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Power Quality Enhancement of a Grid-Connected PV-WECS Hybrid Energy Storage System Using Fuzzy Logic Controller and Dynamic Voltage Restorer

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Abstract: The increasing penetration of renewable energy resources into modern power systems has introduced significant challenges related to voltage regulation, harmonic distortion, renewable intermittency, and grid stability. This paper presents an intelligent grid-connected photovoltaic (PV) and wind energy conversion system (WECS) integrated with a Hybrid Energy Storage System (HESS) for enhancing power quality under varying operating conditions. The proposed system employs a Fuzzy Logic Controller (FLC) to regulate the DC-link voltage and control the Voltage Source Converter (VSC), thereby providing superior dynamic performance compared with conventional control approaches. A Dynamic Voltage Restorer (DVR) is incorporated at the Point of Common Coupling (PCC) to compensate voltage sag, voltage swell, and severe grid disturbances, ensuring continuous and reliable power delivery to sensitive loads. The coordinated operation of PV, WECS, HESS, FLC, and DVR significantly improves voltage stability, reduces Total Harmonic Distortion (THD), enhances renewable energy utilization, and strengthens fault ride-through capability. The complete system is developed and analysed in the MATLAB/Simulink environment under nonlinear loading conditions and grid disturbances. Simulation results demonstrate that the proposed intelligent control strategy effectively minimises harmonic distortion, maintains stable DC-link voltage, improves transient response, and delivers superior power quality while satisfying IEEE-519 harmonic standards for modern smart grid applications.

Keywords: Photovoltaic System, Wind Energy Conversion System, Hybrid Energy Storage System, Fuzzy Logic Controller, Dynamic Voltage Restorer, Power Quality, Grid-Connected Microgrid

I. INTRODUCTION

The rapid growth in global electricity demand, together with increasing environmental concerns and the depletion of fossil fuel resources, has accelerated the integration of renewable energy sources into modern power systems. Among the available renewable technologies, photovoltaic (PV) systems have become one of the most attractive options owing to their clean operation, modular structure, and declining installation cost [1]. However, the intermittent nature of solar energy introduces voltage fluctuations, power imbalance, and instability in grid-connected applications. To overcome these limitations, hybrid renewable energy systems combining photovoltaic and wind energy conversion systems (WECS) have gained considerable attention because of their complementary generation characteristics, which improve energy availability and reduce dependence on conventional generation [2], [3]. Furthermore, the integration of Hybrid Energy Storage Systems (HESS) enhances power balancing capability by effectively managing renewable energy fluctuations and maintaining continuous power supply [4], [5].

Although hybrid renewable systems improve energy utilisation, the increasing use of power electronic converters introduces several power quality problems, including harmonic distortion, reactive power imbalance, voltage sag, voltage swell, and transient instability at the Point of Common Coupling (PCC). Conventional linear controllers often exhibit reduced performance under nonlinear operating conditions and varying renewable generation. Intelligent control techniques have therefore emerged as effective alternatives because they provide adaptive decision-making capability without requiring precise mathematical modelling. Among these techniques, the Fuzzy Logic Controller (FLC) has demonstrated excellent dynamic response, robust voltage regulation, and effective harmonic suppression under uncertain operating conditions [6], [7].

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In addition, Dynamic Voltage Restorers (DVRs) have become an effective custom power device for compensating voltage disturbances and improving fault ride-through capability during severe grid faults [8], [9].

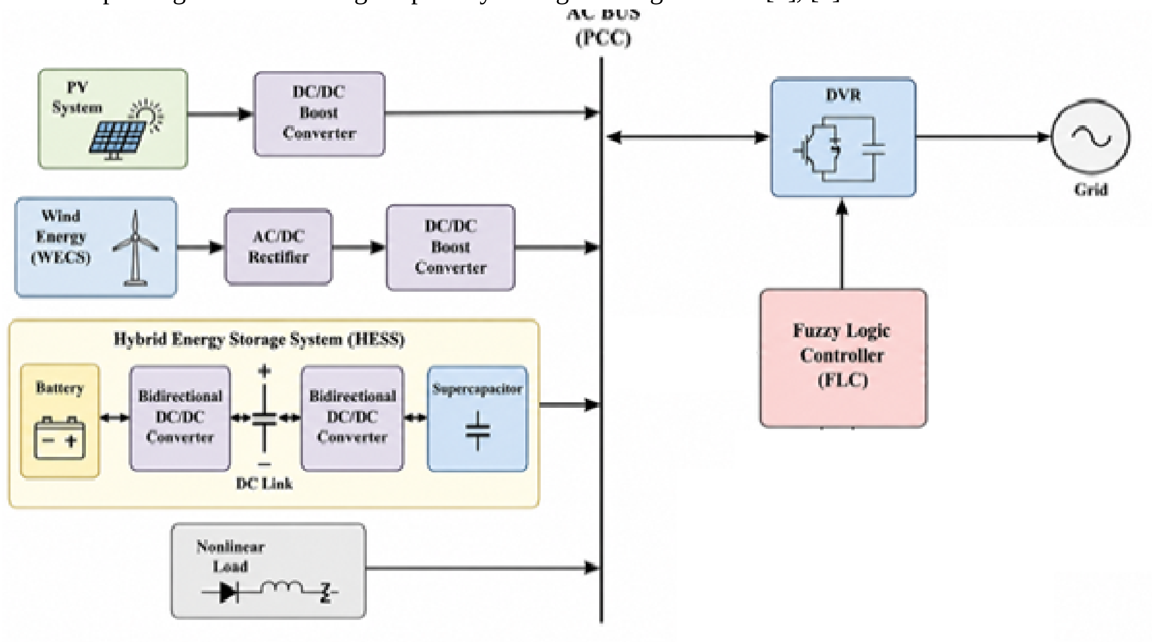

Fig 1. FLC, DVR Based PV-WECS System Configuration.

