# Performance of Fuzzy Logic-Sliding Mode IFOC based Induction Motor Drive

***Rekha Tidke**

Assistant Professor in the Department of Electrical Engineering
Gokhale Education society R. H. Sapat College of Engineering, Nashik, Maharashtra India.

**Abstract**: The study focuses on enhancing the dynamic response of induction motors for electric vehicle applications. A fuzzy logic-sliding mode scheme has been developed to minimize torque ripple and achieve rapid dynamic performance. The combination fuzzy logic (FL) with a sliding mode Indirect field-oriented control used in the induction motor drive. It provides simulation study model and block diagram of the FL-SMC method, including basic field weakening. It also investigates a comparative performance analysis of the IFOC, SMC and FL-SMC (with field weakening) methods. The performance at a standstill to forward speed, and speed reversal has been analysed, keeping focus on torque ripple and speed convergence. It has been observed that the average percentage of speed convergence in the FL-SMC method is 19% and 30% faster, and the average percentage of torque ripple reduction is 3% and 4.6%, compared to the SMC and IFOC methods. The FL-SMC method shows reduced torque, improved speed convergence, and better overall control.

**Keywords—**Induction motor drive, Fuzzy logic, sliding mode, MATLAB Simulink

## 1. Introduction

The use of electric vehicles (EVs) is rapidly growing and is expected to rise even more dramatically in the near future. Many developing urban areas around the world are increasingly choosing EVs as a replacement for traditional internal combustion engine vehicles. The EVs drive on electrical power provided by a battery pack which can be charged on the grid. The battery can either be charged on conventional power generation (coal, diesel) or renewable power (solar plants, wind farms, hydro plants, etc.) as per the availability. However, renewable power would be a priority option for charging the EV battery packs. Electric vehicles (EVs) use various types of electrical motors to achieve propulsion, with alternating current (AC) motors being a popular choice due to their strong performance. Due to hazardous problems in the protection of the environment and limited energy sources, the fast EV growth has been observed. When selecting a traction motor for EV/HEV propulsion systems, several important factors must be considered, including cost, reliability, power density, maintenance requirements, ruggedness, and the maturity of the technology. Permanent magnet (PM) motors, while offering high performance, present challenges such as handling difficulties due to the strong magnetic forces they generate. These forces can cause issues when ferromagnetic materials come into contact with the magnets, potentially complicating maintenance, and operation.

In contrast, IMs generally offer cost advantages over PM motors. The high cost of permanent magnets remains a significant factor in the expense of PM motors. Additionally, IM drives are capable of field weakening or operating in a constant-power mode, over a wide range of speeds—a flexibility that PM motors do not inherently possess. This capability allows IMs to maintain efficiency and performance across various operating conditions. Furthermore, IMs can be designed to operate with higher flux densities compared to PM motors, which are constrained by the magnetic properties of the

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permanent magnets used. The IM's affordability and suitability make them an attractive choice for electric vehicle (EV) applications.[1].

When comparing Induction Motors (IM) and Permanent Magnet Synchronous Motors (PMSM) in the context of electric vehicles (EVs), several advantages of IMs become evident, particularly in terms of cost-effectiveness, durability, and performance across a range of conditions. For instance, EVs like the Mahindra e2oPlus and the Mahindra E Verito, both powered by 3-phase Induction Motors, showcase how IMs can provide a solid balance between affordability and functionality, with the e2oPlus offering a relatively low price point of ₹7.46 - 8.22 lakhs. On the other hand, PMSMs, as seen in high-end models like the Tesla Model X (₹74.7 lakhs) and the Hyundai Ioniq 5 (₹46 lakhs), require the use of rare-earth magnets, making them more expensive and subject to supply chain fluctuations. While PMSMs may offer better efficiency and torque density, especially at lower speeds, IMs excel in providing more reliable long-term performance with minimal maintenance, as demonstrated in vehicles such as the Mercedes-Benz EQC and Audi e-tron 55, both equipped with 3-phase Induction Motors, showcasing strong power outputs of 300 kW and 140 kW respectively. Therefore, for EVs aiming for a balance between cost, reliability, and performance, particularly in mid-range vehicles, Induction Motors appear to be a better choice over PMSMs, as they offer long-lasting, low-maintenance solutions at a more accessible price point [2-4].

Furthermore, incorporating a QZSI into the system offers notable advantages. Its single-stage AC-DC-DC conversion not only simplifies the design but also reduces costs. The QZSI improves DC bus utilization and ensures a continuous input current, contributing to a more efficient and cost-effective power conversion process. These improvements support both enhanced performance and reduced overall expenses in EV systems.

The study explores the technological aspects of powertrain systems in Battery Electric Vehicles (BEVs), focusing on advancements in EV architecture, electrical machines, and optimization techniques for green mobility. It discusses the challenges in commercializing electric drivetrains and provides an overview of current BEV powertrain technologies, along with prospects. The study identifies and classifies commonly used converter topologies in EVs, offering valuable insights for researchers and engineers. Additionally, it reviews state-of-the-art converter topologies, future vehicle strategies, and the role of power electronics in EV development [5-7].

