulting command signals are sent to the pulse width modulation (PWM) block for execution. This robust control strategy guarantees that Permanent Magnet (PM) motors operate accurately and efficiently across a range of applications.

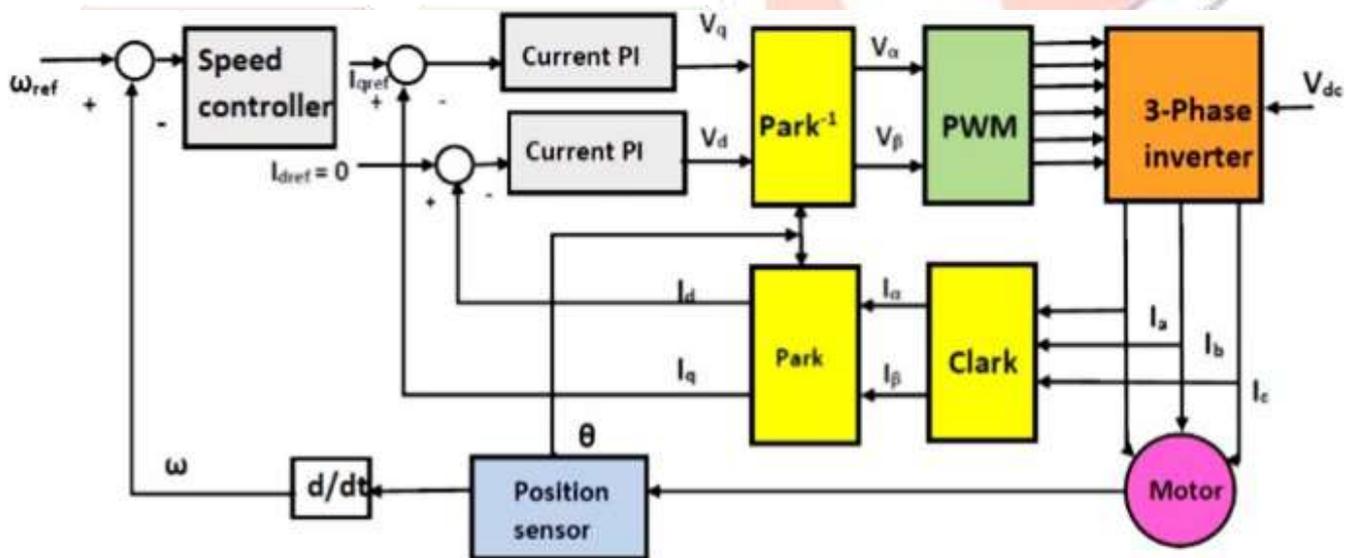


Fig. 3 Field oriented control of Electric vehicle.

The performance of the FOC system can be summarized in the following steps:

1. Measurement of stator currents and rotor angle.
2. Transformation of stator currents into a two-axis stationary reference frame through the Clarke transformation.
3. Conversion of the α - β currents into a rotating reference frame using the Park transformation, yielding dq values that remain constant under steady-state conditions.

4. The speed regulator produces a quadrature-axis current reference (with the direct-axis current reference set to zero for operation below the rated speed). The direct-axis current (d-current) regulates the air gap flux, while the quadrature-axis current (q-current) governs torque production.
5. Current error signals are processed by the controllers to generate reference voltages for the inverter.
6. These reference voltages are transformed back into the abc domain.
7. The PWM signals needed for driving the inverter are calculated based on these reference values.

This comprehensive control methodology ensures that PM motors achieve optimal performance, maintaining both precision and efficiency across diverse operational scenarios. By utilizing advanced computational tools and mathematical transformations, FOC offers a powerful means for the precise control of electric motors.

IV. FUZZY LOGIC CONTROL

While the Proportional-Integral (PI) controller is commonly employed for speed regulation in Electric Vehicles (EVs), it can suffer from the negative impacts of load disturbances, speed variations, and changes in system parameters if its gains are not continuously fine-tuned. The introduction of artificial intelligence techniques, particularly Fuzzy Logic Controllers (FLC), has significantly enhanced speed control performance for drive systems. Among various intelligent control strategies, FLC stands out for its simplicity, rapid response, and robustness against load variations. To address the limitations of the PI controller, a FLC with 49 rules has been specifically designed for the speed control of Permanent Magnet Synchronous Motor (PMSM) drives. The FLC notably enhances the dynamic performance of the drive compared to traditional PI control methods [23-24].

