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Design and Performance Analysis of a Fuzzy Logic Controlled Hybrid Wind-Solar-Battery Energy System for Induction Motor Applications

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Abstract: The increasing demand for reliable and high-quality electrical power has accelerated the integration of renewable energy resources into modern power systems. Although wind energy has emerged as a promising renewable source, its intermittent nature introduces significant fluctuations in power generation, affecting system stability and power quality. To overcome these limitations, this paper proposes a hybrid Wind–Solar–Battery Energy System employing a Fuzzy Logic Controller (FLC) for enhanced power management and improved operational performance. The proposed system integrates a photovoltaic (PV) array, a wind energy conversion unit, a battery energy storage system (BESS), power electronic converters, a common DC bus, and a voltage source inverter supplying an induction motor load. Initially, a conventional PI controller is considered for system regulation; however, a fuzzy logic–based control strategy is introduced to improve dynamic response, minimize steady-state error, and reduce Total Harmonic Distortion (THD). The complete hybrid system is modeled and analyzed using MATLAB/Simulink under varying operating conditions. Simulation results demonstrate that the proposed fuzzy logic–controlled hybrid system provides superior power quality, enhanced voltage regulation, effective battery energy management, and reliable power delivery compared with the conventional PI-controlled system. The proposed approach effectively improves renewable energy utilization while ensuring stable operation of induction motor loads under fluctuating environmental conditions.

Keywords: Hybrid Renewable Energy System, Wind Energy Conversion System, Photovoltaic System, Battery Energy Storage System, Fuzzy Logic Controller, Induction Motor, Total Harmonic Distortion, MATLAB/Simulink.

I. INTRODUCTION

Growing electricity demand and environmental concerns associated with fossil-fuel-based generation have increased the adoption of renewable energy resources. Solar photovoltaic (PV) and wind energy are widely used because of their availability and low environmental impact. However, their dependence on weather conditions causes power fluctuations, creating challenges in maintaining a reliable supply and acceptable power quality.

Battery Energy Storage Systems (BESS) mitigate renewable-power variations by storing surplus energy and supplying it during generation deficits. Nevertheless, a wind–battery system remains dependent on wind availability. Integrating solar PV with wind generation improves energy availability by utilizing the complementary characteristics of the two sources. Battery storage further supports power balancing and continuous load operation.

In the proposed system, the PV array is connected to a common DC link through a DC–DC boost converter, whereas the variable AC output of the wind-driven Permanent Magnet Synchronous Generator (PMSG) is rectified before DC-link integration. A bidirectional DC–DC converter controls battery charging and discharging, while a voltage-source inverter supplies three-phase AC power to the induction-motor load.

System performance depends significantly on the adopted control method. Although Proportional–Integral (PI) controllers are simple to implement, their performance is sensitive to gain tuning, parameter variations, and nonlinear operating conditions. Fuzzy Logic Control (FLC) offers greater flexibility by using linguistic rules and membership functions without requiring an exact mathematical model.

This work develops a fuzzy logic-controlled wind–solar–battery energy system in MATLAB/Simulink. Its performance is evaluated in terms of load-voltage quality, battery operation, motor response, and Total Harmonic Distortion (THD). The proposed controller is compared with conventional PI control under similar simulation conditions. The results show that the load-voltage THD decreases from 16.24% to 12.75%, corresponding to a relative reduction of approximately 21.49%, while stable power delivery to the induction-motor load is maintained.

II. LITERATURE SURVEY

Recent studies have addressed the intermittency of renewable energy sources through advanced inverter control, energy-storage management, and hybrid generation. Zhang *et al.* proposed a Model Predictive Voltage Control strategy for three-phase inverters with an LCL filter. The use of dual voltage vectors improved reference tracking and reduced Total Harmonic Distortion (THD), although the method introduced greater computational complexity.

Vasebi *et al.* developed a nonlinear lead-acid battery model with an Extended Kalman Filter for accurate State of Charge (SOC) estimation. Their results demonstrated the importance of reliable battery modelling and SOC estimation for effective energy-storage management. Jallouli and Krichen investigated a standalone PV–hydrogen system incorporating battery and fuel-cell storage. Their study showed that coordinated energy management among multiple sources can improve supply continuity and system reliability.

Although conventional Proportional–Integral (PI) controllers are widely used because of their simple implementation, their performance is sensitive to gain tuning, parameter variations, and nonlinear operating conditions. Fuzzy Logic Control (FLC) addresses these limitations through membership functions and rule-based reasoning without requiring an exact system model. This makes it suitable for renewable energy systems subjected to variations in source generation and load demand.

Existing studies have examined inverter control, battery estimation, and hybrid energy management separately. However, limited attention has been given to the comparative performance of PI and fuzzy logic-based control in a wind–solar–battery system supplying an induction-motor load. Therefore, the present work integrates wind generation, solar PV, and battery storage through a common DC link and evaluates the control strategy in terms of load-voltage THD, battery performance, and motor response using MATLAB/Simulink.

III. PROBLEM OUTLINE

The intermittent nature of wind and solar energy creates fluctuations in power generation, making it difficult to maintain a stable supply in standalone renewable energy systems. Although battery storage improves power continuity, reliable operation requires effective coordination among the renewable sources, battery, converters, and load.

Conventional PI controllers are simple to implement but require suitable gain tuning and may show reduced performance under nonlinear and varying operating conditions. These limitations can affect DC-link voltage regulation, transient response, and harmonic performance.

To address these issues, this work proposes a fuzzy logic-controlled wind–solar–battery system for supplying an induction-motor load. The renewable sources and battery are integrated through a common DC link, and the proposed controller regulates inverter operation and power flow. The system is evaluated in MATLAB/Simulink, with emphasis on load-voltage quality, battery performance, motor response, and THD reduction.