Optimizing traction motor control systems is key to improving the performance and efficiency of electric vehicles (EVs). Two advanced control techniques, DTC and IFOC, are widely used for IM and PMSM. It highlights improvements in reducing torque ripple, enhancing transient response, and optimizing powertrain efficiency through stator flux and DC link voltage adjustments to extend vehicle range. The review also discusses the performance of key strategies like FOC, DTC, and FS-MPC, noting their strengths and challenges. In summary, DTC, IFOC, and FS-MPC enhance motor control, reduce torque ripple, and improve powertrain efficiency, leading to better EV performance and range. Ongoing research is focused on overcoming challenges for more efficient EV powertrains [8-12]. The design and control methods to enhance the energy efficiency of electric machines for EVs Illustrated in [13]. It covers motor design requirements such as power density, efficiency, and cost, in line with governmental targets. The review explores key design parameters, winding configurations, materials, construction technologies, and control methods that affect the power loss characteristics of traction machines.

The paper examines different types of power converters, including DC-DC, DC-AC, and AC-DC converters, and their roles in enhancing the performance and efficiency of EVs. The authors discuss the operational principles, advantages, and limitations of each converter type, providing a detailed analysis of their applications in EV systems. By highlighting recent advancements and emerging trends in converter technology, the review serves as a valuable resource for understanding the current state and future directions of power conversion in electric vehicles. The unique ability of ZSI to provide both voltage bucking and boosting capabilities within a single stage, addressing limitations inherent in conventional inverters is presented in [14]. The paper explains details the operational principles of the ZSI, including its use of an impedance network to achieve improved voltage and current control. By offering a more flexible and robust approach to power conversion, the ZSI provides significant advantages in terms of efficiency, reliability, and reduced component complexity. This research marks a pivotal advancement in inverter technology, demonstrating the ZSI's potential for diverse industrial applications and contributing to the evolution of power electronics.

How the ZSI with its innovative impedance network offers distinct advantages over traditional voltage-source and current-source inverters by enabling both voltage bucking and boosting within a single stage describes in [15]. It also, discusses the ZSI's operational principles, highlighting its ability to enhance motor drive performance through improved voltage and current control, and increased fault tolerance. By demonstrating the effectiveness of the ZSI in motor drive applications, the research underscores its potential to improve system reliability, efficiency, and flexibility. This work advances the field of power electronics by showcasing the ZSI's capability to address challenges in motor drive systems, paving the way for more efficient and robust solutions in various industrial and automotive applications. F. Z. Peng, M. Shen, and K. Holland investigate the use of the Z-source inverter (ZSI) in the traction drive systems of fuel cell-battery HEVs [16]. The paper emphasizes the ZSI's capability to improve power conversion efficiency by allowing both voltage bucking and boosting within a single stage, which is particularly beneficial for integrating multiple energy sources like fuel cells and batteries.

The two control strategies for bidirectional Z-source inverters (BZSI) in electric vehicle applications presented in [17-19]. The first uses IFOC for precise motor speed control, from zero to rated speed with full load torque in motoring and regenerative braking modes. It incorporates PWM voltage modulation, shoot-through control, and a dual-loop controller for capacitor voltage management. The second strategy employs a Proportional-Resonance (PR) controller for AC current regulation during battery charging/discharging, also with a dual-loop controller for capacitor voltage. Additionally, a three-phase quasi-Z-source matrix converter is proposed, offering a buck-boost function and efficient motor speed control. Simulation results validate the effectiveness of all methods. The demonstration how the QZSI improves the performance of the five-phase induction motor by offering both voltage boosting and bucking capabilities in a single stage, as discussed in [20]. It analyzed the impact of this configurations on motor efficiency, dynamic response, and control precision. The paper emphasizes the advantages of using QZSI technology, such as enhanced system flexibility and improved performance compared to traditional inverters. This research highlights the potential of QZSI in advanced motor drive systems, particularly for applications requiring robust and efficient power conversion. A robust SMC strategy specifically designed for managing the speed of two-wheel EV drives explores in [21]. It details the development of a sliding mode controller that enhances speed regulation and stability, addressing common challenges in electric vehicle drive systems. The authors provide a thorough analysis of the control algorithm's performance, emphasizing its robustness in maintaining accurate speed control despite variations in operating conditions and external disturbances. The research demonstrates the effectiveness of this approach in improving the reliability and performance of two-wheel EVs, contributing valuable insights into the design of robust control systems for electric vehicle applications.