Fuzzy Logic Controllers utilize linguistic variables and a user-defined rule base, effectively incorporating human expertise into control systems. The overall control framework for an Electric Vehicle using an FLC is depicted in Figure 5. This framework implements closed-loop control for both speed and current. The three-phase currents (i_a , i_b , and i_c) are measured within the rotor circuit and converted into DC components (i_d and i_q) through Park's transformation. These DC components are subsequently integrated into the current feedback loop. The FLC manages the deviation between the reference speed and the actual speed, producing current references for the d and q axes (i_{dref} and i_{qref}). Individual FLC controllers then manage these references for the DC components, i_d and i_q . The regulated DC currents are utilized to generate the required three-phase stator currents and voltages, which are supplied to the voltage source inverter. This inverter subsequently produces the necessary torque and speed for the motor.

By employing an FLC, the system demonstrates improved adaptability and robustness in speed control across varying operational conditions, effectively overcoming the shortcomings of the conventional PI controller. The integration of FLC within the control strategy for EVs not only enhances the system's responsiveness to dynamic changes but also boosts overall efficiency and performance in a wide range of driving scenarios. The application of fuzzy logic for controlling PMSM drives exemplifies the transformative potential of intelligent control techniques in advancing electric vehicle technology [28-29].

In the Fuzzy Logic Controller (FLC), two fuzzy input variables are employed: speed error (ω_e) and the rate of change in speed error ($d\omega_e/dt$). These inputs are processed to yield an output, ΔI , which is then summed or integrated to produce the actual output, I_f . Each input variable is described by five membership functions: large negative (LN), small negative (SN), zero (Z), small positive (SP), and large positive (LP). These membership functions are symmetrical around their advantageous and disadvantageous values. The output variable change (ΔI) is similarly represented by five membership functions, ranging from negative (N) to positive (P). Triangular functions are chosen for their robustness in defining these memberships. The creation of fuzzy rules, or the knowledge base, is a critical aspect of this system. The IF-THEN weighted 25 rules are detailed in Table 1. To implement the FLC, the speed and the reference speed are sampled, and the speed error is computed as $w_e(y) = w_{reff}(y) - w(y)$

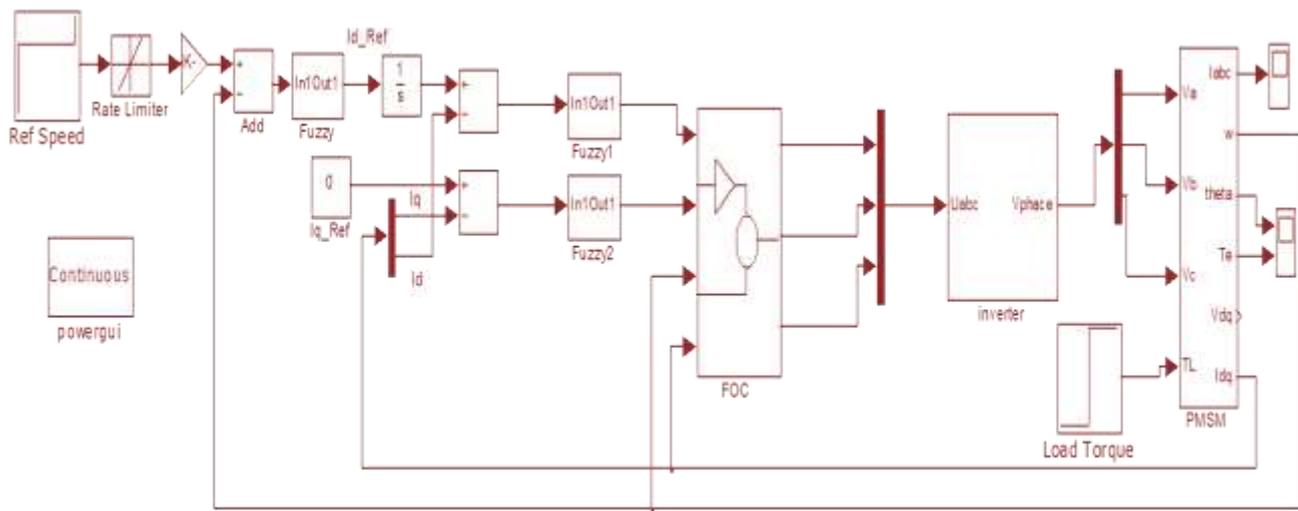


Fig.4. Basic control scheme of Electric Vehicle using FLC

Here's a summary of the process:

1. *Fuzzy Input Variables:* The FLC uses speed error (ω_e) and the rate of change of speed error ($d\omega/dt$) as its input variables.

