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Extended Condition Monitoring of Grid-connected Industrial Induction Motors using SMC Technique

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ABSTRACT

The control method for a vehicle that combines Sliding Mode Control (SMC) and Active Power Control (APC) for three-phase induction motors that encounter unmeasured speed circumstances and unknown disturbances is examined in this work. The primary contribution is the creation of an improved controller with a time-varying gain mechanism that maintains balanced performance and rapid response while managing the peak phenomena often associated with abrupt changes in speed, torque, and loads. Starting from a conservative setting and smoothly transitioning to a high-gain system, the active power control model with the suggested sliding controller is made to adapt to real-time changes and offers a quantitative balance between transient peaks and response precision. A sliding-mode controller with active disturbance compensation is implemented based on accurate assessments of disturbances and reconstructed states from the proposed system. This greatly decreases abrupt vibrations, a persistent problem in classic SMC. The remarkable durability of the Sliding Mode Controller (SMC) and its capacity to manage the intricate nonlinear nature of these motors in a manner that is less complicated than more sophisticated alternatives are what make it unique, particularly in induction motor applications. Since a three-phase induction motor is a highly nonlinear system and its properties, such as internal resistance, fluctuate with temperature and loads, we must examine how it operates in order to comprehend why. The software simulation results of the proposed SMC based on the extended state observer (ESO) model showed THD < 3.5%, with response time < 15 ms, along excellent chattering elimination and high real-time compensation.

1. Introduction

In contemporary engineering applications, such as robotic arms, self-driving cars, and precision manufacturing machinery, precisely regulating the movement of mechanical systems continues to be a significant difficulty. These systems are subject to a number of uncertainties, such as external perturbations, un-modeled dynamics, and parameter changes. If these uncertainties are not well managed, they might lower control performance and potentially cause instability. Many different control solutions have been developed over the past few decades to address the tracking control problem for induction motors and mechanical systems. Due to its simplicity and ease of use, classical proportional-integral-derivative (PID) control is still in widespread usage. However, when there are significant uncertainties and disruptions, its performance frequently declines [1, 2].

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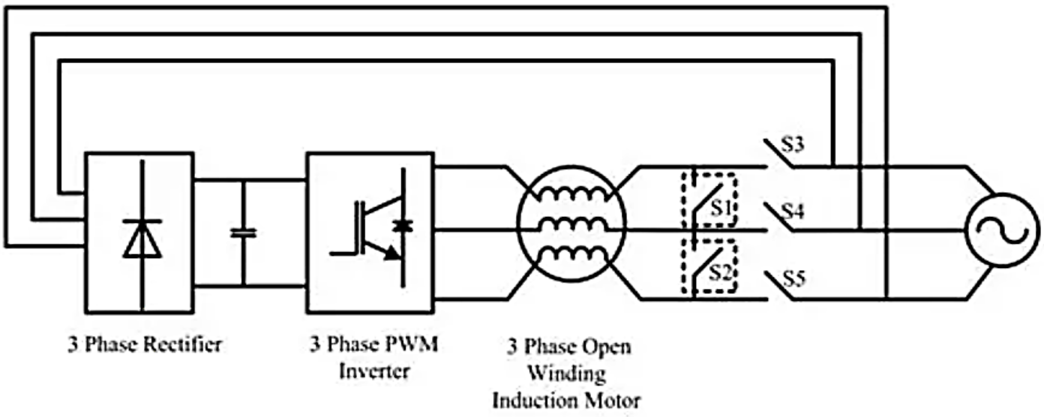


Figure 1: Schematic diagram of three phase induction motor grid-connected inverters controller systems [2, 3].

Although adaptive control methods may address parametric uncertainties by adjusting controller settings online, they may exhibit a delayed transient response and be vulnerable to disturbances that change quickly. Although robust control techniques, like H-infinity synthesis, ensure performance limitations in the worst-case scenario, they are often conservative and may necessitate accurate explanations of uncertainty. A fuzzy adaptive PID control technique based on the geometric modeling of motion error parameters has been proposed by certain research to solve problems of motion accuracy deterioration and poor stability in wheeled robots. The necessity of enhancing control performance in electro-hydraulic servo systems by thoroughly examining optimum PID control methods has been covered in other works [2, 3]. To forecast future research trends, the benefits, drawbacks, and application situations of various controllers were also examined. To overcome the performance constraints of traditional fixed-gain PID controllers for hybrid robots with configuration-dependent dynamics, a fuzzy gain-scheduled PID technique was put forward. In order to effectively lessen the detrimental effects of dynamic property fluctuations, methods integrating fuzzy logic and clustering analysis were also developed to modify control settings live based on the rate of change, analogous faults, and gravity. To address the issue of low accuracy in predicting the remaining life of mechanical systems under complex operating conditions, other studies proposed a prediction model that combines performance evaluation and geometrically fractional-order steady-state Levy motion with adaptive nonlinear deviation. The accuracy was successfully improved [3, 4].

The rest of the sections and remaining content of this article will be organized as follows. The latest published articles related to the topic will be included in Section 2, along with their analysis to identify the researchers' contributions and to look at the proposed control models for three-phase induction motor systems, pinpointing the study problem and scientific contribution. This will be followed by an explanation of the study methodology and design steps, with a review of the software simulation tuning parameters in Section 3, as well as a clarification of the data set sources. Section 4 includes a review of the software simulation results of the proposed sliding mode control system, along with a discussion of the diagrams and obtained readings. Finally, the conclusions and recommendations are addressed in Section 5 of this research.