This project proposes an intelligent PV–WECS–HESS based grid-connected microgrid employing a Fuzzy Logic Controller together with a Dynamic Voltage Restorer to enhance overall system performance as shown in Fig. 1. The FLC regulates converter operation by maintaining DC-link voltage stability and reducing switching-induced harmonics, while the DVR injects the required compensating voltage during grid disturbances to preserve load voltage quality. The coordinated operation of renewable energy sources, hybrid energy storage, intelligent control, and voltage compensation significantly improves voltage regulation, transient response, renewable energy utilisation, and harmonic performance. The proposed system is implemented in MATLAB/Simulink and evaluated under different operating scenarios to verify its effectiveness in enhancing power quality and ensuring reliable smart grid operation [10]–[15].

II. LITERATURE SURVEY

The integration of photovoltaic systems into grid-connected microgrids has been extensively investigated owing to the growing demand for sustainable and environmentally friendly electricity generation. Researchers have reported that although PV systems offer significant environmental advantages, their intermittent nature causes voltage fluctuations, frequency deviations, and reduced power quality under changing weather conditions. To improve renewable energy penetration and system reliability, hybrid energy systems combining photovoltaic generation with wind energy have been widely adopted. These hybrid configurations provide complementary power generation characteristics, thereby improving overall energy availability and reducing dependency on conventional utility sources [16], [17]. Hybrid Energy Storage Systems (HESS), consisting of batteries and supercapacitors, have also been introduced to smooth renewable power fluctuations and improve dynamic energy management [18], [19].

Several control strategies have been proposed to improve the dynamic performance of renewable-energy-based microgrids. Conventional Proportional–Integral (PI) controllers remain popular because of their simple implementation; however, their fixed parameters limit performance under nonlinear operating conditions, parameter uncertainties, and renewable intermittency. Consequently, intelligent control methods such as Fuzzy Logic Controllers, Artificial Neural Networks, Adaptive Controllers, and Model Predictive Control have attracted considerable attention due to their superior robustness and adaptive behaviour. Among these techniques, Fuzzy Logic Controllers have demonstrated improved DC-link voltage regulation, faster transient response, lower steady-state error, and significant harmonic reduction without requiring an accurate mathematical model of the system [20]–[23].

Recent research has also focused on improving power quality through the integration of Dynamic Voltage Restorers and advanced converter control strategies.

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DVRs effectively compensate voltage sag, voltage swell, and transient disturbances by injecting an appropriate series voltage at the Point of Common Coupling, thereby protecting sensitive loads during grid faults. Combined with intelligent converter control and hybrid renewable energy integration, DVR-based systems significantly improve voltage regulation, fault ride-through capability, and harmonic suppression while satisfying IEEE-519 harmonic standards. Despite these advancements, further research is still required to develop coordinated control strategies that simultaneously optimise renewable energy utilisation, storage management, voltage stability, and harmonic mitigation under highly dynamic operating conditions. The proposed FLC-based PV–WECS–HESS system with DVR addresses these challenges through intelligent adaptive control and coordinated voltage compensation [24]–[30].

III. METHODOLOGY

The proposed system consists of a grid-connected photovoltaic (PV) array, Wind Energy Conversion System (WECS), Hybrid Energy Storage System (HESS), Voltage Source Converter (VSC), Dynamic Voltage Restorer (DVR), and a Fuzzy Logic Controller (FLC) operating in a coordinated manner to improve power quality and system reliability. Initially, the photovoltaic array converts solar irradiance into DC power, while the wind turbine generates variable AC power according to wind speed. The generated wind power is converted into DC through an AC/DC rectifier, whereas the PV output is regulated using a DC/DC boost converter. Both renewable sources are integrated into a common DC-link, which serves as the primary energy exchange point of the system. The HESS, comprising a battery and a supercapacitor connected through bidirectional DC/DC converters, compensates for renewable power fluctuations by absorbing excess energy during surplus generation and supplying energy during power deficits. This coordinated energy management maintains a stable DC-link voltage and ensures continuous power delivery under varying environmental conditions.