Ghezoua, et al. [22], explore the application of SMC for a four-wheel electric vehicle (EV) drive system. The study presents a detailed analysis of how SMC can be utilized to manage the individual torque and speed of each wheel in a multi-motor setup. The authors highlight the benefits of using SMC, including enhanced control precision and robustness in handling dynamic driving conditions. The research demonstrates that SMC effectively improves vehicle stability and performance by addressing the challenges of managing multiple drive units. This work contributes to advancing EV drive technology by showcasing how sliding mode control can be implemented to achieve more reliable and responsive vehicle performance. Solea, et al. [23], explore the use of SMC to enhance the performance of induction motors. It details the design and implementation of an SMC strategy aimed at improving control precision under various operating conditions. The study emphasizes the benefits of SMC, including its robustness to disturbances and parameter changes, and its capability to maintain stable and precise control. Through a combination of simulations and practical experiments, the paper demonstrates that SMC significantly improves motor response and reliability. This research highlights SMC as an effective method for advancing induction motor control in both industrial and automotive settings. In [24], it explores the implementation of Direct Torque Control (DTC) for a mathematically modeled induction motor drive using a hybrid control strategy that combines a PI-Type-I Fuzzy Logic Controller (FLC) and a Sliding Mode Controller (SMC). The FLC is employed to adjust the PI parameters dynamically, improving the adaptability of the control system to varying operating conditions. The SMC, known for its robustness, is integrated to handle uncertainties and disturbances, further enhancing the drive's performance. The combination of FLC's adaptability and SMC's robustness leads to a more stable and efficient control system.

This paper is structured as follows: Section I provides the introduction, while Section II details the design of the proposed controller. Section III presents the MATLAB simulation and results under various operating conditions. Finally, Section IV offers the conclusion, summarizing the most effective control module for the operation of the induction motor under different operating conditions, followed by the references.

## 2. IM MODEL WITH DESIGN OF CONTROLLER

Field-Oriented Control (FOC) is a widely adopted technique for controlling the speed and torque of induction motors, offering high precision and dynamic performance. This method allows an induction motor to operate similarly to a separately excited DC motor. The equivalent equations of the stator and rotor dynamics of a squirrel-cage induction machine in synchronously rotating $d^e - q^e$ axes are obtained as below.

$$0 = R_r\ i_{qr} + \frac{d\psi_{qr}}{dt} + \omega_{sl}\,\psi_{dr} \tag{1}$$

$$0 = R_r\ i_{dr} + \frac{d\psi_{dr}}{dt} - \omega_{sl}\,\psi_{qr} \tag{2}$$

$$V_{ds} = R_s\ i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_e\psi_{qs} \tag{3}$$

$$V_{qs} = R_s\, i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_e\psi_{ds} \tag{4}$$

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_{ds}\, i_{qs} - \psi_{qs}\, i_{ds}) \tag{5}$$

Where as $V_{ds}, V_{qs}, i_{ds}, i_{qs}, \psi_{ds}$ and $\psi_{qs}$ is stator d-axis and q-axis voltage, current and flux respectively. $R_s, R_r, L_m, L_r$ and $P$ is "stator resistance, rotor resistance, mutual inductance, rotor inductance and pole pairs" respectively IM motor parameters [25-27].

The IM motor equivalent circuit equations are rearranged and modified for design of proposed controller.

$$\frac{di_{ds}}{dt} = \frac{1}{L_s\,\sigma}[V_{ds} - [R_s + \frac{{L_m}^2}{t_r\,L_r}]\, i_{ds} + \frac{L_m}{L_r}\frac{1}{t_r}\psi_{dr} + \frac{L_m}{L_r}\ \omega_m\,\psi_{qr} + L_s\,\sigma\,\omega_e i_{qs}] \tag{6}$$

$$\frac{di_{qs}}{dt} = \frac{1}{L_s\,\sigma}\left[V_{qs} - \left[R_s + \frac{{L_m}^2}{t_r\,L_r}\right] i_{qs} + \frac{L_m}{L_r}\frac{1}{t_r}\psi_{qr} - \frac{L_m}{L_r}\;\omega_m\,\psi_{dr} - L_s\,\sigma\,\omega_e i_{ds}\right] \tag{7}$$

$$\frac{d\psi_{dr}}{dt} = -\frac{R_r}{L_r}\psi_{dr} + \frac{R_r L_m}{L_r}\,i_{ds} + \omega_{sl}\,\psi_{qr} \tag{8}$$

$$\frac{d\psi_{qr}}{dt} = -\frac{R_r}{L_r}\psi_{qr} + \frac{R_r L_m}{L_r}\,i_{qs} - \omega_{sl}\,\psi_{dr} \tag{9}$$

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\psi_{dr} i_{qs} - \psi_{qr}\,i_{ds}) \tag{10}$$

Field weakening involves reducing the strength of the motor's magnetic field, enabling it to operate at speeds beyond its base limit. This process allows the motor to achieve higher speeds while drawing less current. As the motor reaches higher speeds, the voltage required to maintain the same torque increases. By weakening the magnetic field, the motor can sustain these higher speeds without surpassing the voltage limits of the power supply.