2. Literature Review

This section covers the basic theoretical ideas behind different control systems for three-phase induction motors to maintain their performance stability under changing operational conditions in industrial load distribution networks. It will introduce the latest scientific contributions through researchers' proposals in accredited publications and highlight the main advantages of these control techniques, along with understanding their limitations and issues. The section will also include an analysis of the gaps and scientific challenges faced by researchers to identify and define the study problem and key obstacles. Additionally, this section explains the novelty and scientific contribution of the proposed sliding control technique.

Many researchers have proposed sliding control techniques and various hybrid models to manage instant changes in the performance of induction motors. The latest contributions will be reviewed by going over recently published related articles and analyzing the advantages of the proposed models while also highlighting their main problems and working limitations.

2.1 Related Studies

Table 1: Summaryy of the most recent published articles related to the thesis topic.

Year & Author(s)	Employed Technique	Study Contribution	Limitations & Gaps
2025 – Guo et al. [13, 14, 22]	Model-Free Predictive Current Control (MFPCC) with Improved Sliding Mode Observer (SMO) and Dual Low-Pass Filters (DLPFs)	Proposed enhanced disturbance observation accuracy for Open-End Winding Induction Motors, reducing sensitivity to high-frequency noise and improving current harmonics and tracking error.	Focused on OEWIM topology; conventional ESO limitations addressed but SMO complexity may increase computational burden; validation limited to specific motor configuration.
2025 – Review Study [15]	Comprehensive review of Sliding Mode Control variants (Terminal, Super-Twisting, Adaptive) for electric drives	Critically assessed SMC development trajectory and integration with FOC, DTC, and MPC; highlighted synergistic benefits and role of sliding mode observers for sensor-less operation.	Provides comparative analysis but lacks specific experimental validation; does not address partial-order sliding specifically; focuses on general electric drives rather than grid-connected industrial motors.
2025 – Review Study [17]	Comprehensive review of 240+ publications on IM control (2019-2025)	Systematic synthesis of control strategies including FOC, DTC, MPC, and intelligent algorithms; highlighted AI-based DTC as optimal balance between torque dynamics and robustness.	Algorithmic complexity and high hardware requirements constrain industrial adoption; limited focus on grid-connection challenges; partial-order and extended state observation not specifically addressed.
2025 – EFEA Conference [16]	Evaluation of SPWM-FOC under harmonic distortion from grid-connected PV systems	Established comprehensive baseline for IM drive performance under 5th-19th order harmonics (5-30% distortion); quantified PF reductions (>6%) and THD (>100% at high distortion).	Only evaluates performance degradation without proposing mitigation strategies; does not incorporate sliding mode or ESO techniques; limited to FOC framework.
2025 – Sivaprasad [18]	GWO-optimized Floating DC Link Converter for grid-connected IM	Achieved THD reduction to 1.55% (compliant with IEEE standards) and maintained constant speed/torque under unbalanced voltage sags; cost-effective compared to DVR and three-phase VSCs.	Grey Wolf Optimizer performance depends on parameter tuning; lacks dynamic disturbance observation capability; does not integrate sliding mode control with ESO for robustness.
2025 – Franklin Open [19]	Current Multiplier Approach (CMA) with Rotor Flux-Oriented Sensorless Scheme for EV applications	Demonstrated bidirectional power flow control with unity power factor and THD reduction; validated on hardware with IEEE 519-2014 compliance	Focused on EV applications rather than general industrial motors; lacks partial-order sliding control; sensorless scheme may have limited

	for grid-connected EV operation.	accuracy under severe grid disturbances.

Also, a brief analytical review was applied to previous studies to identify the main gaps and shortcomings in the study, in order to recognize the key problems and challenges faced by the studies in Table 2.

Table 2: SumRelated studies gaps analysis review summary.

Aspect	Key Findings	Common Gaps
Sliding Mode Control	Provides robustness against parameter variations and external disturbances ; variants include terminal, super-twisting, and adaptive SMC	Chattering remains challenging ; partial-order SMC not widely applied to grid-connected IMs
Extended State Observation	ESO estimates disturbances for compensation in MFPCC ; improves parameter insensitivity	Conventional ESO has poor steady-state performance and high-frequency noise sensitivity
Grid-Connected Operation	Harmonic distortion from PV systems significantly degrades IM performance ; regenerative energy feedback enables energy saving	Few studies address combined disturbance rejection and harmonic mitigation
Optimization Techniques	GWO algorithm outperforms ANN, ANFIS, ABC, and PSO in THD reduction	Optimization methods lack real-time adaptive capability under dynamic grid conditions

2.2 Study Problems & Challenges

Industrial induction motors are the backbone of the industrial sector, but running them connected to the power grid faces major challenges like unexpected load fluctuations, harmonic distortions from renewable energy sources, and errors in parameter modeling. Traditional control methods fail to tackle all these challenges together, leading to efficiency drop, increased harmonic currents, and unstable torque. Plus, relying on physical sensors raises costs and reduces reliability. That’s why there’s an urgent need to develop an advanced control approach that combines the robustness of sliding mode control with the precision of extended state monitoring, while considering partial-order design, to ensure high and reliable performance for grid-connected induction motors under tough and changing operating conditions.

2.3 Study Novelty & Scientific Contribution

The innovation is in creating a unique hybrid approach that integrates an extended state observer and fractional-order sliding control into a single framework appropriate for grid-connected induction motors. In addition to attaining a fractional order in the control structure that lowers computing cost and improves dynamic responsiveness, this design goes beyond conventional techniques by concurrently estimating and correcting for internal and external disturbances. By offering a comprehensive solution that increases energy efficiency, dramatically lowers harmonic distortions, and guarantees torque and speed stability even in the face of network impedance changes and load disturbances, this study helps close the gap between sophisticated robust control theories and real-world industrial applications. Additionally, the study provides a methodical framework that may be used to a variety of industrial motor applications.