2. *Membership Functions:* Both input variables are represented by five membership functions: large negative (LN), small negative (SN), zero (Z), small positive (SP), and large positive (LP). The output variable change (ΔI) is also represented by five membership functions ranging from negative (N) to positive (P), with triangular functions employed for their robustness.

3. *Fuzzy Rule Base:* The formulation of fuzzy rules is essential. The system relies on an IF-THEN rule base consisting of 25 rules, which are illustrated in Table 1.

4. *Computation of Speed Error:* Sample the speed w and ' w_{ref} ' and compute the speed error $w_e(y) = w_{ref}(y) - w(y)$ and change in error $cw_e = w_e(y) - w_e(y-1)$

5. *Processing and Output Generation:* The inputs (ω_e and $d\omega/dt$) are processed through the fuzzy inference system to produce the output ΔI . This output is then integrated or summed to obtain the final output, I_f , which is used for controlling the motor. The amplitude of output of FLC is given as: $I_w(y) = I_w(y-1) + \Delta I_w$

The FLC's use of linguistic variables and fuzzy rules allows it to incorporate human-like reasoning into the control process, providing a flexible and adaptive control strategy that can effectively handle variations and disturbances in speed and load conditions.

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

V. SIMULATION RESULTS & DISCUSSION

To assess the proposed topology and modulation techniques, a model has been developed and simulated. Permanent Magnet Synchronous Motors (PMSMs) are extensively used across various applications, including computer peripherals, robotics, adjustable speed drives, and electric vehicles. The increasing demand for PMSM motor drives highlights the necessity for simulation tools that can effectively manage motor drive simulations. Simulations are crucial in the development of new systems, such as motor drives, as they help to reduce both costs and time. These tools offer dynamic simulations of motor drives within a visual environment, facilitating the innovation and enhancement of new systems.

The speed control model for the PMSM drive utilizing Field Oriented Control (FOC) has been implemented in the MATLAB environment, employing Simulink and the Power System Blockset (PSB) toolboxes to simulate the drive's performance with a PI controller. As illustrated in Figure 5, the simulated results show a speed reference of 1000 rpm ($\omega_r = 1000$ rpm) under no load conditions (i.e., $T_L = 0$ Nm). The results indicate that the drive requires approximately 5 to 6 cycles to reach the desired speed setpoint. Furthermore, it is evident from Figure 5 that the speed response exhibits neither overshoot nor oscillations, confirming the effective design of the proposed field control scheme. Figure 6 presents the electromagnetic torque of the PMSM drive, while Figure 7 displays the stator voltages for phases R, Y, and B supplied to the PMSM drive. It is apparent that the voltage magnitudes remain constant throughout the operation.