When the motor rotor speed is below the base speed $\omega_b$ , the $i_{ds}$ reference is equal to the rated current value. When the speed of motor exceeds $\omega_b$ , the $i_{ds\_ref}$ reference calculated by following equations,

$$i_{ds\_ref} = \frac{|\omega_b|}{|\omega_m|}\,i_{ds\_base} \tag{11}$$

A FLC converts a linguistic control approach into an automatic control approach and fuzzy rules are created by knowledge or practice database. Initially, the input current error $e\,i_{qs\_ref}$ and the change in current error $e^{*}i_{qs\_ref}$ has been placed to be the input variables of the FLC. Then the output variable of the FLC is offered by the control of variation in current $e\,i_{qs\_ref}$ denoted as $i_{qs\_FL}$. In the real variables of the current error and variation in current error are transformed into fuzzy variables $e\,i_{qs\_ref(k)}$ and $e^{*}i_{qs\_ref(k)}$ that can be recognized by the level of MF in the fuzzy set. Same for $e\,i_{ds\_ref}$ shown in **fig.1.**

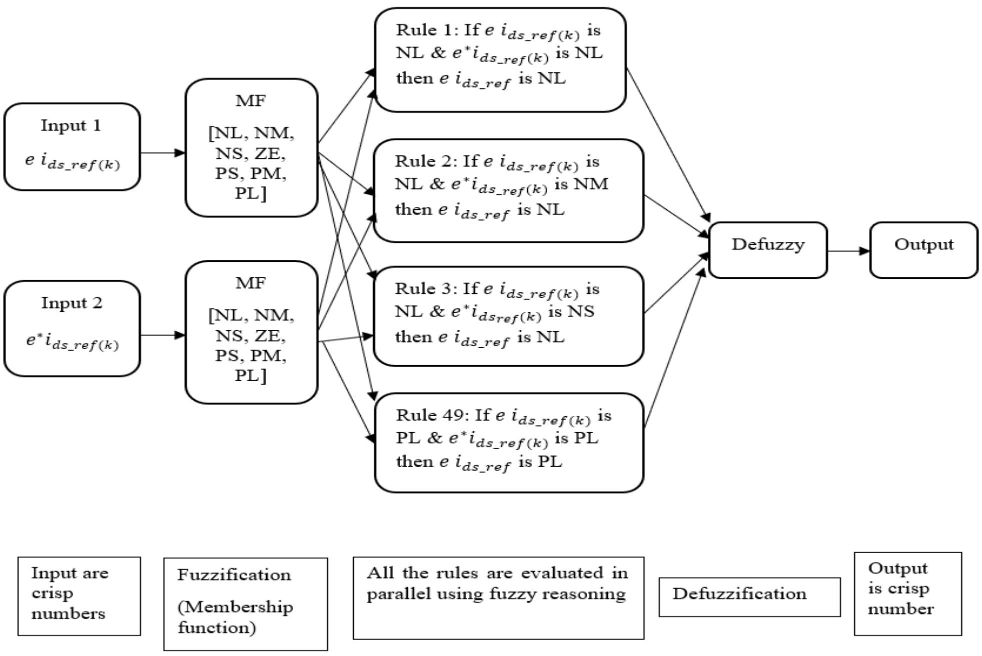


**Fig 1: Fuzzy logic IF -THEN rule**

In Sliding Mode Control (SMC), the sliding surface is designed to be robust, reducing sensitivity to certain uncertainties and disturbances. However, a major drawback of SMC is the chattering phenomenon, which arises from the rapid switching of control inputs. In contrast, Fuzzy Logic Control (FLC) adjusts control inputs based on both the current error and the rate of change of the error, offering a more adaptive response. At each step, FLC normalizes the current input, enhancing system performance and ensuring smoother control.

The two sliding surfaces are required $s_1$ and $s_2$ , one is for $i_{ds}$ control and other one is for $i_{qs}$ control.

$$s_1 = i_{ds\_FL} - i_{ds} \tag{12}$$

$$s_2 = i_{qs\_FL} - i_{qs} \tag{13}$$

The final voltage equivalent control law values obtained with help of fuzzy logic controlled current values and derivatives of sliding surface eq. (12) and (13).

$$V_{ds}^{equ} = L_s\,\sigma\,[\dot{i}_{ds\_FL} + \frac{1}{L_s\,\sigma}\,R_\sigma i_{ds} + \frac{1}{L_s\,\sigma}\frac{L_m}{L_r}\frac{1}{t_r}\psi_{dr\_ref} + \omega_e i_{qs}] \tag{15}$$

$$V_{qs}^{equ} = L_s\,\sigma\,[\,\dot{i}_{qs\_FL} + \frac{1}{L_s\,\sigma}\,R_\sigma i_{qs} + \frac{1}{L_s\,\sigma}\frac{L_m}{L_r}\,\omega_m\,\psi_{dr\_ref} + \omega_e i_{ds}] \tag{16}$$

The **fig.2** gives detailed FL-SMC controller schematic with field weakening. The $Z^{-1}$ is a MATLAB delay function.