IV. OBJECTIVES

The objective of this work is to develop a MATLAB/Simulink model of a hybrid wind–solar–battery energy system for supplying an induction-motor load. The proposed system coordinates renewable generation and battery power through a common DC link and implements fuzzy logic-based control to improve voltage regulation and power quality. Its performance is compared with conventional PI control by evaluating battery operation, motor response, and load-voltage Total Harmonic Distortion under identical simulation conditions.

V. PROPOSED METHODOLOGY

The proposed hybrid system integrates a photovoltaic array, wind-driven PMSG, Battery Energy Storage System (BESS), power electronic converters, a common DC link, and a voltage-source inverter to supply an induction-motor load, as shown in Fig. 1.

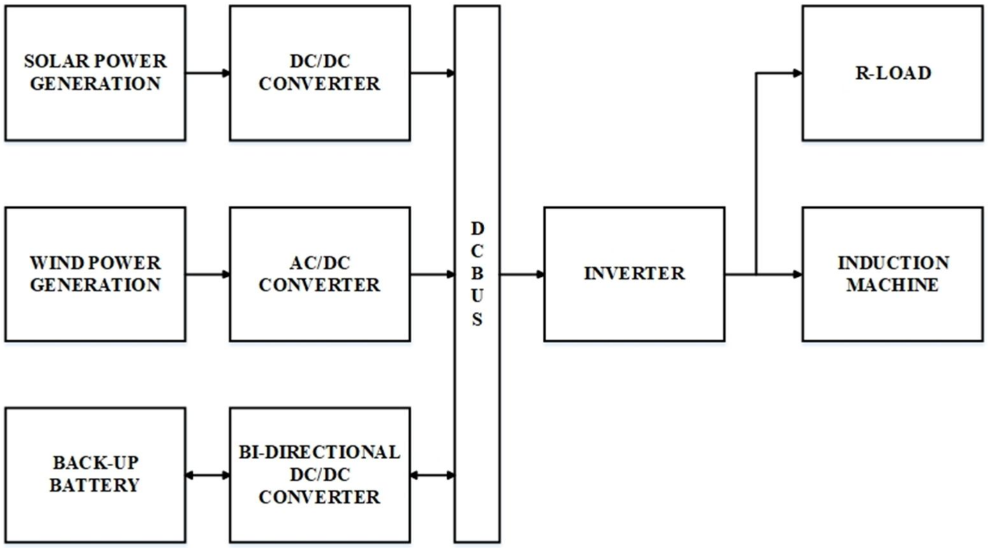

Figure 1:Overall configuration of the proposed hybrid wind–solar–battery energy system

The variable PV output is regulated through a DC–DC boost converter, whereas the three-phase output of the wind generator is converted into DC using an AC–DC rectifier. Both sources supply a common DC link, which acts as the main power-transfer interface of the system.

The battery is connected to the DC link through a bidirectional DC–DC converter. It absorbs surplus renewable power during charging and supplies power during a generation deficit, subject to its operating limits. The voltage-source inverter converts the DC-link power into three-phase AC power, while an output filter attenuates switching harmonics before the supply reaches the induction motor.

A fuzzy logic-based control strategy regulates power flow and inverter operation using measured system variables and rule-based decision-making. Compared with conventional PI control, the proposed controller is evaluated for voltage regulation, motor response, battery performance, and load-voltage THD. The complete system is implemented and analysed using MATLAB/Simulink.

VI. MATHEMATICAL MODELING

The mathematical model of the proposed hybrid system describes the behaviour of the photovoltaic array, wind-energy conversion system, battery storage, DC link, power converters, and induction motor. The principal governing equations are presented below.

A. Photovoltaic System

The PV array converts solar irradiance into DC electrical power and is connected to the common DC link through a boost converter. Using the single-diode model, the PV output current is expressed as

$$I_{PV} = I_{ph} - I_0\left[\exp\left(\frac{V_{PV} + I_{PV}R_s}{nN_sV_t}\right) - 1\right] - \frac{V_{PV} + I_{PV}R_s}{R_{sh}} \qquad (1)$$

where $I_{PV}$and $V_{PV}$are the PV output current and voltage, $I_{ph}$is the photocurrent, $I_0$is the diode saturation current, $R_s$and $R_{sh}$are the series and shunt resistances, $n$is the diode ideality factor, $N_s$is the number of series-connected cells, and $V_t$is the thermal voltage.

The PV output power is $\quad P_{PV} = V_{PV}I_{PV} \qquad (2)$

The boost converter regulates the variable PV output and steps up its voltage to the required DC-link level.

B. Wind-Energy Conversion System

The wind-energy conversion system consists of a variable-speed wind turbine coupled to a Permanent Magnet Synchronous Generator (PMSG). The kinetic power available in the wind is

$$P_w = \frac{1}{2}\rho A v_w^3 \qquad (3)$$

The mechanical power extracted by the wind turbine is $P_m = \frac{1}{2}\rho A C_p(\lambda, \beta) v_w^3$ (4)

where ρ is the air density, $A = \pi R^2$ is the turbine swept area, v_w is the wind speed, C_p is the turbine power coefficient, and β is the blade-pitch angle.

The tip-speed ratio is defined as $\lambda = \frac{\omega_t R}{v_w}$ (5)

where ω_t is the turbine angular speed and R is the blade radius. The mechanical torque applied to the generator is $T_m = \frac{P_m}{\omega_t}$ (6)

The three-phase output of the PMSG is converted into DC power through a controlled AC–DC rectifier before being supplied to the common DC link.