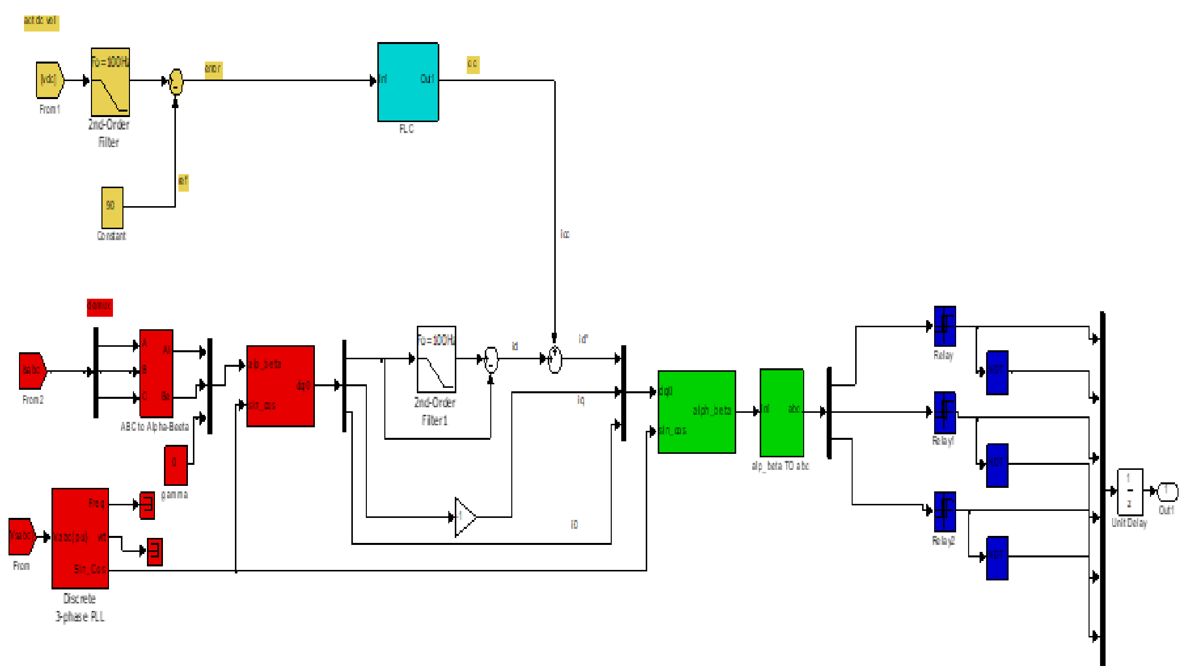

Fig 2.Propounded Controller for DVR.

The above Fig. 2 shows the DC-link voltage is continuously monitored and compared with its reference value, and the resulting voltage error together with the change in error are applied to the Fuzzy Logic Controller (FLC). Unlike conventional PI controllers, the FLC utilizes linguistic rules and membership functions to generate the reference direct-axis current ((i_d^*)), enabling adaptive control under nonlinear operating conditions. Simultaneously, a three-phase Phase-Locked Loop (PLL) synchronizes the controller with the utility grid by estimating the grid angle required for the Park transformation.
The Three-phase currents are transformed into synchronous reference frame.

$$i_d = \frac{2}{3}\left[i_a\cos\theta + i_b\cos\left(\theta - \frac{2\pi}{3}\right) + i_c\cos\left(\theta + \frac{2\pi}{3}\right)\right] \quad \ldots(1)$$

$$i_q = -\frac{2}{3}\left[i_a\sin\theta + i_b\sin\left(\theta - \frac{2\pi}{3}\right) + i_c\sin\left(\theta + \frac{2\pi}{3}\right)\right] \quad \ldots(2)$$

The fuzzy controller maps the inputs $(e, \Delta e)$ into the output current reference.

$i_d^* = F(e, \Delta e)$…..(3)

where

$F: (e, \Delta e) \rightarrow i_d^*$ ….(4)

The measured three-phase currents are transformed from the stationary (abc) frame into the synchronous (dq) reference frame, where the direct-axis current controls active power while the quadrature-axis current regulates reactive power. Since the proposed system operates at unity power factor, the reference quadrature-axis current is maintained at zero. The reference voltage signals obtained after inverse Park transformation are processed through a PWM generator to produce six complementary gate pulses for the Voltage Source Converter. Consequently, the converter injects balanced sinusoidal currents into the utility grid while maintaining DC-link voltage stability and minimizing harmonic distortion.

To further enhance power quality and fault ride-through capability, a Dynamic Voltage Restorer (DVR) is connected in series with the utility grid at the Point of Common Coupling (PCC). During normal operating conditions, the DVR remains inactive while continuously monitoring the grid voltage. When voltage sag, voltage swell, or severe disturbances such as three-line-to-line-to-ground (LLLG) faults occur, the DVR rapidly injects the required compensating voltage through a series injection transformer to restore the load-side voltage to its rated value. The coordinated operation of the PV system, WECS, HESS, FLC-controlled VSC, and DVR significantly improves voltage regulation, reduces Total Harmonic Distortion (THD), suppresses DC-link voltage fluctuations, enhances renewable energy utilization, and ensures uninterrupted power supply to sensitive loads. The entire proposed system is modelled and validated in the MATLAB/Simulink environment under nonlinear loading conditions and grid disturbances, demonstrating superior dynamic performance, improved transient response, enhanced fault ride-through capability, and compliance with IEEE-519 power quality standards.

IV. SIMULATION RESULTS AND DISCUSSION

In the Fig. 3 proposes the hybrid renewable energy system, the conventional Proportional–Integral (PI) controller is replaced by a Fuzzy Logic Controller (FLC) to improve the overall power quality and Low Voltage Ride Through (LVRT) capability during severe grid disturbances, particularly under Three-Line-to-Line-to-Ground (LLLG) faults. Although the PI controller performs satisfactorily under linear operating conditions, its fixed proportional and integral gains limit its performance when the renewable generation, load demand, and grid conditions vary rapidly. During sudden voltage sags or severe symmetrical faults, the PI controller exhibits slow response, overshoot, oscillations, and poor harmonic suppression, leading to degradation of power quality at the Point of Common Coupling (PCC).