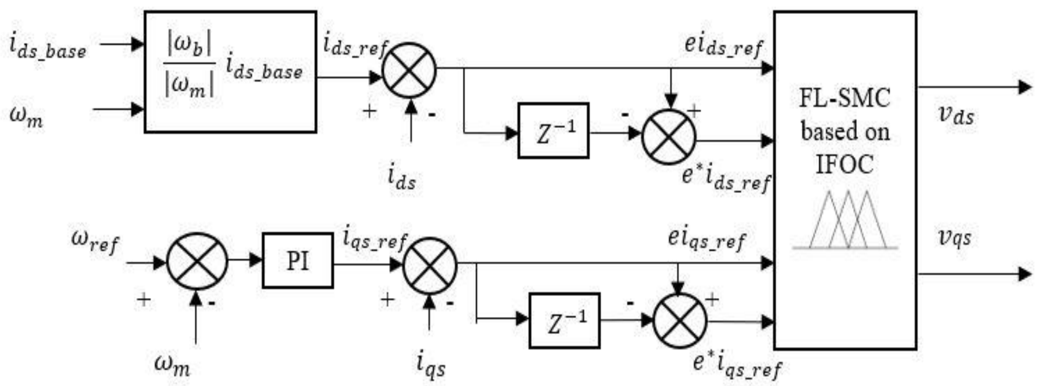


**Fig 2: Schematic of FL-SMC method with field weakening**

The Fuzzy Logic (FL) component is combined with Sliding Mode Control (SMC) to regulate the direct and quadrature axis currents, improving the overall performance of the motor. The FL-SMC approach is applied to investigate the dynamic behavior of the IM drive under the proposed control strategy,

ensuring optimal performance under various operating conditions.
The FL-SMC voltages from **fig 2** as below

$$v_{ds} = V_{ds}^{equ} + V_{ds}^{n} \quad (17)$$

$$v_{qs} = V_{qs}^{equ} + V_{qs}^{n} \quad (18)$$

The voltage discontinuous control $V_{ds}^{n}$ and $V_{qs}^{n}$ is defined as

$$V_{ds}^{n} = k_1 \ sat\,(\frac{s_1}{\varphi_1}) \quad (19)$$

$$V_{qs}^{n} = k_2 \ sat\,(\frac{s_2}{\varphi_2}) \quad (20)$$

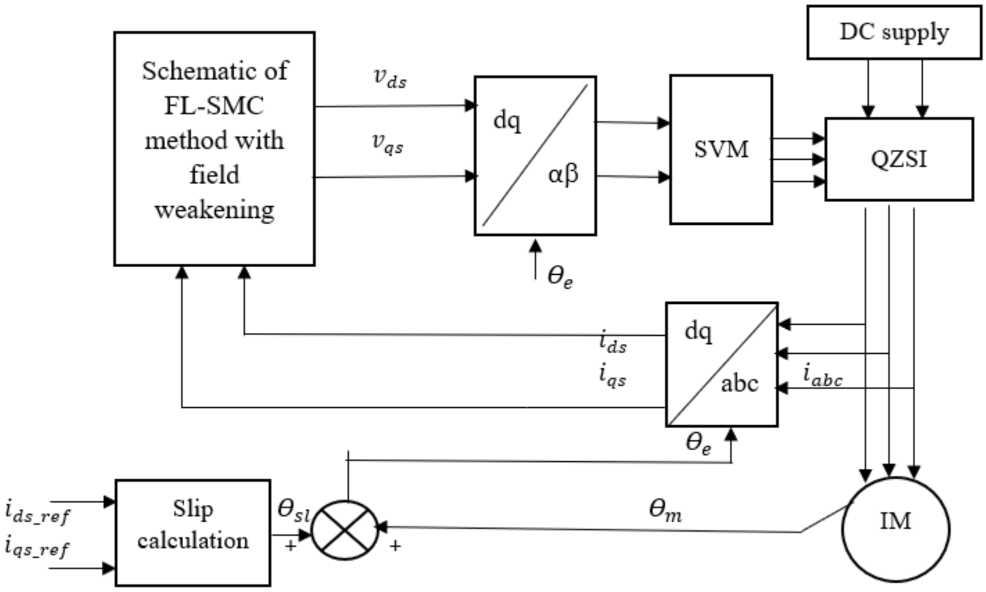


**Fig 3: The block diagram of FL-SMC Hybrid Controlled IM drive**

The complete block diagram **Fig. 3** of IM drive is powered by a Quasi-Z-Source Inverter (q-ZSI), which addresses a significant limitation of traditional Z-Source Inverters (ZSI). ZSIs suffer from the issue of discontinuous input current, which can degrade battery life and reduce the efficiency of electric vehicles (EVs) and hybrid electric vehicles (HEVs). In contrast, the q-ZSI solves this problem by restructuring the components of the Z-source network, ensuring a continuous input current. This continuous input current is crucial for maintaining the stability and longevity of the power supply, especially in applications like EVs and HEVs, where energy efficiency is paramount.