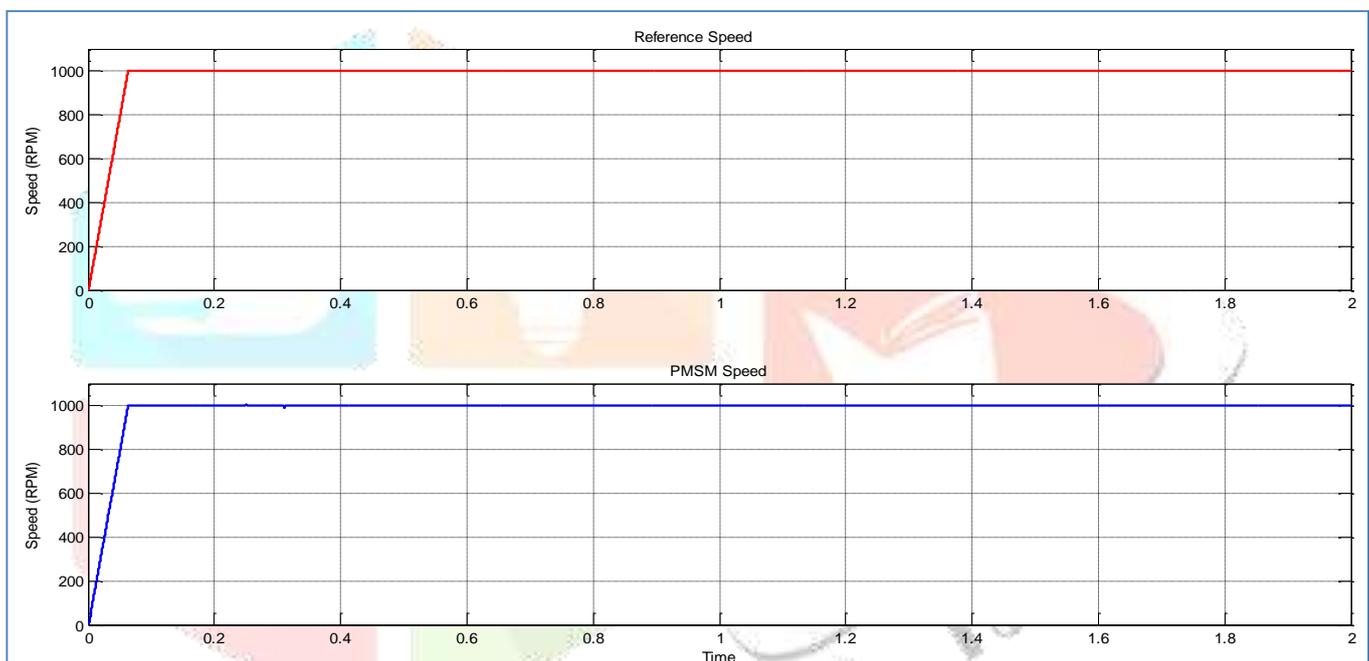


Fig. 5 Reference and Actual speed of PMSM drive

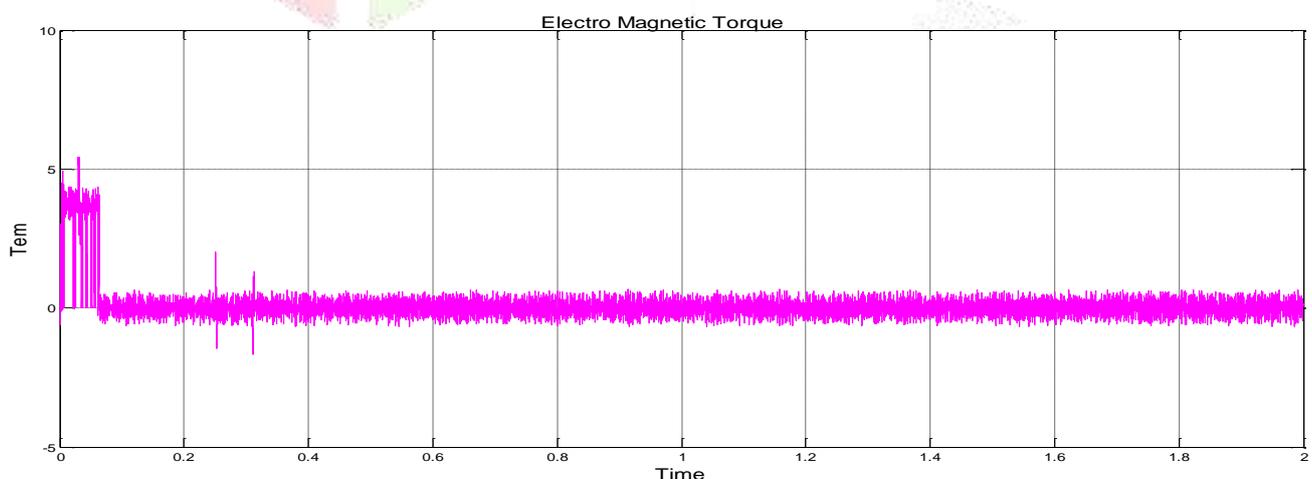


Fig. 6 Electromagnetic torque of PMSM drive

In figure 8 shows the torque and stator current response of Permanent magnet synchronous motors drive for a set speed of $\omega_r = 1000$ rpm with sudden change in load torque occurs at ($t=1$ sec) from 5 to 10 Nm. The sudden application of load on the motor shaft cause a small dip in the rotor speed, which recovers quickly resulting in zero steady state speed error