2. Methodology

In this chapter, we will go over the details of the design and methodology of the proposed sliding mode control model for the catheter to handle instantaneous load changes in three-phase induction motors used in industrial power systems. The mathematical model will be derived and explained, including the required equations for a high-order sliding mode control system with three-phase induction motor parameters under dynamic conditions and changes. The steps of the programming methodology needed to design and implement the sliding mode controller in the simulation system using MATLAB will also be clarified and explained. Additionally, the chapter will include a review of the design parameter tables for the basic units that make up the simulation software system, along with the sources of the operational data and their specifications.

3.1 Mathematical Modeling

In this section, a summary of the most important mathematical equations (the mathematical model) of the sliding mode control model will be reviewed for controlling changes in load, torque, and speed in three-phase induction motors, with all constants and variables defined under each equation in a scientific and systematic approach. Thus, a brief scientific mathematical summary of a sliding mode control (SMC) model for a three-phase induction motor, focused on handling load torque, speed, and parameter variations has been demonstrated as below.

1) Mechanical Speed Dynamics

The mechanical rotor equation is defined, which shows the change in motor speed based on the difference between the electromagnetic torque and the load torque, minus the viscous friction [15, 16].

$$J\dot{\omega}_r = T_e - T_L - B\omega_r \quad (1)$$

Where, J denotes the total moment of inertia of rotor plus load, ω_r represents the rotor angular speed, $\dot{\omega}_r$, indicates the time derivative of rotor speed, T_e denotes the electromagnetic torque, T_L indicates the load torque, and B represents the viscous friction coefficient.

2) Speed Tracking Error

The controller tries to force the actual speed ω_r to follow the reference speed ω^* using the below formula [15, 16]:

$$e_\omega = \omega^* - \omega_r \quad (2)$$

Such that, e_ω represents the speed error, ω^* indicates the reference or commanded speed, and ω_r denotes the actual rotor speed.

Also, a typical sliding surface might be expressed as:

$$s = \dot{e}_\omega + \lambda e_\omega \quad (3)$$

Whereas, s represents the sliding surface, $\dot{e}_\omega$ denotes the derivative of speed error, and λ indicates the positive design constant that sets convergence rate. The sliding surface may be found using this formula. The system exhibits robust and well-damped behavior as the route approaches s=0.

3) Sliding Mode Control Law

Two components make up the control input: an equivalent portion and a discontinuous conversion part. The sliding mode controller's resilience to load torque disruptions and parameter uncertainty is attributed to this configuration.

$$u = u_{\text{eq}} - k\,\text{sgn}(s) \quad (4)$$

Where, u, represents the control input, commonly stator voltage reference, current reference, or torque-producing command depending on the implementation, u_{eq} indicates the equivalent control that keeps s=0, also, k denotes the positive switching gain, and sgn(s) depicts the sign function. A simple practical form is often used to reduce the clicking problem with the following equation:

$$u = u_{\text{eq}} - k\,\text{sat}\left(\frac{s}{\phi}\right) \quad (5)$$

Whereas, sat(·) denotes the saturation function. ϕ: boundary-layer thickness.

4) Electromagnetic Torque Relation

The typical torque expression in the dq frame for a three-phase induction motor can be expressed such as [17, 18]:

$$T_e = \frac{3}{2} p\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \quad (6)$$

Such that, T_e indicates the electromagnetic torque, p denotes the number of pole pairs, λ_{ds}, λ_{qs} represents the stator flux linkages in the d- and q-axes, and i_{ds}, i_{qs} denotes the stator currents in the d- and q-axes. Also, if the rotor-flux-oriented control is employed, the torque could be simplified as follows [19, 20]:

$$T_e = K_T \lambda_r i_{qs} \quad (7)$$

Where, K_T represents the torque constant. λ_r, denotes the rotor flux magnitude, and i_{qs} torque-producing current component.

5) Compact Induction Motor Electrical Model

The motor is often described in a nonlinear state-space form in order to build and fine-tune the control mechanism. Because it directly incorporates disturbances and uncertainty simulations, this integrated model is helpful for sliding control.

$$\dot{x} = f(x) + g(x)u + d(t) \quad (8)$$

Whereas, x represents the state vector, commonly currents, fluxes, and speed, $f(x)$ denotes the nonlinear motor dynamics, $g(x)$ indicates the input gain matrix, u denotes the control input, and $d(t)$ indicates the lumped disturbance term, including load torque variation, parameter mismatch, and external disturbances. Hence, a concise SMC design for a three phase induction motor might be therefore expressed such as [19, 20]:

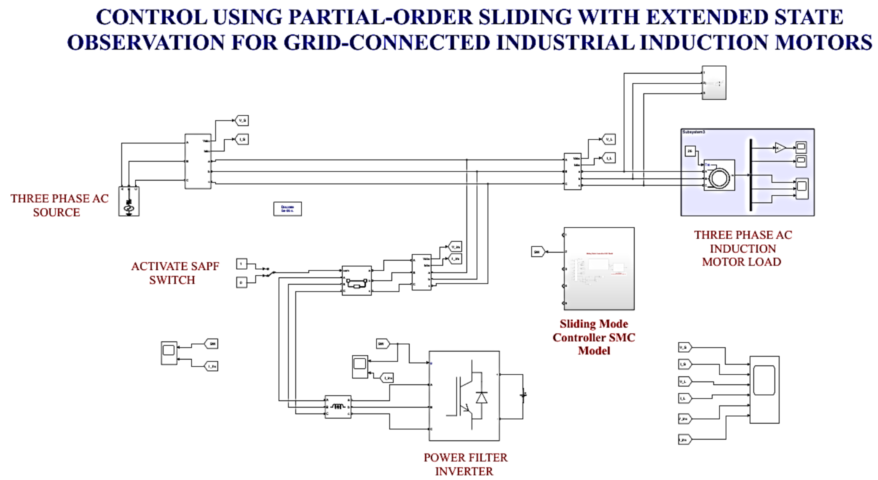
$$J\dot{\omega}_r = T_e - T_L - B\omega_r, s = \dot{e}_\omega + \lambda e_\omega, u = u_{\text{eq}} - k\,\text{sgn}(s) \quad (9)$$

In addition to simulating and representing mechanical dynamics, these equations seek to control speed and perform reliable conversion control in the face of loads and torque disturbances.