C. Battery Energy Storage System

The battery stores surplus renewable energy and supplies power when the combined wind and PV generation is insufficient. Its State of Charge (SOC) is expressed as

$$SOC(t) = SOC(t_0) - \frac{1}{3600 Q_n} \int_{t_0}^{t} \eta_b \, i_b(\tau)\, d\tau \qquad (7)$$

where $SOC(t_0)$ is the initial SOC, Q_n is the rated battery capacity in ampere-hours, i_b is the battery current, and η_b is the charging or discharging efficiency. In this work, positive battery current represents discharging, whereas negative current represents charging.

The battery power is $P_b = V_b i_b$ (8)

where V_b is the battery terminal voltage. The battery is interfaced with the common DC link through a bidirectional DC–DC converter.

D. DC-Link Dynamics

The common DC link combines the conditioned power obtained from the PV array, wind generator, and battery. Applying Kirchhoff's current law at the DC link gives

$$C_{dc} \frac{dV_{dc}}{dt} = i_{PV} + i_w + i_b - i_{inv} \qquad (9)$$

where C_{dc} is the DC-link capacitance, V_{dc} is the DC-link voltage, and i_{PV}, i_w, i_b, and i_{inv} are the PV, wind, battery, and inverter currents, respectively.

The DC-link voltage error is defined as $e(k) = V_{dc}^* - V_{dc}(k)$ (10)

where V_{dc}^* is the reference DC-link voltage. This error is processed by the controller to maintain the required voltage and power balance.

E. Converter Model

The PV subsystem employs a DC–DC boost converter. Under ideal continuous-conduction operation, its output voltage is $V_o = \frac{V_{in}}{1-D}$ (11)

where V_{in} and V_o are the converter input and output voltages, respectively, and D is the switching duty ratio, with $0 < D < 1$.

The battery-side bidirectional converter controls the direction of power flow between the battery and DC link. It operates in charging mode when renewable generation exceeds load demand and in discharging mode during a generation deficit.

F. Induction-Motor Model

The mechanical dynamics of the induction motor are represented by

$$J \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \qquad (12)$$

where J is the combined moment of inertia, ω_m is the mechanical rotor speed, T_e is the electromagnetic torque, T_L is the applied load torque, and B is the viscous-friction coefficient.

The stator-voltage equations in the synchronous dq reference frame are

$$v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_e \psi_{qs} \qquad (13)$$

$$v_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_e \psi_{ds} \qquad (14)$$

where v_{ds} and v_{qs} are the stator dq-axis voltages, i_{ds} and i_{qs} are the corresponding currents, R_s is the stator resistance, ψ_{ds} and ψ_{qs} are the stator flux linkages, and ω_e is the synchronous electrical angular frequency.

G. Total Harmonic Distortion

The Total Harmonic Distortion of the load voltage is calculated as

$$THD_V = \frac{\sqrt{\sum_{h=2}^{N} V_h^2}}{V_1} \times 100\% \qquad (15)$$

where V_1 is the RMS magnitude of the fundamental voltage component, V_h is the RMS magnitude of the h^{th}-order voltage harmonic, and N is the highest harmonic order considered.

FFT analysis is performed using the same signal selection, fundamental frequency, time window, and harmonic range for both control strategies. The relative THD reduction is calculated as

$$THD_{\text{reduction}} = \frac{THD_{PI} - THD_{FLC}}{THD_{PI}} \times 100 \qquad (16)$$

Using the measured values of 16.24%and 12.75%,

$$THD_{\text{reduction}} = \frac{16.24 - 12.75}{16.24} \times 100 = 21.49\% \qquad (17)$$

Therefore, the proposed control strategy reduces the load-voltage THD by approximately 21.49%relative to conventional PI control.

VII. RESULTS AND DISCUSSION

The proposed fuzzy logic-controlled hybrid wind–solar–battery system was modelled and simulated using MATLAB/Simulink. As shown in Fig. 2, the model integrates a PV array, wind-driven PMSG, battery storage, power converters, a common DC link, voltage-source inverter, and induction-motor load.

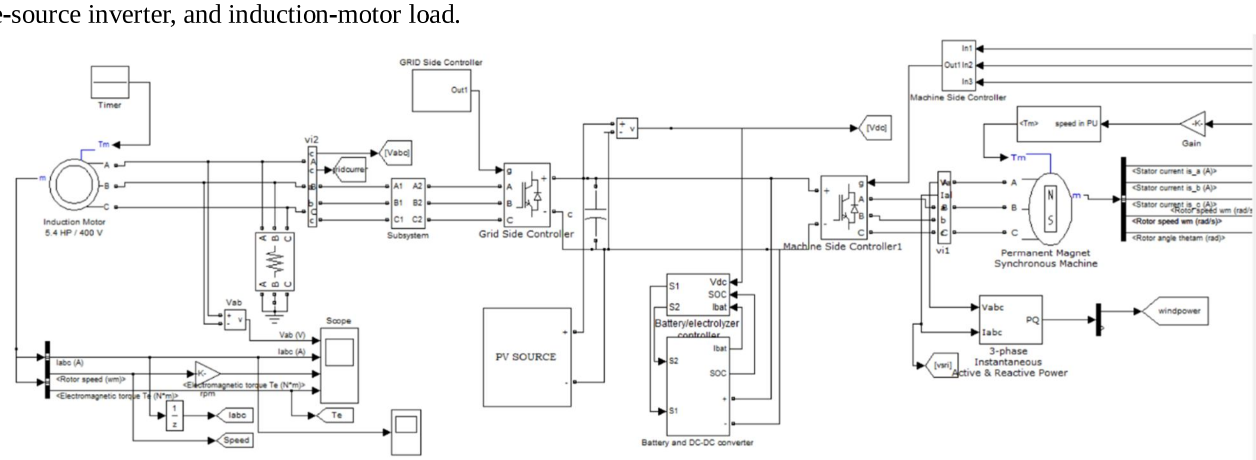

Figure 2: Complete MATLAB/Simulink model of the proposed hybrid renewable energy system.