The q-ZSI (quasi-Z-source inverter) overcomes the main drawback of the traditional ZSI, which is the discontinuous input current that can shorten battery life and degrade the performance of EVs/HEVs. By rearranging the components of the Z-source network, the q-ZSI ensures continuous input current while retaining all the benefits of the ZSI. It enables a two-stage DC-DC-AC conversion in a single stage, simplifying the power conversion process and improving system efficiency by reducing energy losses. Additionally, the q-ZSI provides extensive voltage buck-boost capabilities, allowing it to manage a wide range of input and output voltages, which is especially useful for EVs and HEVs with varying power demands. Compared to traditional voltage-source inverters (VSIs), the q-ZSI offers a broader output voltage range, reduces component requirements, and is more compact and cost-effective. These advantages make the q-ZSI an ideal solution for powering induction motors in electric and hybrid vehicles, enhancing performance, energy efficiency, and overall cost-effectiveness.

## 3. PERFORMANCE EVALUATION WITH MATLAB SIMULATION

MATLAB Simulink is employed as the primary simulation tool to design and model the FL-SMC method in IM drive. The modeling process involves creating a detailed representation of the induction motor dynamics, specifically utilizing a squirrel cage induction motor, which is commonly used in industrial applications due to its robustness and reliability. In Simulation studies, the induction motor's mathematical model is developed, incorporating key parameters such as resistance, inductance, and rotor dynamics. The FL-SMC method integrates fuzzy logic and sliding mode control techniques to enhance performance under various operating conditions, ensuring smooth and responsive control of the motor.

3.1 Comparative Performance Evaluation Under Speed Variation

For the performance analysis of the proposed controller applied to an induction motor drive, a 3-phase squirrel cage induction motor with the following specifications is utilized: 4 poles, 4 kW rated power, and a rated speed of 1430 rpm. The system is using a space vector pulse width modulation (SVPWM) technique, with a switching frequency set at 5 kHz. During the analysis, the motor operates with a different reference rotor speed in rpm and a consistent load torque in Newton-meters (Nm). The comparative analysis has been observed for IFOC, SMC and FL-SMC methods.