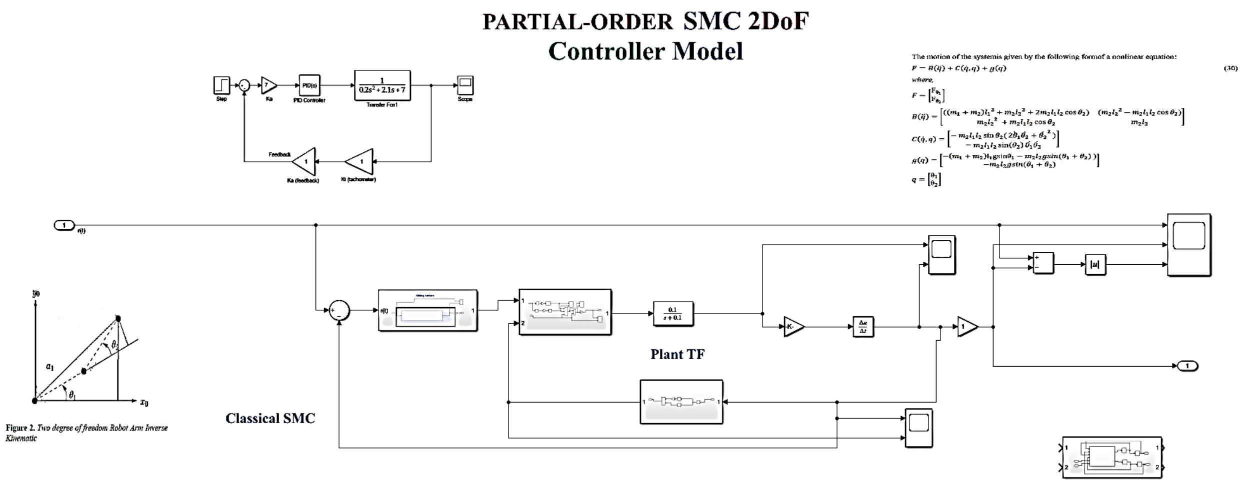
3.2 The Proposed Model Structure

This study points to an adaptable and effective control technique to deal with issues related to sudden changes and increased loads in three-phase induction motors, aiming to improve the overall efficiency of the system. The approach suggests an efficient controller for the industrial induction motor system model using sliding control based on feedback current measurements and instantaneous load changes measured from sensors for the three-phase inverter current. The proposed method helps reduce costs and the negative effects of torque and motor speed variations. MATLAB2023 was used as a practical program to model the proposed system. This application gives designers the useful tools they need to model the problem and highlight the key computational elements. Figure 2 shows the proposed diagram of the SMC controller designed to adjust the dynamic changes of the three-phase induction motor used in the industrial power system model. The sliding controller monitors changes in the amount of direct current supplied from the three-phase inverter and fed back from the induction motor, keeping track of all instantaneous variations to maintain the desired level for maximum supplied power. The direct voltage adjustment supplied by the sliding controller is converted to the AC inverter change equation to inject it into the grid at maximum power according to the load values associated with the grid.

Thus, concerning Figure 2 that illustrates the MATLAB simulation system for implementing the study topic requirements using the proposed SMC model. The proposed system consists of a typical three phase induction motor with active power inverter injection system. The induction motor current and voltages are sensed to be analyzed and decomposed to their components in order to find the changes and variations due to load changes. The proposed SMC model will detect the small changes in the induction motor currents and voltages components to detect the little variations and control them. These detected small variations signals will be transformed to control signals through the harmonic unit to control the inverter current and inject the required changes back to the grid network to enhance the induction motor operation. Also, Figure 3 shows the flowchart of the proposed control system using an SMC system to keep up with the dynamic changes of the three-phase induction motor used in the industrial power system model.



(a)



(b)

Figure 2: MATLAB Simulink of the three phase induction motor inveteter injection using SMC controller, (a) Complete MATLAB Simulink model, (b) The proposed SMC model MATLAB Simulink model.