The simulation results demonstrate coordinated power delivery from the renewable sources and battery. The inverter produces a balanced three-phase load voltage with a peak value of approximately ±400 V. The induction motor reaches a steady-state speed of approximately 1200–1250 rpm, while its electromagnetic torque remains within 4–5 N\cdotpm, indicating stable motor operation. After the initial transient, the battery voltage, current, and power settle near 245 V, 10.2 A, and 2.5 kW, respectively. These nearly constant quantities indicate stable interaction between the battery, bidirectional converter, and common DC link.

FFT analysis shows that the load-voltage THD decreases from 16.24%with conventional PI control to 12.75%with fuzzy logic-based control. This corresponds to an absolute decrease of 3.49percentage points and a relative reduction of approximately 21.49%. Overall, the proposed controller maintains stable power delivery to the induction motor while improving load-voltage waveform quality. The reduction in THD demonstrates better harmonic performance than the conventional PI-controlled configuration.

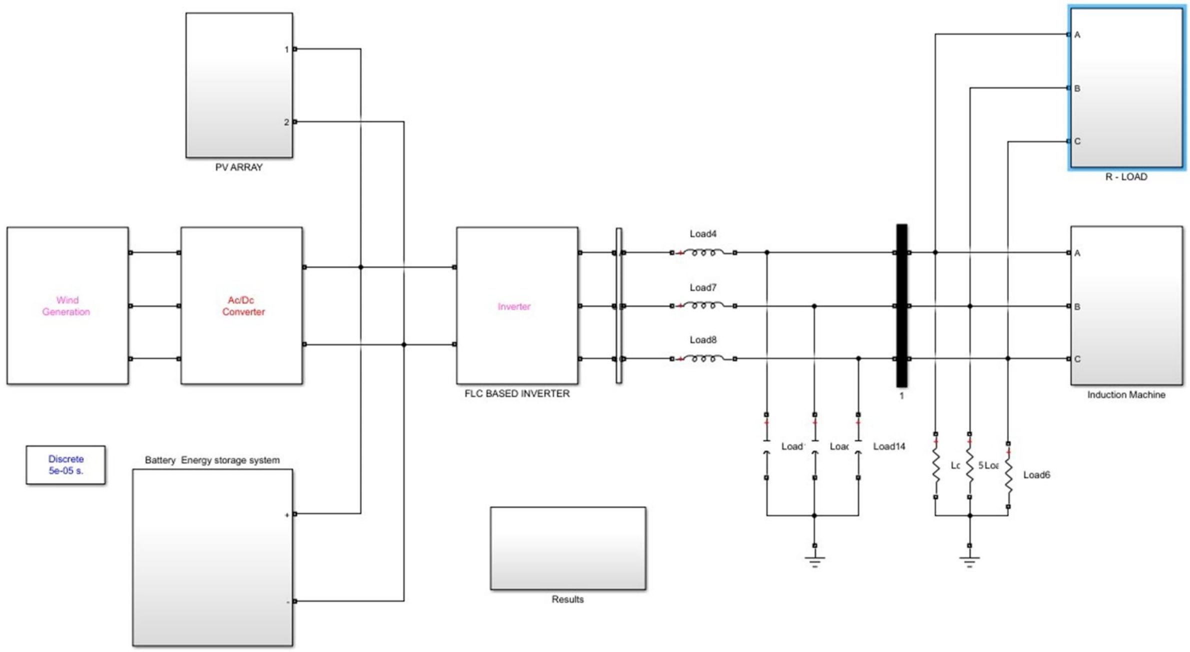

Figure 3: Top-level power-stage architecture of the simulated hybrid system.

Shows the complete MATLAB/Simulink model of the proposed hybrid energy system. The model combines the PV array, wind-driven PMSG, battery storage, power converters, common DC link, voltage-source inverter, filter, and connected loads. Measurement blocks are included to examine source generation, battery operation, load performance, and power quality.

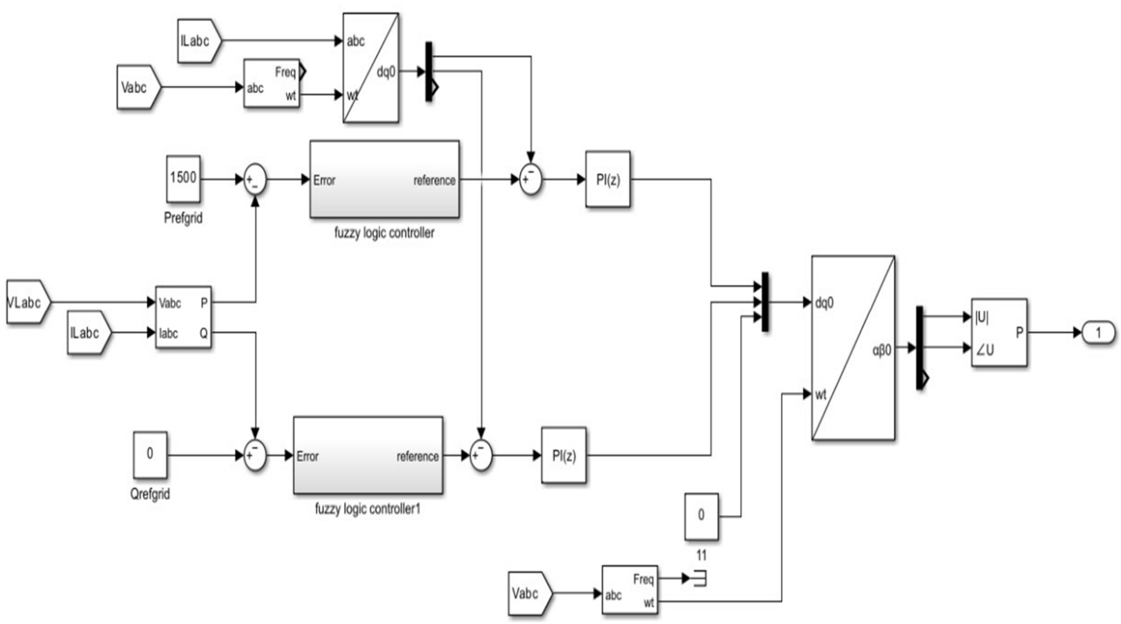

Figure 4: Proposed fuzzy logic-based inverter control architecture.