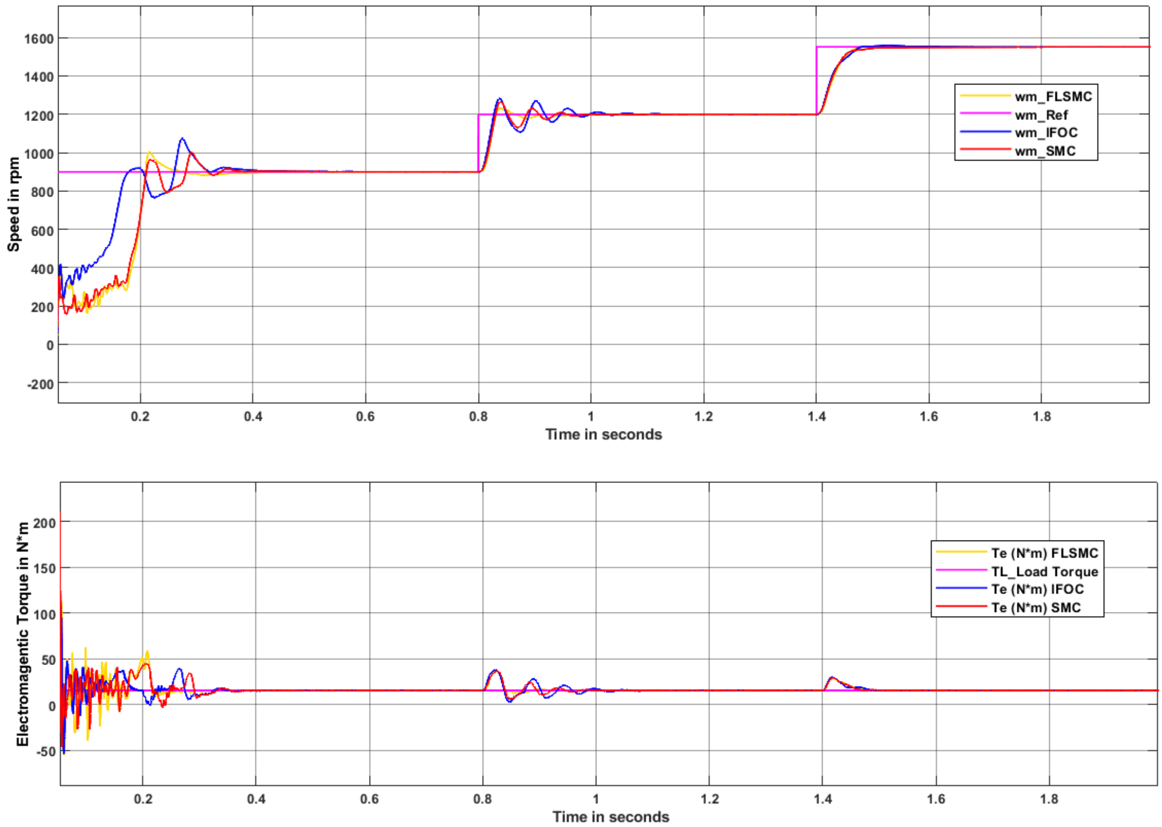


**Fig. 4: Speed response under the step speed operation**

In the analysis of the control techniques under constant torque and step speed conditions, both the FL-SMC method, conventional IFOC method and SMC method were tested with a constat 15 Nm load torque. Speed reference input was varied in steps, beginning at 900 rpm, then 1200 rpm, and then reaching 1550 rpm high speed shown in fig. 4

Simulation results, demonstrate that the FL-SMC method achieves significantly faster speed convergence compared to the SMC and IFOC methods. This indicates that the FL-SMC method responds more quickly and accurately to changes in reference speed, effectively tracking the desired speed with minimal delay.

*Table 1: Speed convergence time during speed operation*

| Speed in rpm | Speed waveform Convergence time | | |
|---|---|---|---|
| | IFOC | SMC | FL-SMC |
| 900 | 0.5 s | 0.43 s | 0.4 s |
| 1200 | 0.4 s | 0.35 s | 0.23 s |
| 1550 | 0.3 s | 0.25 s | 0.2 s |

It has been observed that the average percentage of speed convergence in the FL-SMC method is 19% and 30% faster as compared to the SMC and IFOC methods using data from **Table 1.**

System run at various constant load torque and its observation has been notes in **Table 2.** It has been observed that at low-speed low load torque condition, the ripple contents more as compared to other conditions in all 3 methods noted in **Table 3**. The average torque ripples are 8.5%, 6.9% and 3.9% of IFOC, SMC and FL-SMC method respectively. Hence the reduction in torque ripple in FL-SMC is 4.6% and 3% less as compared to IFOC and SMC method.

*Table 2: Percentage of torque ripple in speed operation*

| Speed in rpm | Load torque in Nm | Torque ripple in Percentage | | |
|---|---|---|---|---|
| | | IFOC | SMC | FL-SMC |
| 0-900 | 15 | 2.6 | 2.4 | 2.3 |
| | 20 | 1.9 | 1.8 | 1.7 |
| | 25 | 2.3 | 2.1 | 1.4 |
| 900-1200 | 15 | 12.3 | 10.3 | 3.3 |
| | 20 | 9.5 | 6.5 | 3.1 |
| | 25 | 7.6 | 6.6 | 3.1 |
| 1200-1550 | 15 | 17.2 | 12.2 | 7.5 |
| | 20 | 12.6 | 11.6 | 6.7 |
| | 25 | 10.4 | 8.4 | 5.9 |

*Table 3: Average torque ripple*

| Torque Nm | Average Torque ripple in % | | |
|---|---|---|---|
| | IFOC | SMC | FL-SMC |
| 15 | 10.7 | 8.3 | 4.37 |
| 20 | 8 | 6.63 | 3.83 |
| 25 | 6.77 | 5.7 | 3.47 |

It has been observed from the performance evaluation of IFOC, SMC and FL-SMC method, the FL-SMC method demonstrates better results as compared to other methods.

### 3.2 Comparative Performance Evaluation Under Load Variations

In this performance analysis, the system operates at its rated speed under a step load torque. The load torque varies from a low value of 5 Nm to a reference load torque of 15 Nm in step with 10 Nm then 15Nm and reduced to 5 Nm. The applied load torque $T_L$, the electromagnetic torque *Te* and the speed response of the FL-SMC method with IFOC and SMC are shown in **Figure 5.**