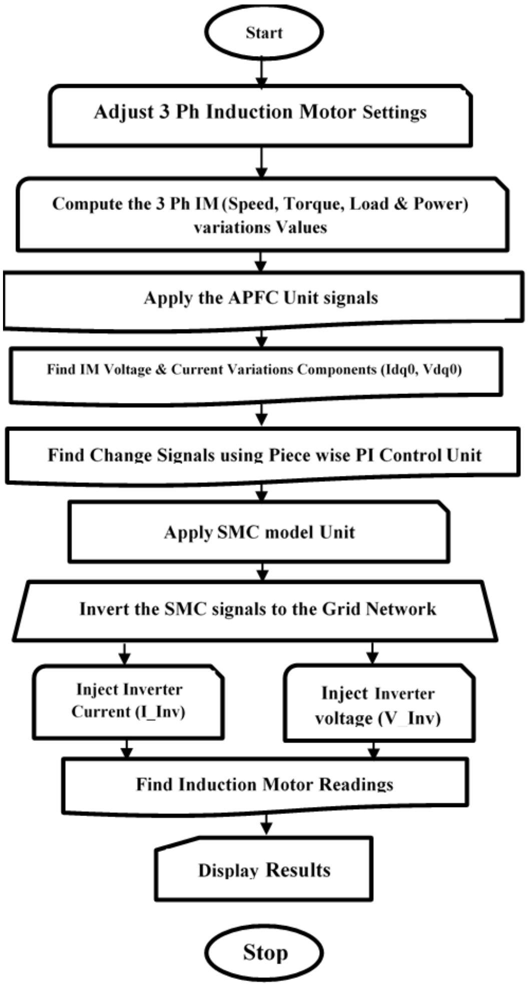


Figure 3: Methodology flow diagram steps of the proposed SMC controller for dynamic variations of three phase induction motor grid power system model.

Figure 3 starts with the simulation by defining the system parameters through the proposed simulation model in MATLAB Simulink. Environmental effects on the three-phase induction motor (variable loads, speed, and torque) are added to test the efficiency of the control model under extreme real conditions. This is followed by simulating the application of the SMC model using the three-phase inverter current effect to achieve the best possible performance. In addition, sudden load changes from the imported data are applied to realistically represent load effects. Tables 3 and 4 show the system and controller parameters used in the MATLAB/Simulink simulation.

Table 3: Design parameters of the three-phase induction motor model

Parameter Symbol	Description	Value / Unit
$\mathbf{P_{rated}}$	Rated Power	3 kW
$\mathbf{V_{rated}}$	Rated Stator Voltage (Line-to-Line)	380 V (RMS)
$\mathbf{f_{rated}}$	Rated Frequency	50 Hz
$\mathbf{R_s, R_r}$	Stator and Rotor Resistances	1.4 Ω, 1.2 Ω

Ls, Lr, Lm	Stator, Rotor, and Mutual Inductances	0.15 H, 0.15 H, 0.14 H
J	Total Moment of Inertia	0.02 kg·m²
B	Viscous Friction Coefficient	0.001 N·m·s/rad
P	Number of Pole Pairs	2
V_{dc}	DC Link Voltage	540 V
f_{sw}	Inverter Switching Frequency	10 kHz

Table 4: Design parameters of the proposed SMC controller model.

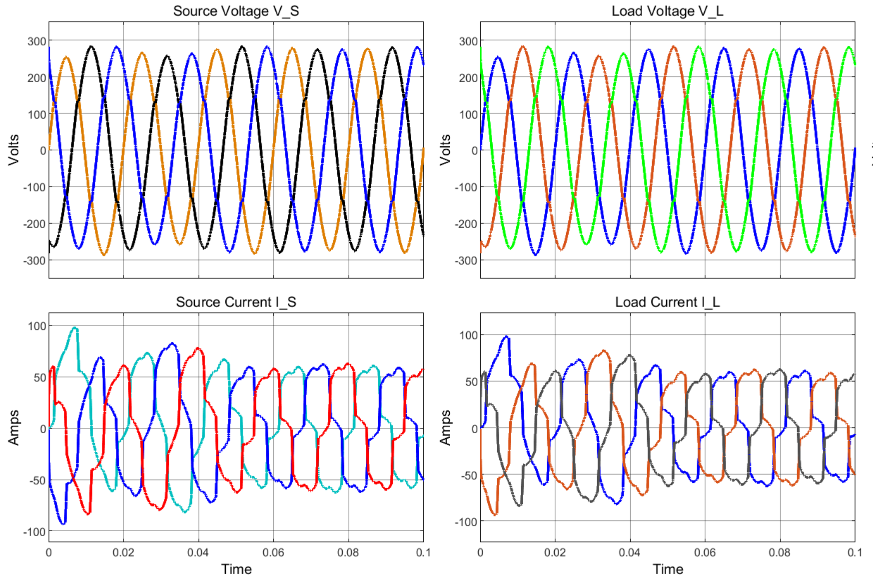
Parameter Symbol	Description	Value / Unit
Λ	Sliding Surface Slope Constant	150
K	Switching Gain (Discontinuous Part)	25
Φ_{ϕ}	Boundary-Layer Thickness (for sat function)	0.05
ω_o	ESO Observer Bandwidth	500 rad/s
β1,β2	ESO Correction Gains	1000, 250000
Ts	Simulation Sampling Time	2 ms (FPGA-equivalent)
T_{dead}	Inverter Dead-Time Compensation	1 ms

4. Results & Discussion

In this section, the simulation results of the proposed model will be successfully reviewed by running a MATLAB simulation of the designed system and evaluating it according to the specified design constraints. The simulation results are presented here through the upcoming figures as they appeared during the execution stages of the designed system simulation. Also, comparison validation with most related recent published articles will be obtained in this section.

4.1 Simulation Results

Using MATLAB Simulink, the proposed three-phase industrial induction motor model - SMC was implemented in the control system to handle dynamic changes and increased loads in industrial networks. The simulation results of the proposed system were extracted, examined, and discussed in the order they appeared. This section will discuss the simulation results while providing scientific analysis. Thus, the MATLAB simulation results of the obtained source, load, and inverter voltages and currents of the three phase induction motor load model have been recorded without and with SMC effect as shown in Figure 4. shows the simulation results for the three-phase voltage and current waves of the induction motor. We can observe a high level of matching between the three phases and the displacement angle, which recorded 120 degrees. This balance reflects the efficiency of the motor model mathematically. The results also confirm that the system's dynamic response is excellent when applying the proposed sliding controller. The results shown in the figure above highlight the accuracy of the sensors used in the feedback loop, ensuring stable operation free from unwanted oscillations under varying load conditions.