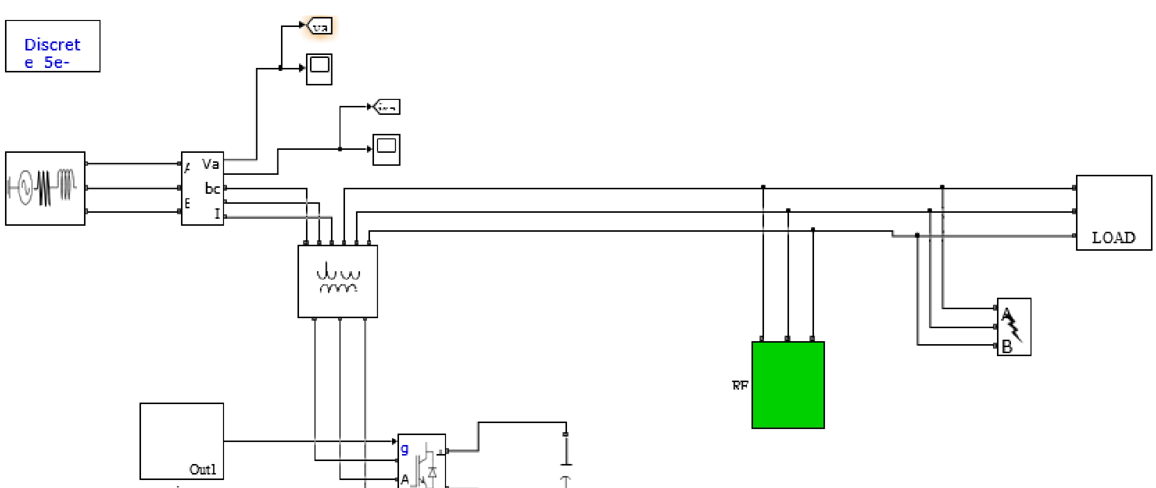

Fig 3.Simulation Circuit with FLC with LVRT

The FLC eliminates these limitations by providing intelligent nonlinear control based on linguistic decision-making rather than precise mathematical modelling. It continuously evaluates the system error and change in error and generates an adaptive control signal that responds instantly to changing operating conditions.Consequently, the inverter produces smoother switching signals, resulting in improved voltage regulation, reduced converter oscillations, and enhanced PCC voltage quality. This adaptive control capability enables the hybrid PV–WECS–HESS system to maintain stable operation under varying renewable generation, nonlinear loads, and severe grid faults.

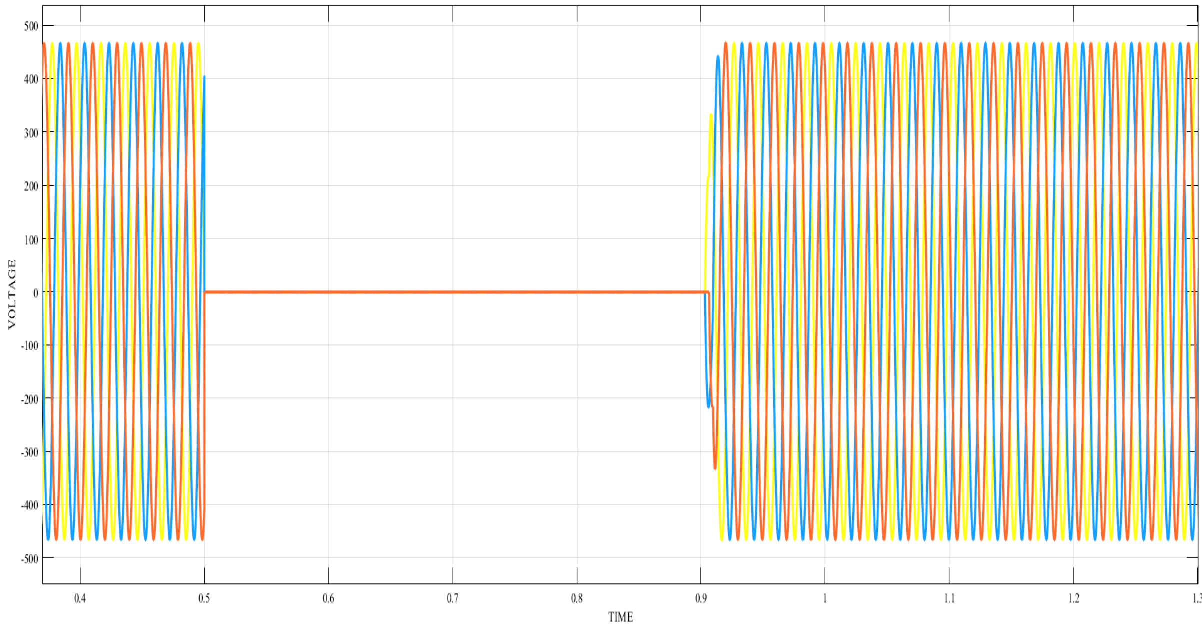

Fig 4. Hybrid system PCC voltage under LLG Fault.