The measured three-phase voltages and currents are transformed into the synchronous dqreference frame, and the active- and reactive-power errors are processed by the controllers. The resulting reference signals are converted back into three-phase quantities and supplied to the SVPWM unit to generate inverter-switching pulses.

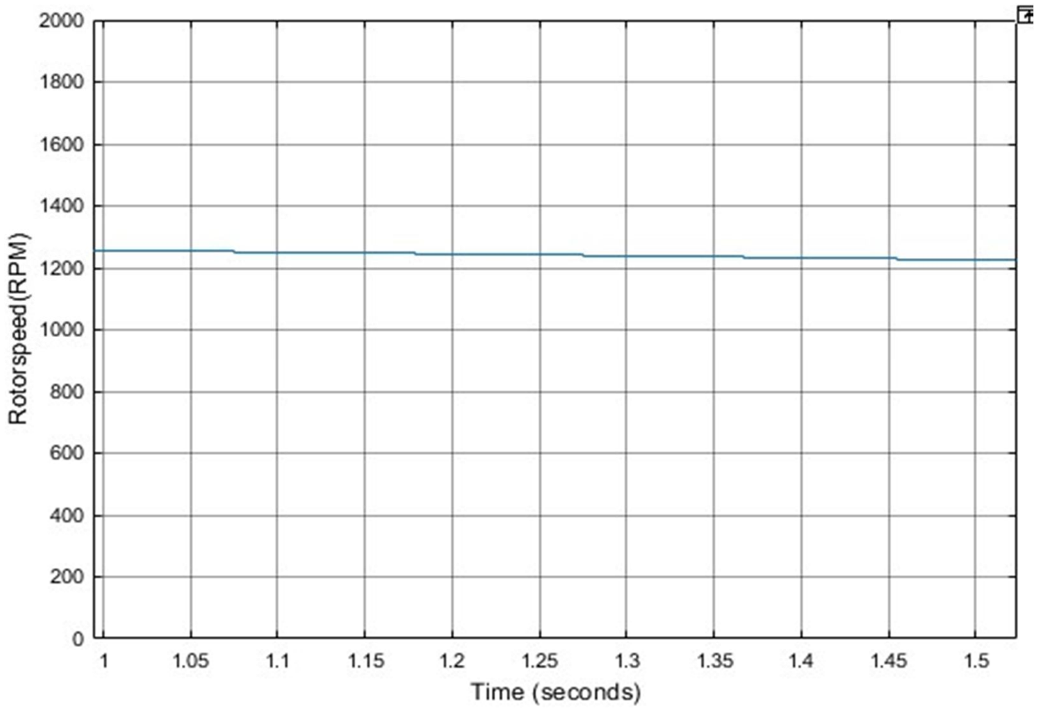

Figure 5: Induction-motor rotor-speed response under conventional PI control.

During the displayed steady-state interval, the rotor speed remains approximately within 1200–1250 rpm, with a gradual reduction toward 1200 rpm.

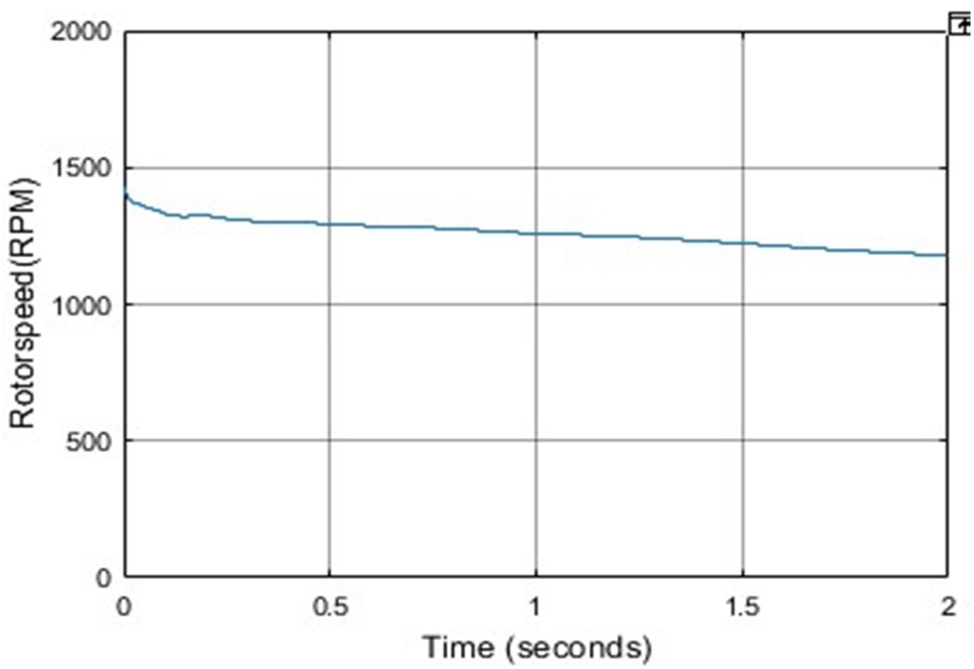

Figure 6: Induction-motor rotor-speed response under fuzzy logic-based control.