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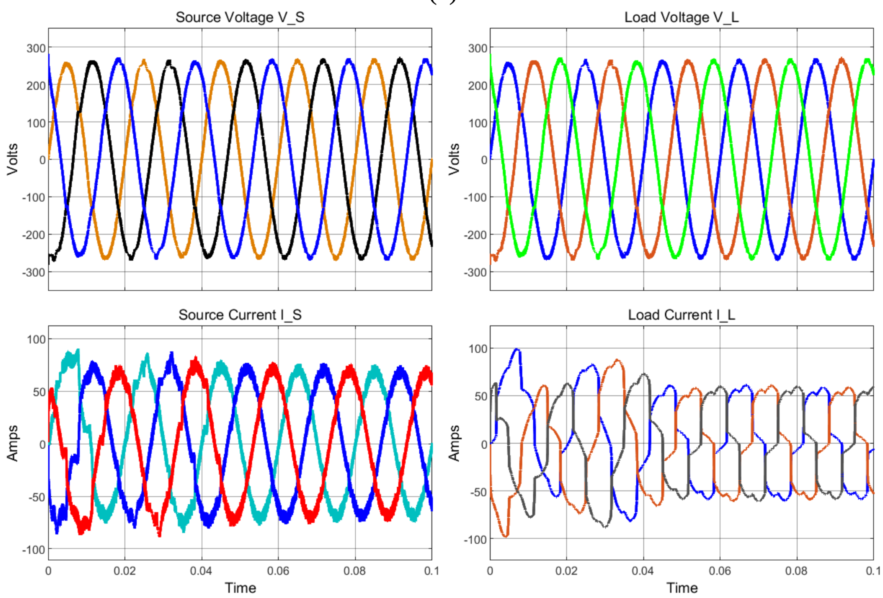
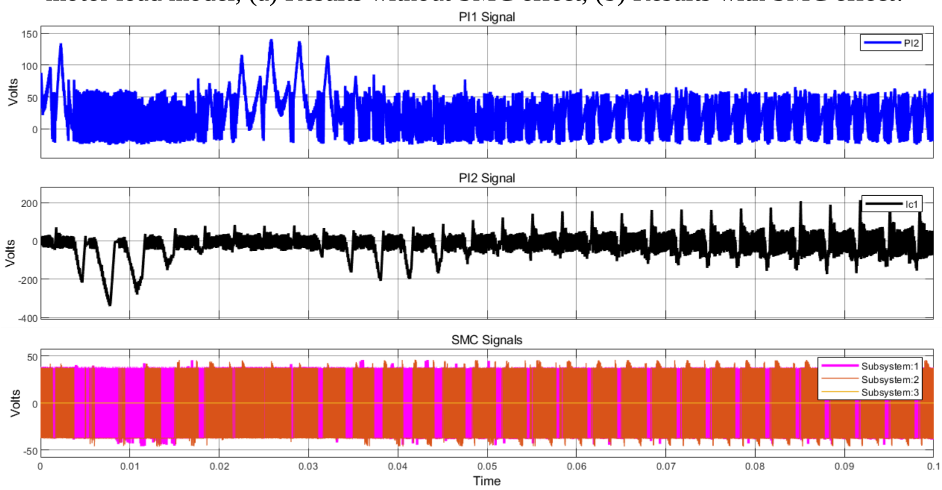


(b)

Figure 4: MATLAB simulation results of the obtained source, load voltages and currents of the three-phase induction motor load model, (a) Results without SMC effect, (b) Results with SMC effect.