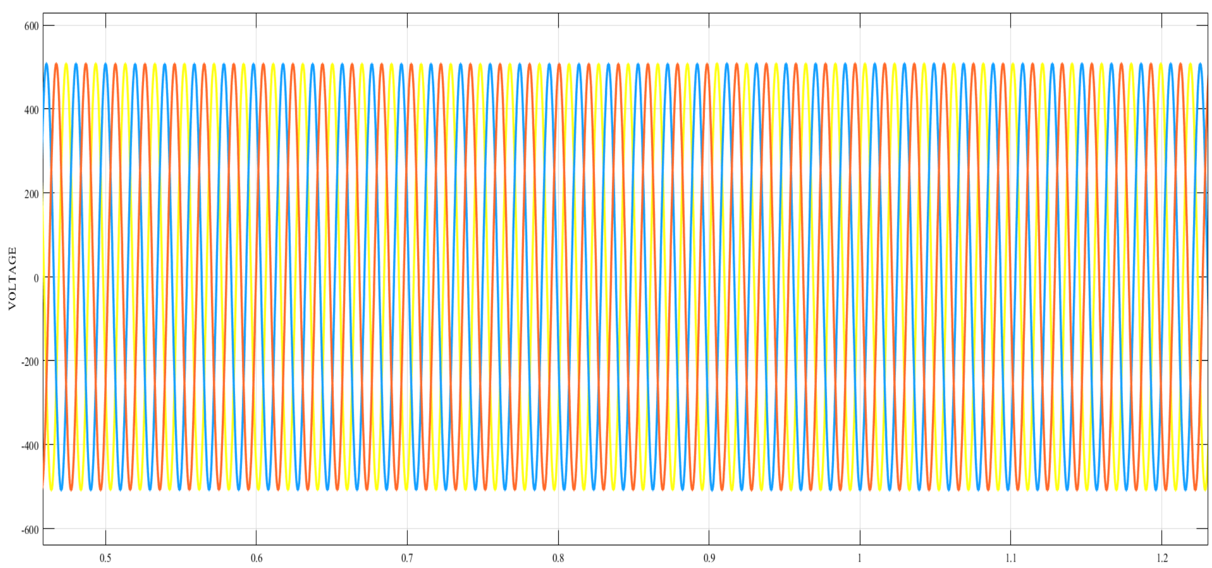

Fig 5.Restored PCC Voltage with FLC in hybrid system.

One of the primary objectives of this FLC is to minimize the Total Harmonic Distortion (THD) of the PCC voltage. During normal operation, nonlinear loads and converter switching introduce harmonic currents that distort the PCC voltage waveform.

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Under LLLG fault conditions, the harmonic content further increases because of sudden voltage collapse, current imbalance, and converter stress as shown in Fig. 4 & Fig. 6. Unlike the PI controller, which reacts only after the error becomes significant, the FLC predicts the trend of voltage deviation using fuzzy inference rules and initiates corrective action immediately. This rapid decision-making improves inverter current tracking and produces nearly sinusoidal output voltages with minimal switching ripple. The fuzzy controller also coordinates effectively with the Voltage Source Converter (VSC), battery energy storage system, photovoltaic array, and Wind Energy Conversion System to maintain balanced power flow and stable DC-link voltage. As a result, harmonic distortion at the PCC is significantly reduced, voltage waveform quality is improved as in Fig. 5, and the proposed system complies more effectively with IEEE-519 harmonic standards. Therefore, replacing the PI controller with the FLC directly contributes to improved power quality, enhanced voltage stability, and better converter performance.