The rotor speed decreases from approximately 1400 rpmduring startup and approaches approximately 1200 rpmby the end of the simulation without sustained oscillations.

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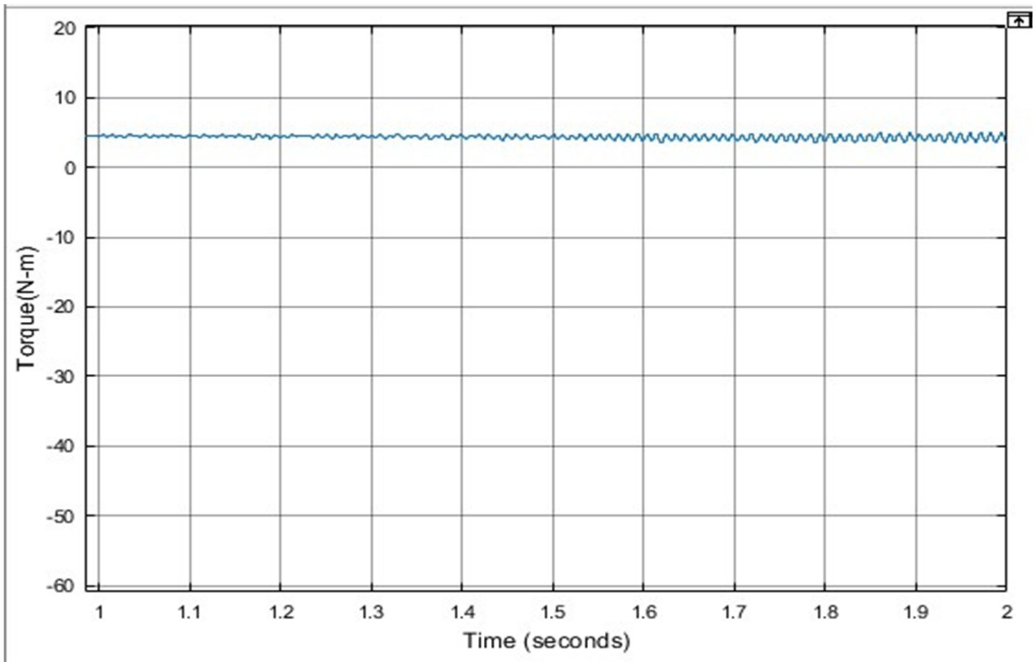

Figure 7: Electromagnetic-torque response under conventional PI control.

During the displayed steady-state interval, the electromagnetic torque remains approximately within 4-5 N·m, with small oscillations.

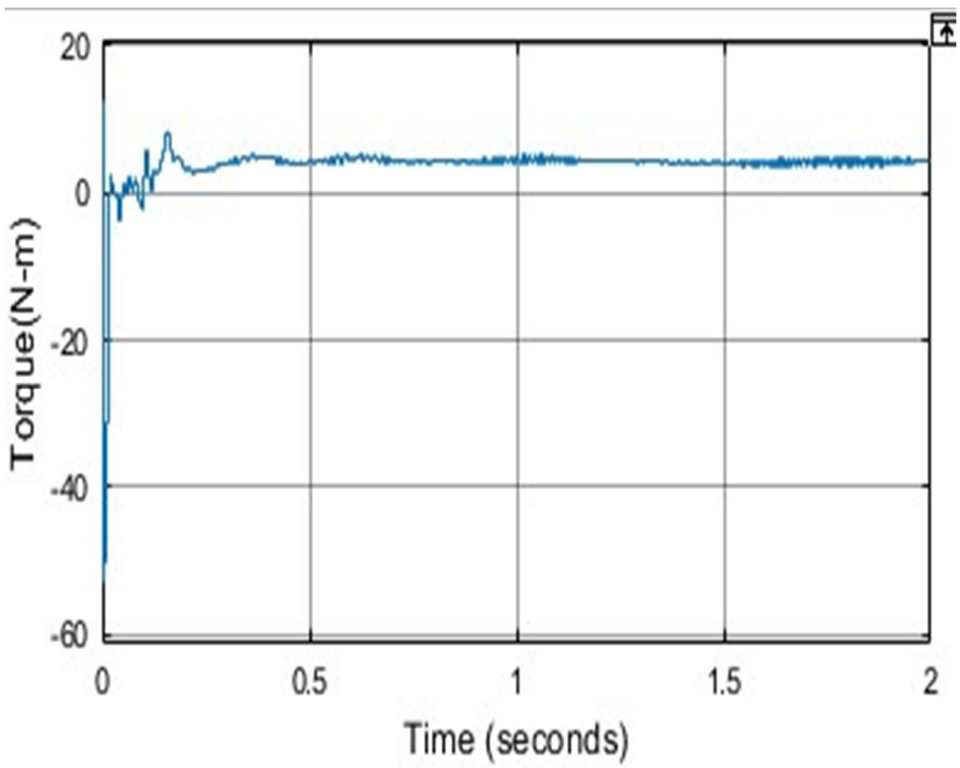

Figure 8: Electromagnetic-torque response under fuzzy logic-based control.

Following the startup transient, the electromagnetic torque approaches a steady value of approximately 4-5 N·m.