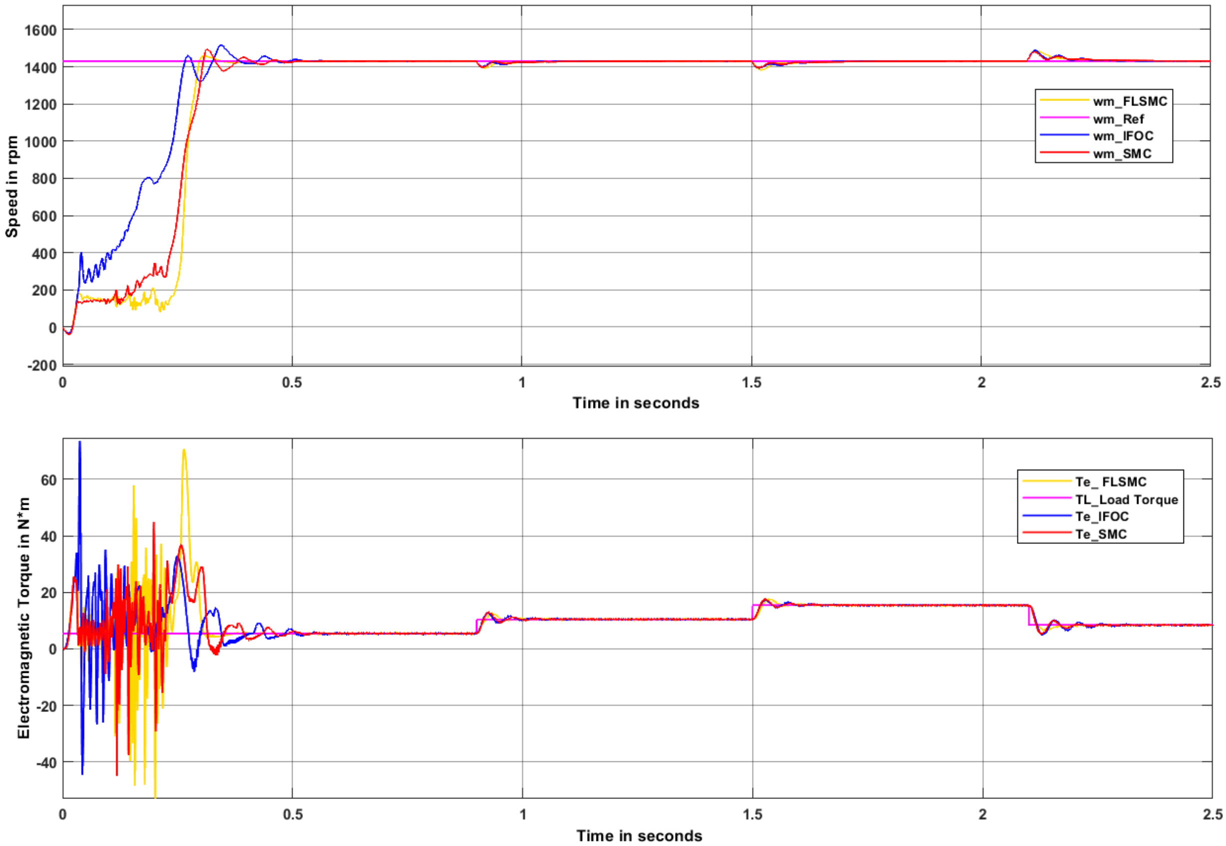


**Fig. 5: Torque and Speed response under the load torque operation**

***Table 4: Percentage of torque ripple in Load variation***

| Speed in rpm | Torque change Case | Parameter | IFOC | SMC | FL-SMC |
|---|---|---|---|---|---|
| 1430 | 5 to 10 Nm | Convergence time in s | 0.45 | 0.35 | 0.25 |
| | | % Torque ripple | 17.63 | 6.9 | 4.8 |
| | 10 Nm to 15 Nm | Convergence time in s | 0.8 | 0.7 | 0.7 |
| | | % Torque ripple | 4.85 | 3.975 | 3 |
| | 15 to 5 Nm | Convergence time in s | 0.55 | 0.35 | 0.3 |
| | | % Torque ripple | 13.95 | 3.88 | 2.87 |

The Speed response reveals a consistent speed tracking during the step load change with IFOC, SMC and FL-SMC method **Fig 5.** From the speed waveform, it is observed that the FL-SMC achieves fast convergence, with a response time of 0.2 seconds. The torque response convergence and ripple noted in **Table 4.** The average torque ripple reduction in FL-SMC is 6.25% and 1.37 % less as compared to IFOC and SMC method.

## 4. CONCLUSIONS

A performance evaluation has been conducted in MATLAB Simulink environment among three control strategies: IFOC scheme, SMC scheme, and the newly FL-SMC method. It has been examined for speed convergence and speed tracking in an wide speed range and load variation achieves fast convergence and quick tracking in speed. The comparative performance evaluation has been observed that, the average percentage of speed convergence in the FL-SMC method is 19% and 30% faster and the reduction in torque ripple in FL-SMC is 4.6% and 3% as compared to the SMC and IFOC method in speed variation operation. During torque variation, the average torque ripple reduction in FL-SMC is 6.25% and 1.37 % less as compared to IFOC and SMC method. The FL-SMC method demonstrated better dynamic performance in speed and load variation as compared to other 3 methods.

**Declarations:**

Ethics approval and consent to participate: Informed Consent

Consent for publication: Informed Consent

Competing interests: No Completing interest

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Rekha Tidke has received the degree B.E. and M.E. from the K. K. Wagh College of Engineering, Nashik; under the university of Pune, India. She received **Ph.D. degree** in the Electrical Engineering at S.V. National Institute of Technology, Surat in India, **in 2025**. Her research interests include electrical machines, control drives, its applications in electric vehicle. Presently working as Assistant Professor in the Department of Electrical Engineering of Gokhale Education society R. H. Sapat College of Engineering, Nashik, Maharashtra India.