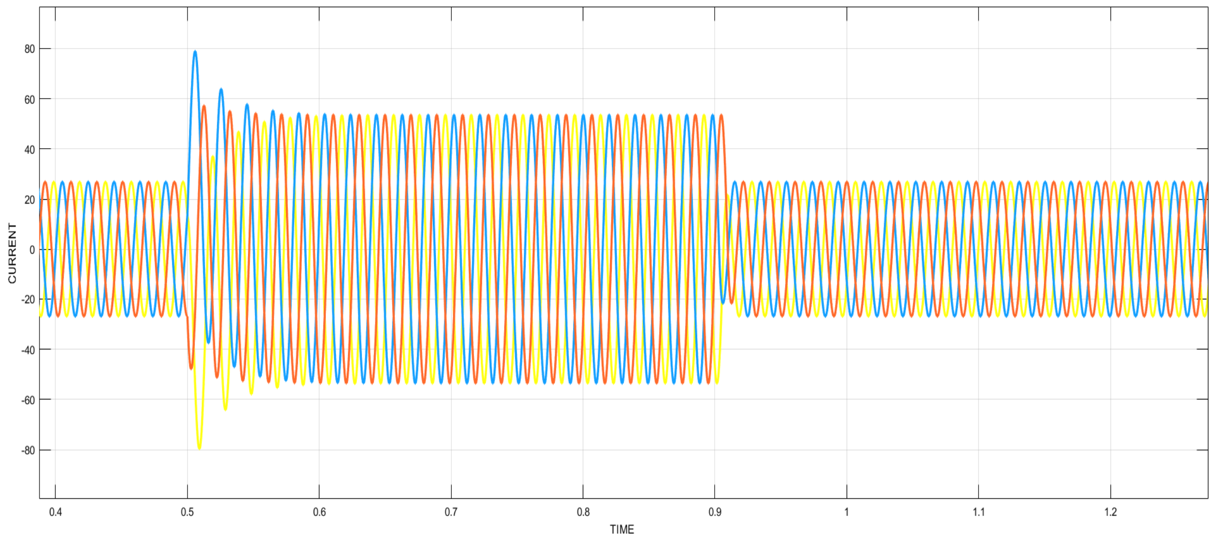

Fig 6. Hybrid system PCC Current under LLG Fault

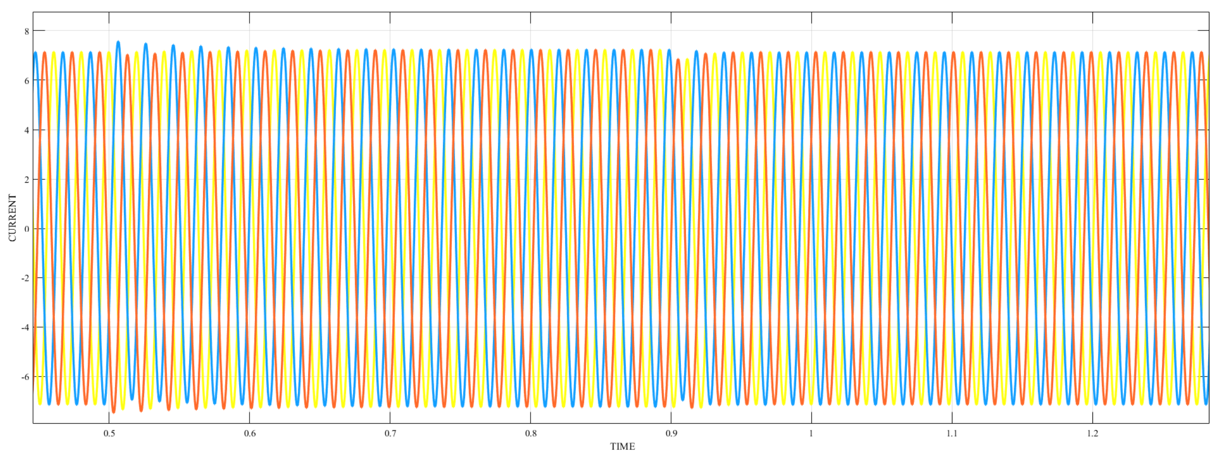

Fig 7. Restored PCC Current with FLC in hybrid system

The most significant advantage of the proposed FLC appears during severe Three-Line-to-Line-to-Ground (LLLG) faults, where the system must satisfy Low Voltage Ride Through (LVRT) requirements. During an LLLG fault, the grid voltage suddenly decreases, causing a large reduction in PCC voltage, rapid increase in converter current, DC-link voltage oscillations, and possible inverter disconnection. In the proposed system, the FLC continuously monitors the PCC voltage deviation and immediately generates optimized gating signals for the Voltage Source Converter. Simultaneously, the Dynamic Voltage Restorer (DVR) injects the required compensating voltage into the distribution feeder to restore the PCC voltage close to its rated value. Since the FLC responds much faster than the conventional PI controller, it minimizes voltage recovery time, suppresses oscillations, and prevents excessive transient currents during the fault period.

The intelligent coordination between the FLC and DVR enables uninterrupted power delivery to sensitive loads while ensuring continuous operation of the photovoltaic system, Wind Energy Conversion System, and Hybrid Energy Storage System. Consequently, the proposed hybrid system successfully satisfies LVRT requirements by maintaining voltage stability, protecting converter components, and preventing renewable energy disconnection during severe grid disturbances.

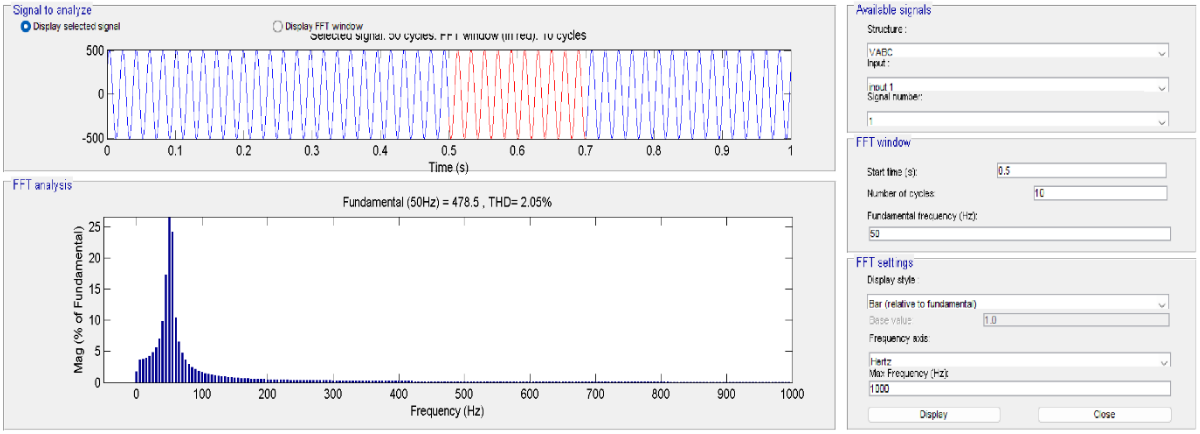

Fig 8. PCC voltage THD for hybrid system with FLC

The proposed hybrid renewable energy system integrates Photovoltaic (PV), Wind Energy Conversion System (WECS), Hybrid Energy Storage System (HESS), Dynamic Voltage Restorer (DVR), and a Voltage Source Converter under the supervision of the Fuzzy Logic Controller. The FLC serves as the central intelligent controller that coordinates power sharing among all renewable sources and energy storage devices according to real-time operating conditions. During periods of high solar irradiance and sufficient wind speed, the controller efficiently distributes renewable power to the grid and charges the battery. During low solar generation or wind variations, the HESS supplies the required deficit power without causing significant voltage fluctuations. During LLLG faults, the DVR injects compensating voltage while the FLC adjusts converter operation to maintain stable DC-link voltage and PCC voltage. Because the fuzzy controller adapts continuously to system uncertainties, renewable intermittency, and fault conditions, it significantly reduces battery stress, improves renewable energy utilization, minimizes voltage fluctuations, and maintains stable active and reactive power exchange with the utility grid. This coordinated operation enhances the overall reliability, efficiency, and resilience of the hybrid microgrid.