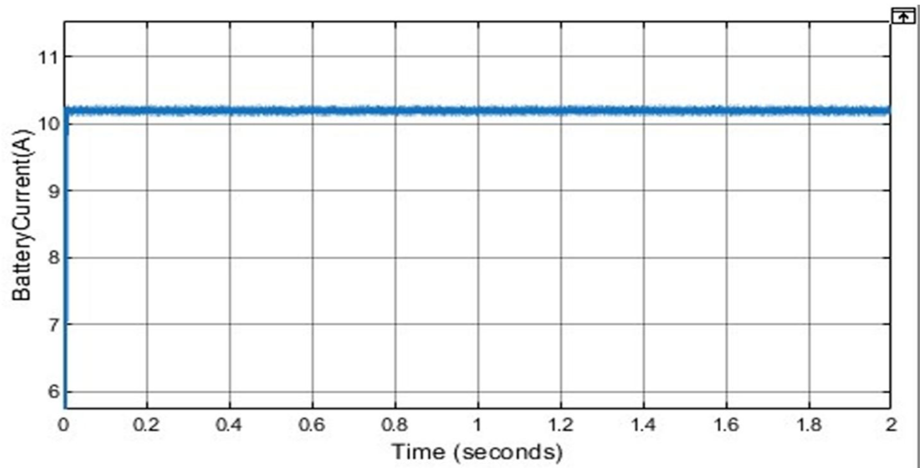

Figure 9: Battery-current response under fuzzy logic-based control.

The battery current settles near 10.2 Aafter the initial transient and remains nearly constant during the displayed interval. Under the adopted sign convention, the positive current represents battery discharge.

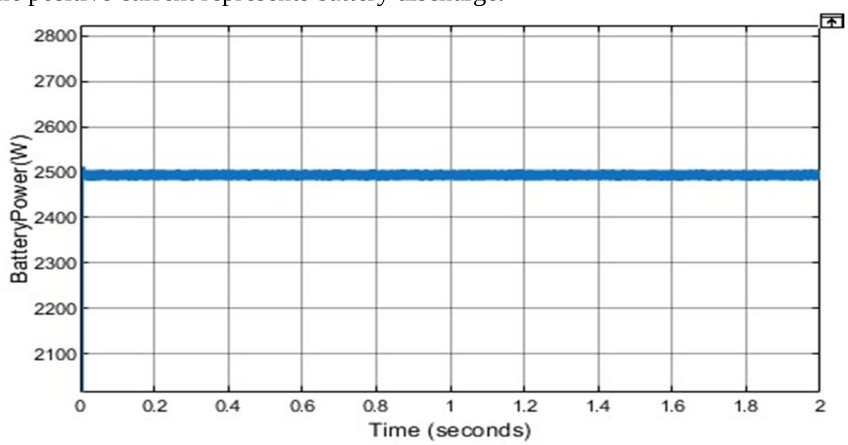

Figure 10: Battery-power response under fuzzy logic-based control.

The battery power remains approximately 2.5 kWwith limited ripple. The positive power confirms battery discharge during the displayed simulation interval.

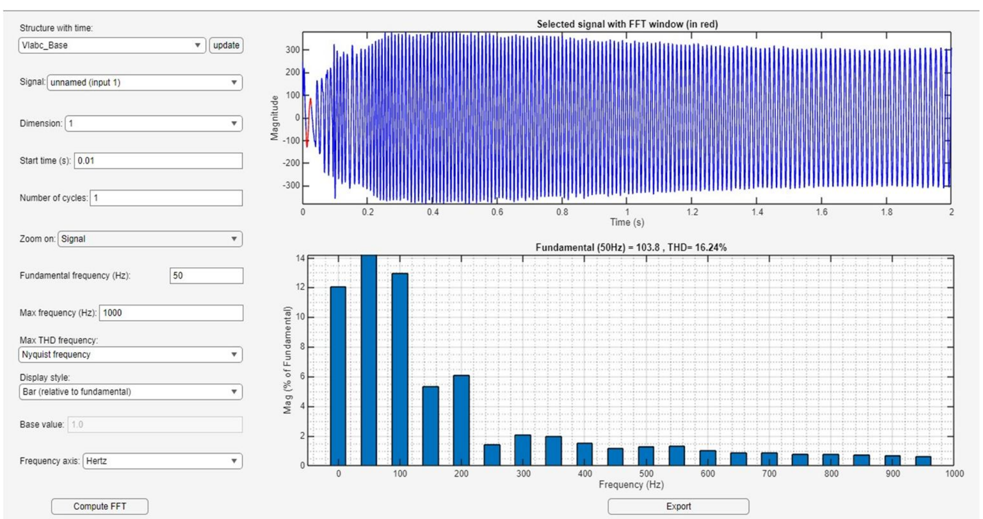

Figure 11: FFT spectrum of the load voltage under conventional PI control.

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The FFT analysis of the load voltage obtained with the conventional PI controller. The measured THD is 16.24%, indicating the presence of considerable harmonic content. This value is used as the reference for evaluating the harmonic-reduction capability of the proposed fuzzy logic-based controller.

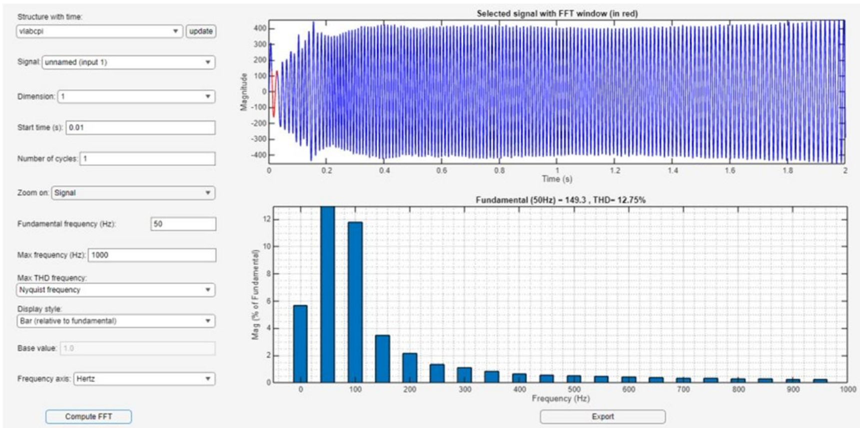

Figure 12: FFT spectrum of the load voltage under fuzzy logic-based control.