Figure 8 illustrates the torque response of the PMSM drive utilizing fuzzy control. It is noted that the torque ripples during abrupt speed changes with the fuzzy logic controller are comparatively smaller than those observed with the PI controller. Torque ripples tend to become more pronounced during the startup phase of the electric vehicle or when there is a shift in the reference speed. This behavior occurs because the electromechanical time constant is significantly longer than the electromagnetic time constant, resulting in a greater instantaneous rate of change of stator flux linkage in relation to rotor flux linkage. Consequently, the system finds it challenging to achieve stability during speed disturbances. When the actual motor torque is less than the desired value, the angle between the stator and rotor flux linkages increases, leading to a rapid rise in torque. Conversely, if the actual torque exceeds the target value, a similar dynamic occurs in the opposite direction. This interplay helps to explain the heightened motor torque ripple observed during speed changes and in the initial stages of the PMSM-electric vehicle (eV) drive operation. As depicted in Figure 9, the motor current approaches a sinusoidal shape. An increased load on the motor shaft generates greater electromagnetic torque, as indicated in the same figure. Under such variations in load, the fuzzy speed controller activates and effectively restores the rotor speed back to the reference value.

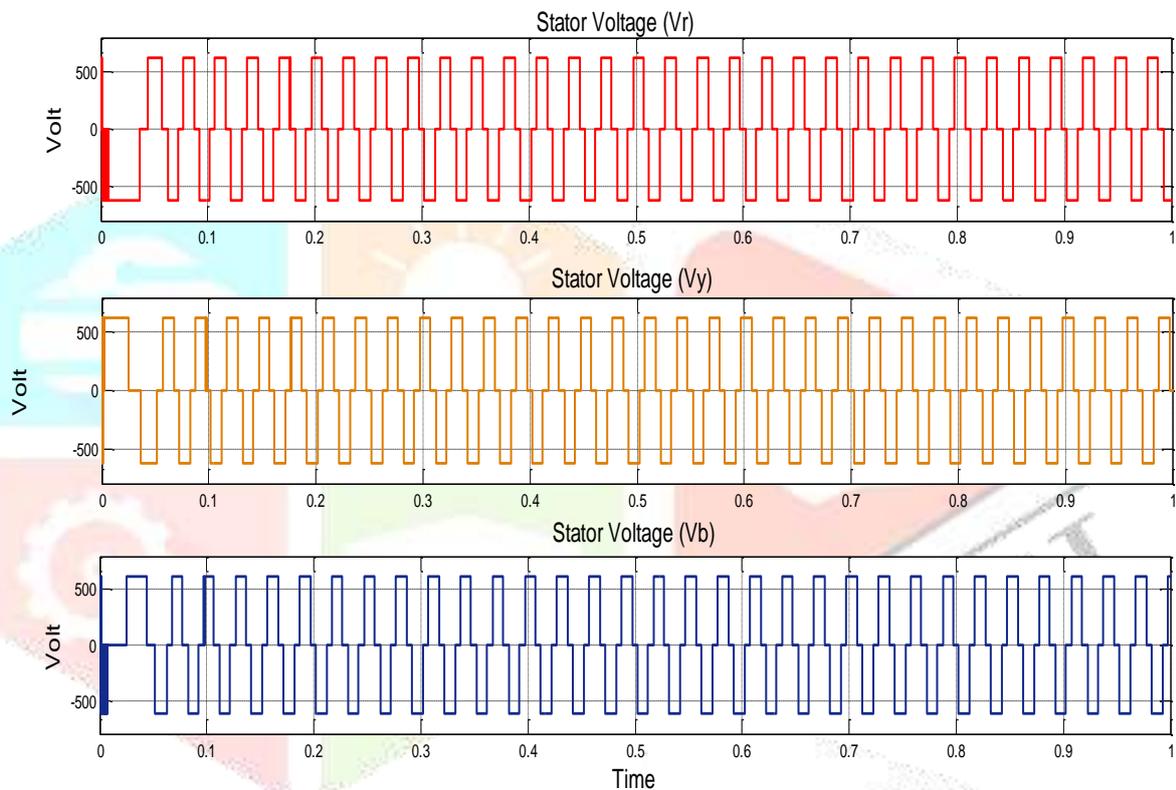


Fig. 7 Three-phase stator voltage of PMSM

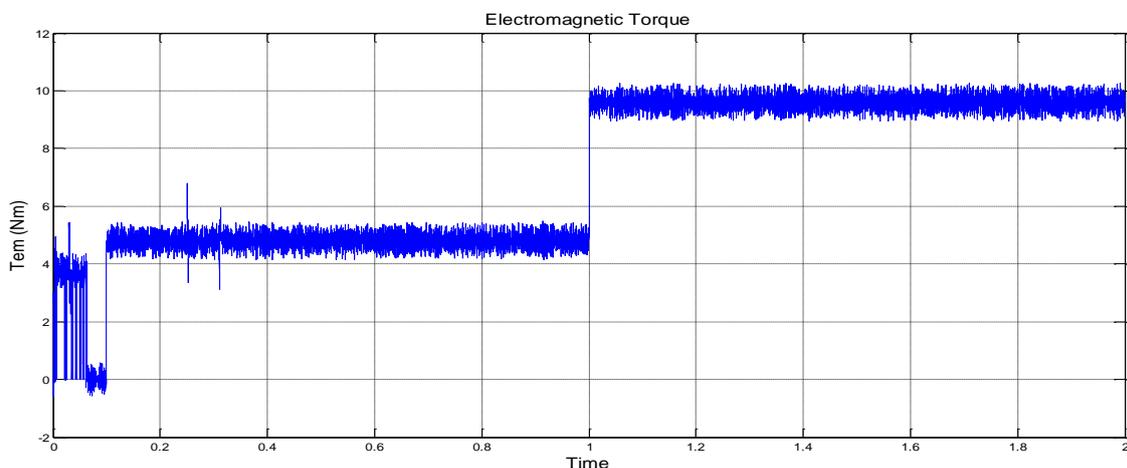


Fig. 8 Electromagnetic torque of PMSM drive

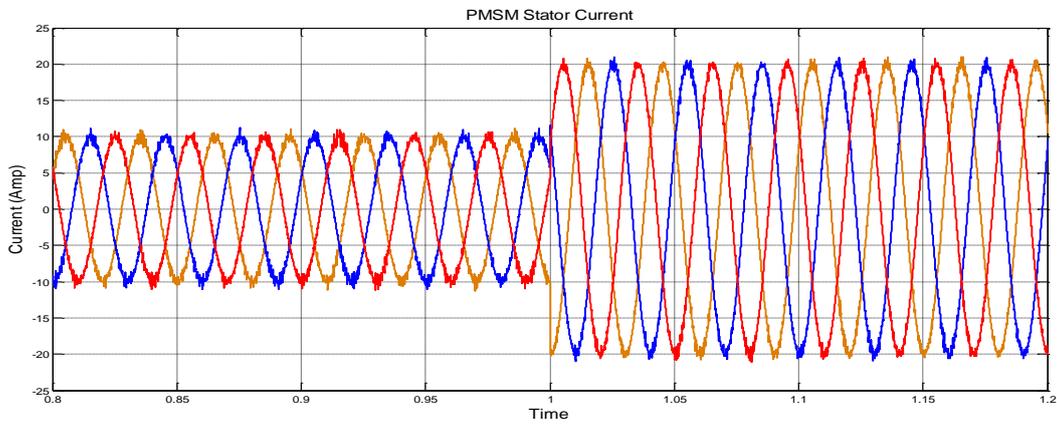


Fig. 9 Three phase motor current (in ampere) with change in load torque

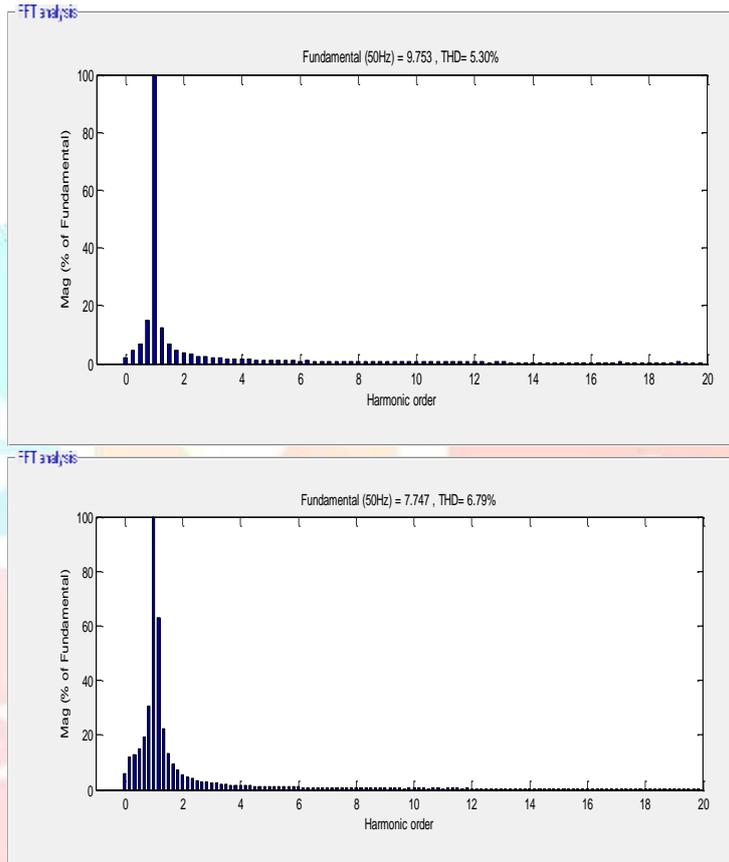
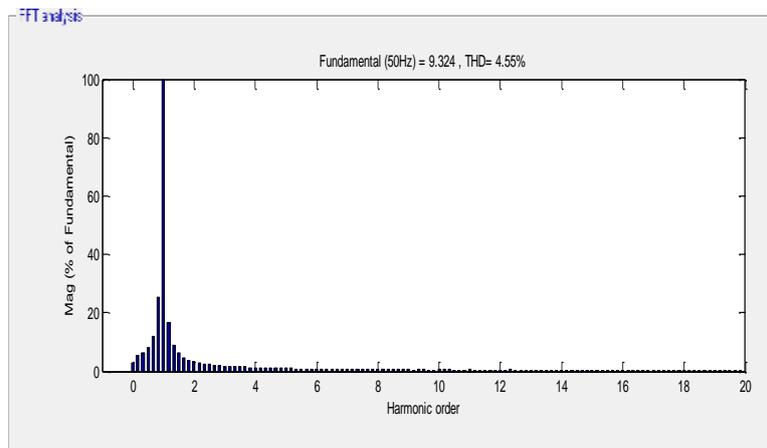


Fig. 10 THD of stator current for starting of Electric vehicle at rated speed, above rated speed



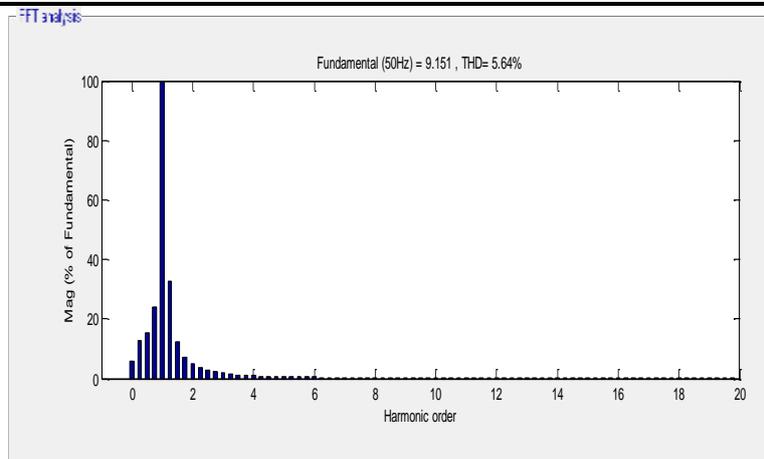


Fig. 11 THD of stator current for rated & above rated speed with FLC based PMSM-eV.

Fig. 10 and Fig. 11 depict the Total Harmonic Distortion (THD) of the stator current during abrupt speed changes using a PI controller and Fuzzy controller respectively.

Table 1-summarizes the THD for PI and Fuzzy controlled PMSM drive. It is clear that by using fuzzy logic controller performance of the PMSM based eV 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	4.5	5.3
Above rated speed	5.6	6.7

VI. CONCLUSION

This study presents a closed-loop vector control system designed specifically for electric vehicles, integrating a fuzzy logic speed controller. The addition of this controller within the speed loop significantly improves the overall performance of the system. Comprehensive simulations have been conducted to compare the performance of the fuzzy control-based electric vehicle system with a conventional drive system that utilizes a PI controller. The results indicate that the proposed approach demonstrates higher efficiency and a better dynamic response across a wide range of load variations compared to traditional methods. The simulation outcomes underscore the enhanced efficiency and dynamic capabilities of the fuzzy control-based electric vehicle system. Thus, the fuzzy logic speed controller emerges as a promising strategy for enhancing the overall performance of electric vehicle systems, providing improved efficiency and superior dynamic responses in diverse operational conditions.

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