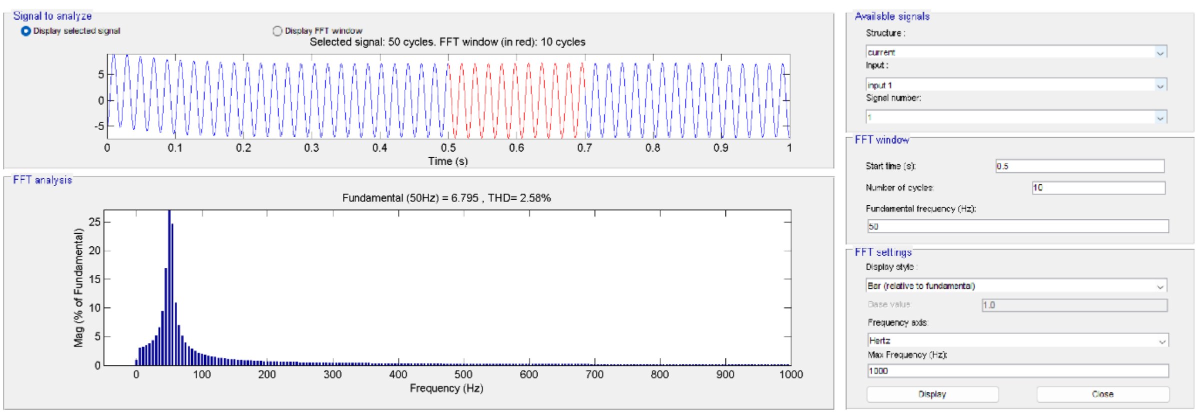

Fig 9. PCC current THD for hybrid system with FLC

The implementation of the Fuzzy Logic Controller substantially improves the overall power quality of the proposed hybrid PV–WECS–HESS microgrid. Compared with the conventional PI-controlled system, the proposed controller exhibits faster transient response, lower steady-state error, improved voltage regulation, superior harmonic suppression, and enhanced fault ride-through capability. The integration of the DVR further strengthens the voltage compensation process by restoring the PCC voltage almost instantaneously during LLLG faults.

Consequently, the proposed system achieves a significant reduction in PCC voltage Total Harmonic Distortion as shown in Fig. 8 & Fig. 9, minimizes voltage sag and voltage fluctuations, improves converter stability, and maintains uninterrupted power supply to sensitive loads. The adaptive characteristics of the FLC also eliminate the need for repeated controller tuning under changing operating conditions, making the system more robust against parameter variations and renewable intermittency. Furthermore, the coordinated control of PV, WECS, HESS, DVR, and the Voltage Source Converter ensures stable DC-link voltage, balanced power flow, efficient renewable energy utilization, and compliance with IEEE-519 power quality standards. Therefore, the proposed FLC-based control strategy provides a highly reliable and intelligent solution for future renewable-energy-based smart microgrids, offering enhanced power quality, improved LVRT capability, increased renewable energy penetration, and superior operational performance under both normal operating conditions and severe LLLG fault scenarios.

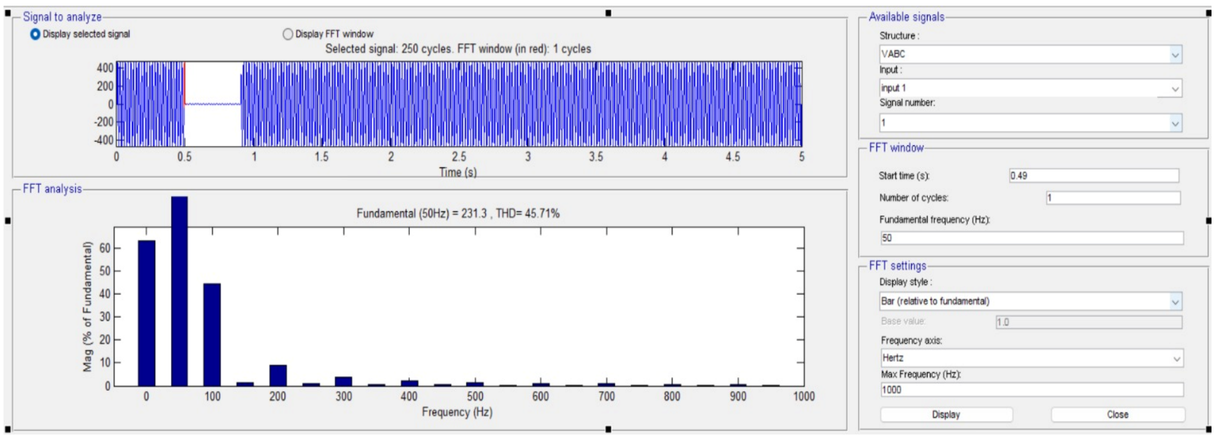

Fig 10. Voltage THD With PI controller at fault condition

The Fig. 10 illustrates the voltage Total Harmonic Distortion (THD) of the conventional PI-controlled system under fault conditions. During the fault interval, the PCC voltage waveform experiences severe distortion due to voltage sag and increased harmonic components. The FFT analysis indicates that the voltage THD reaches **45.71%**, which is significantly higher than the IEEE-519 permissible limit. The large harmonic content demonstrates the inability of the conventional PI controller to maintain voltage quality during grid disturbances, thereby affecting the stability and reliability of the renewable energy system.