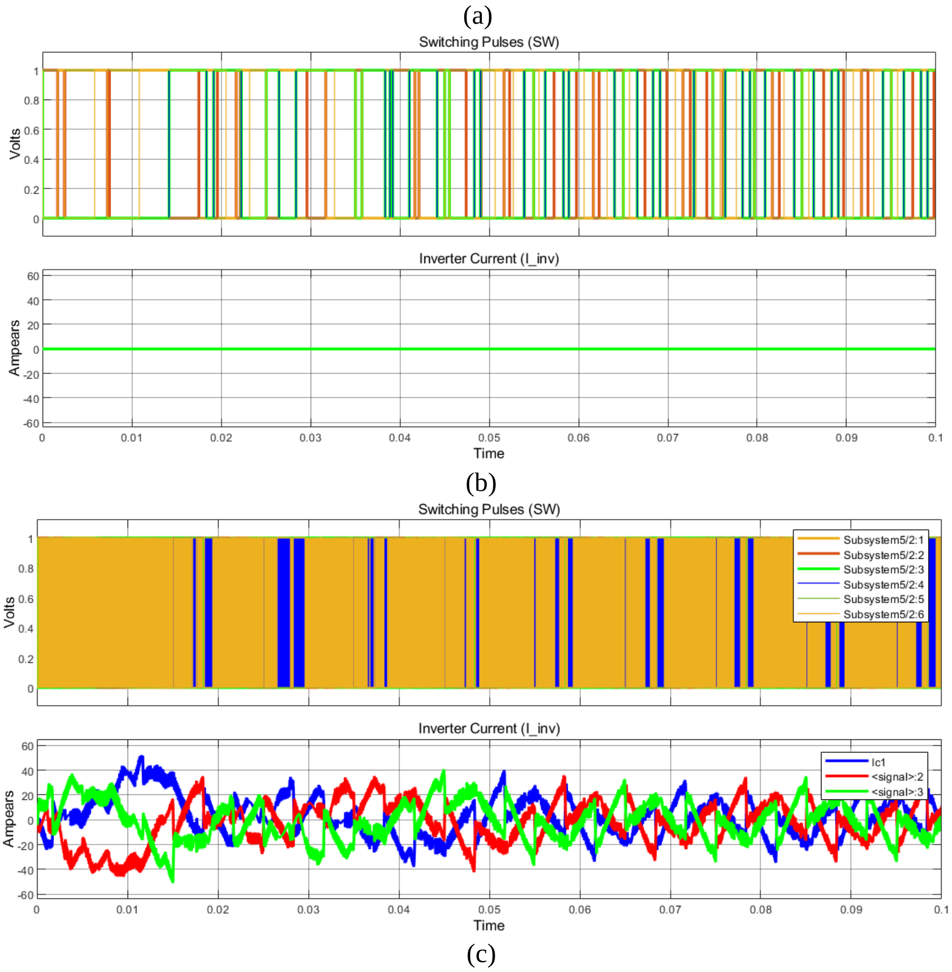
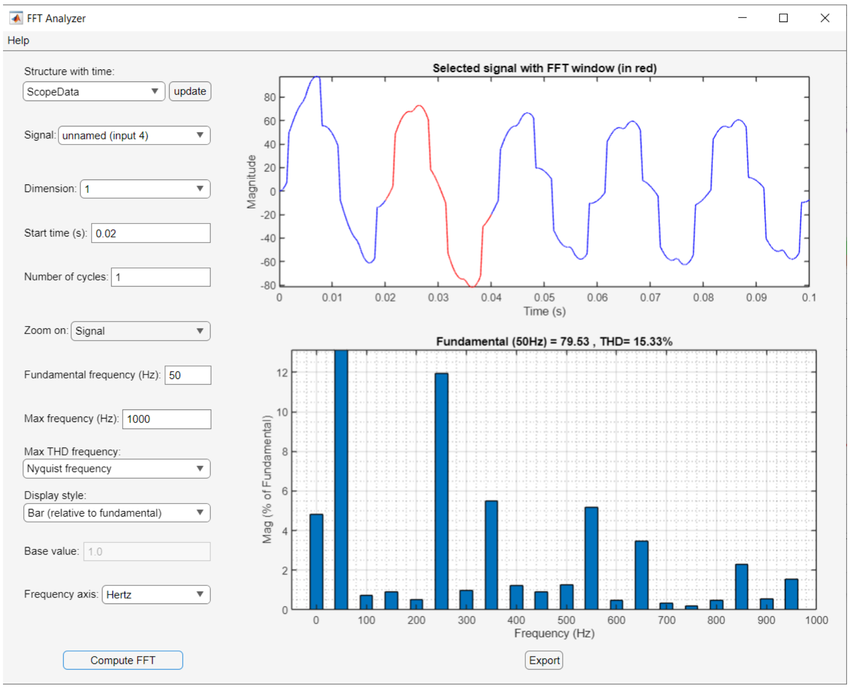


Figure 5: The simulation results of the SMC resulting control pulses with the inverter current signals, (a) The SMC model control signals, (b) Inverter pulses without SMC signals injection, (c) Inverter pulses with SMC signals injection effect.

Figure 5 shows the control pulse curves produced by the sliding controller and the inverter current signals. High accuracy is recorded in generating PWM signals, along with fast tracking of feedback signals from the induction motor. The results confirm the efficiency and success of the sliding control algorithm in reducing the annoying chattering phenomenon in the final voltage and current signals. The stability of the inverter current is maintained despite sudden load changes. These results confirm the ability of the proposed sliding controller to adapt to external disturbances. These outputs indicate that the proposed model achieves excellent protection for the inverter current, improves resulting energy efficiency, and ensures stable motor performance. Then, the results of the total harmonic distortion (THD) metric have been achieved as demonstrated in Figure 6.



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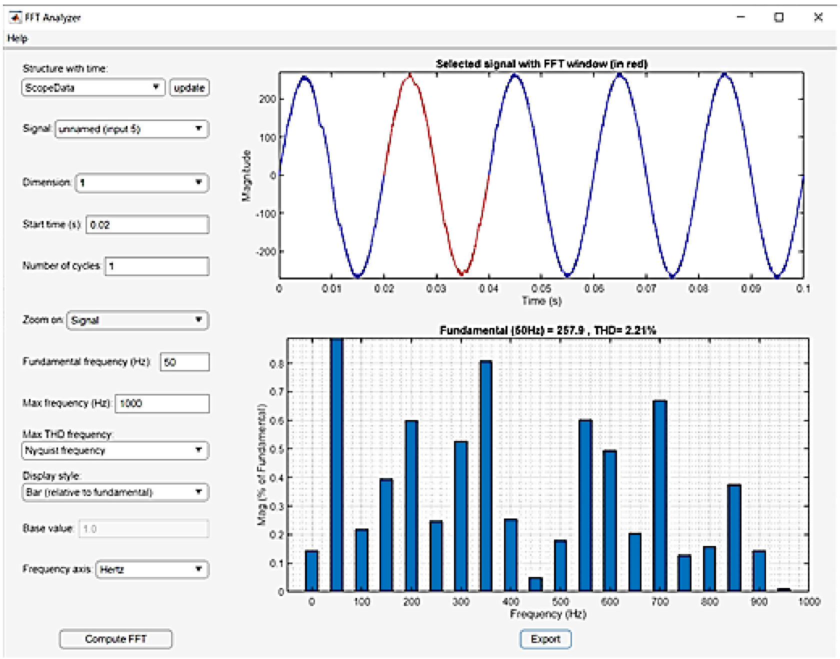
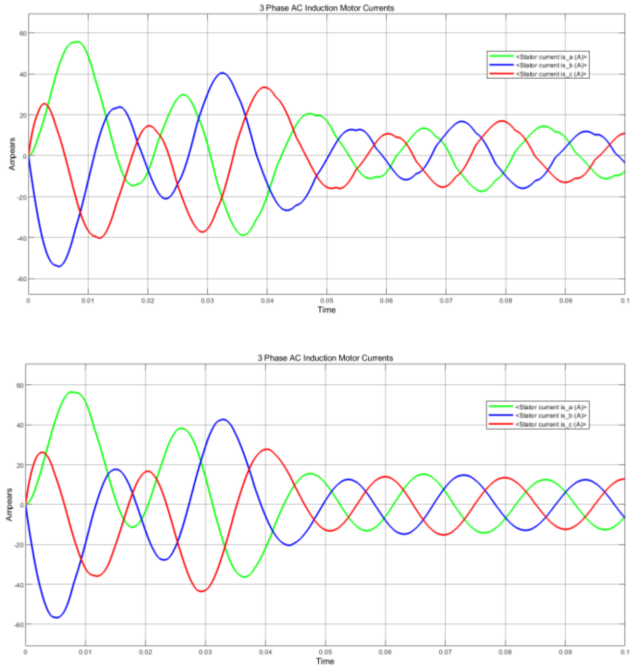