The measured THD is 12.75%, compared with 16.24%under conventional PI control. This corresponds to an absolute decrease of 3.49percentage points and a relative reduction of approximately 21.49%. The result demonstrates improved harmonic performance under the proposed control method.

VIII. CONCLUSION

A hybrid wind–solar–battery energy system employing an FLC–PI control strategy was developed in MATLAB/Simulink to supply an induction-motor load through a common DC link. The motor operated at approximately 1200–1250 rpm, while the steady-state electromagnetic torque remained within approximately 4–5 N\cdotpm. The battery current and power settled near 10.2 Aand 2.5 kW, respectively, during the displayed discharge interval.

The measured THD decreased from 16.24%under conventional PI control to 12.75%under the proposed control strategy, corresponding to a relative reduction of approximately 21.49%. The results demonstrate improved harmonic performance while maintaining stable motor operation. Future work should focus on experimental validation, comparative DC-link analysis, battery SOC evaluation, and further harmonic reduction.

IX. FUTURE SCOPE

Future work may focus on real-time experimental validation using hardware platforms such as dSPACE, OPAL-RT, or FPGA-based controllers. Advanced control methods, including ANFIS and Model Predictive Control, may also be investigated to improve dynamic performance and energy management. Further extensions could include grid-connected operation, optimized battery-management strategies, renewable-source sizing, and the integration of supercapacitors or hydrogen storage. These developments may improve system flexibility, efficiency, and suitability for practical industrial and microgrid applications.

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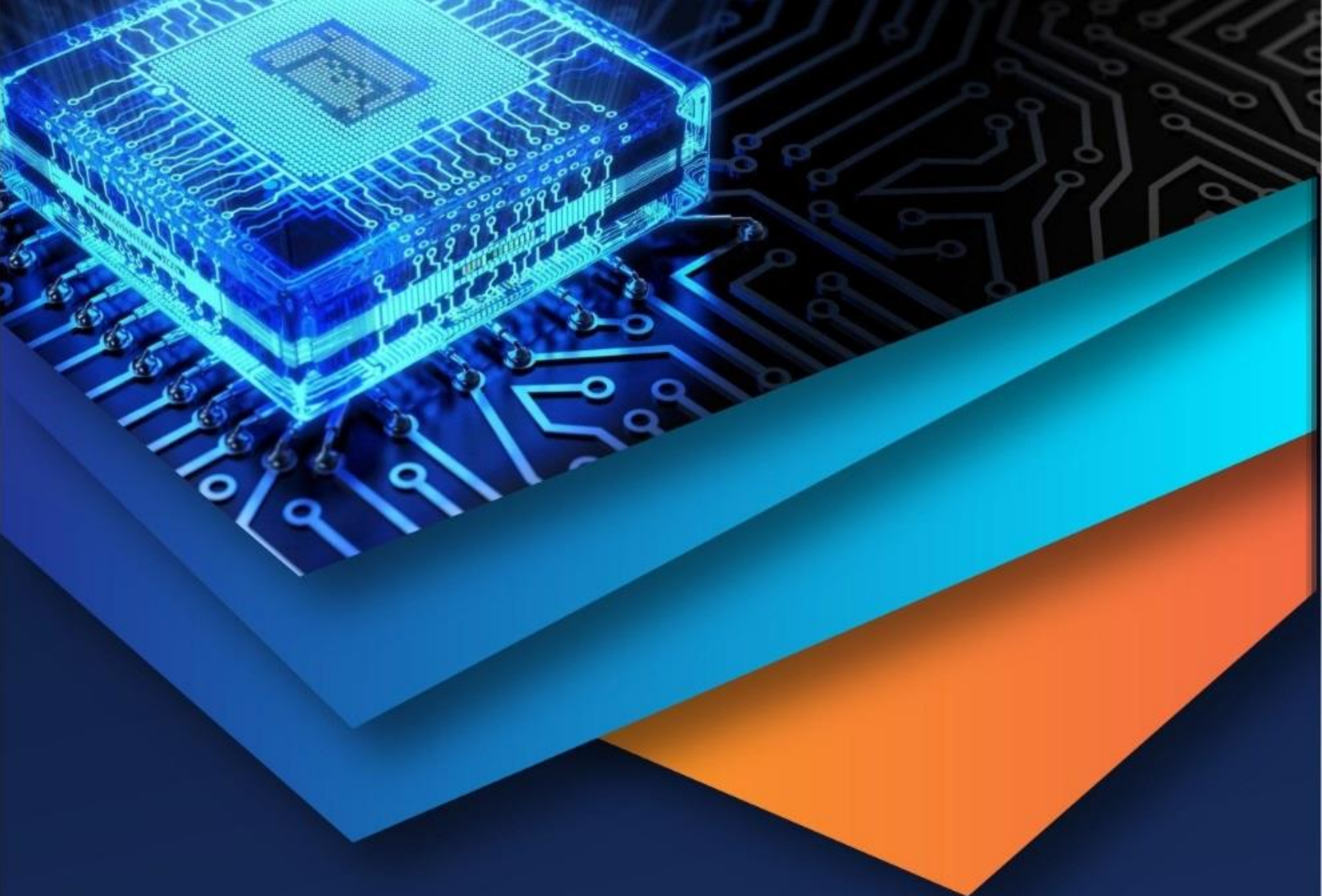

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