(b)

Figure 6: Simulated results of the obtained total harmonic distortion (THD), (a) MATLAB FFT analysis interface without SMC effect, (b) The THD analysis results with SMC effect.

The results in Figure 6 show the analysis of the Total Harmonic Distortion (THD) using the Fast Fourier Transform. The results recorded a noticeable decrease in high harmonic ratios compared to conventional systems. The final result also shows that the THD percentage is within the allowable limits according to global IEEE-519 standards. The lowest recorded value was 2.21, which is considered an excellent reading for the number of distorted harmonics. This reading confirms the success of the sliding mode control algorithm model with the three-phase inverter feedback injection system in keeping up with dynamic load changes in the industrial network. Furthermore, the MATLAB simulation results of the achieved three phase induction motor currents, without and with SMC effect are illustrated in Figure 7. By observing the results in Figure 7, it can be concluded that there is noticeable instability and oscillation in the signals of the three-phase induction motor for torque, speed, and load current when the system operates without the effect of the sliding controller current injection via the inverter current, as shown in Figure 7(a). Meanwhile, the oscillations in the same signals improve when adopting and applying the effect of the sliding controller current injection via the inverter current, as shown in Figure 7(b). This improvement is attributed to the sliding controller's contribution to following the dynamic changes in industrial loads and compensating for them by injecting three-phase inverter current into the network lines supplied to the induction motor. These results confirm the effectiveness and efficiency of the proposed sliding controller model in coping with and compensating for the dynamic changes occurring in industrial loads and their impact on the performance of the induction motor.



(a) (b)

Figure 7: Simulated results of the obtained three phase induction motor currents, (a) Results without SMC effect, (b) Results with SMC effect.

4.2 Results Discussion & Validation

The MATLAB simulation of SMC with extended state observer (ESO) results showed total harmonic distortion (THD) < 3.5%, with response time < 15 ms, which achieved excellent chattering elimination and high real-time compensation. Table 5 demonstrates validation comparison of these simulation results obtained with the proposed SMC model of this study among the most recent related published articles. The verification table results showed a remarkable superiority of the study model compared to the results of recent related publications in terms of THD and response time metrics, which confirms the success of this study through the proposed sliding control model in achieving the best results and the desired scientific contribution.

Table 5: Comparative validation with modern related publications.

Control Strategy	Observer / Compensator	THD (%)	Speed Response Time (ms)	Chattering Mitigation	Robustness to Load Disturbances	Reference
Proposed Method (Partial-Order SMC)	Extended State Observer (ESO)	< 3.5%	< 15 ms	Excellent (Boundary-layer)	High (Real-time compensation)	This Study
Model-Free Predictive Current Control	Improved Sliding Mode Observer (SMO)	~ 4.2%	~ 20 ms	Good	Moderate (Sensor-dependent)	Guo, L., et al (2025) [22]
Fractional-Order Sliding Mode (DTC-SVM)	None (Flux/Torque Estimators)	~ 4.8%	~ 18 ms	Very Good	High (Fractional-order tuning)	Ben Salem, F., et al. (2024). [23]
Robust Active Disturbance Rejection	ADRC + Additional SMC Component	~ 3.8%	~ 25 ms	Good	Very High (Disturbance estimation)	F., Cirrincione, M., & Pucci, M. (2017) [24]
Neuro-Fuzzy SMC	Extended State Observer (ESO)	~ 4.0%	~ 22 ms	Excellent (Fuzzy smoothing)	High (AI-based adaptation)	Larbaoui, A., et al. (2024). [25]

5. Conclusion

In this study, a sliding mode controller with active disturbance compensation was implemented based on precise assessments of load disturbances in industrial applications. One persistent problem with sliding mode controllers is abrupt vibrations, which are much reduced by the suggested control architecture. Particularly in industrial applications, the sliding mode controller (SMC) is renowned for its capacity to manage the intricate nonlinear characteristics of induction motors in a manner that is simpler than more sophisticated alternatives. A three-phase induction motor's performance was examined to determine the causes of the intended and actual behavior in order to find faults in the motor model under changing conditions because it is a nonlinear system and its properties, such as internal resistance, fluctuate with temperature and loads. Results from the SMC Extended State Observer (ESO) software simulation demonstrated THD < 3.5%, reaction time < 15 ms, strong real-time compensation, and excellent chattering removal.

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