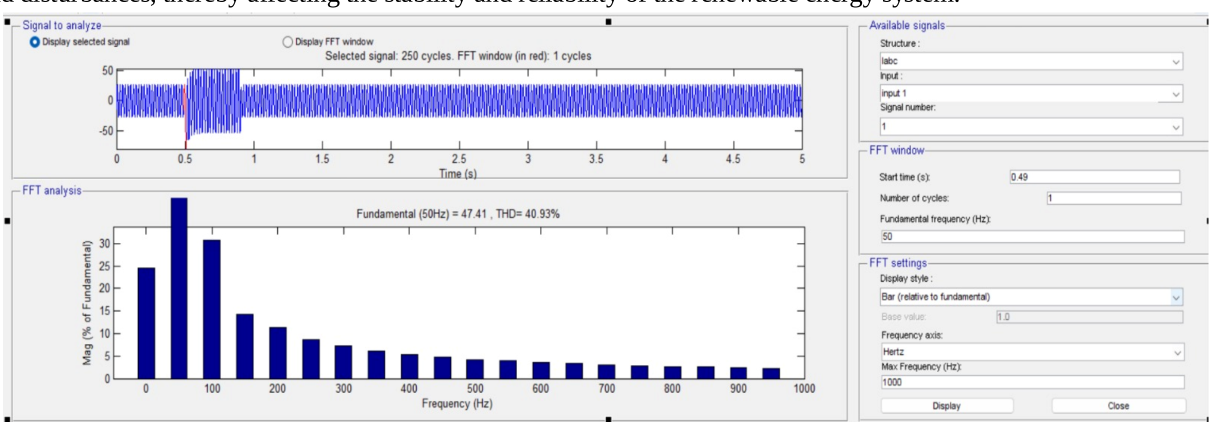

Fig 11.Current THD With PI controller at fault condition.

The Fig. 11 presents the current THD of the conventional PI-controlled system during the fault condition. The current waveform becomes highly distorted owing to the sudden voltage collapse and poor dynamic response of the PI controller. The FFT spectrum shows a current THD of 40.93%, indicating the presence of significant harmonic currents injected into the grid. These harmonics increase converter losses, reduce power quality, and may adversely affect sensitive electrical equipment. The results highlight the necessity of employing an intelligent controller together with a Dynamic Voltage Restorer (DVR) to suppress harmonics and improve fault ride-through capability.

Table 1.THD comparison table of with and without DVR

parameters	With out FLC+DVR+WIND	With FLC+DVR+WIND
Voltage THD at fault	45.71	2.05
Current THD at fault	40.93	2.58

The Table 1 compares the harmonic performance of the conventional PI controller with the proposed FLC+DVR+Wind integrated system under fault conditions. The proposed approach remarkably reduces the voltage THD from 45.71% to 2.05% and the current THD from 40.93% to 2.58%. This substantial reduction confirms the effectiveness of the Fuzzy Logic Controller in coordinating the hybrid renewable energy sources while the Dynamic Voltage Restorer compensates voltage disturbances during faults. The obtained THD values satisfy the IEEE-519 standard, demonstrating that the proposed control strategy significantly enhances power quality, system stability, and fault ride-through performance compared with the conventional PI-controlled system.

V. CONCLUSION

This studyrepresents a grid-connected photovoltaic (PV) and Wind Energy Conversion System (WECS) integrated with a Hybrid Energy Storage System (HESS) employing a Fuzzy Logic Controller (FLC) and a Dynamic Voltage Restorer (DVR) to enhance power quality and system reliability. The coordinated integration of multiple renewable energy sources with intelligent control effectively addressed the challenges associated with renewable intermittency, voltage fluctuations, harmonic distortion, and grid disturbances. The FLC provided adaptive DC-link voltage regulation by generating appropriate converter control signals without requiring an accurate mathematical model, thereby offering faster dynamic response and superior robustness under varying operating conditions. Simultaneously, the HESS maintained power balance by compensating renewable energy fluctuations, while the DVR mitigated voltage sag, voltage swell, and fault-induced disturbances at the Point of Common Coupling (PCC), ensuring continuous power supply to sensitive loads. MATLAB/Simulink results demonstrated that the proposed system significantly reduced Total Harmonic Distortion (THD), improved voltage regulation, enhanced transient response, and maintained stable converter operation during both steady-state and fault conditions. Furthermore, the proposed control strategy improved renewable energy utilization, minimized DC-link voltage ripples, and achieved effective active and reactive power management while satisfying IEEE-519 harmonic standards. Therefore, the proposed intelligent PV–WECS–HESS system represents an efficient and reliable solution for future smart grid applications requiring high renewable energy penetration, improved power quality, and enhanced operational stability.

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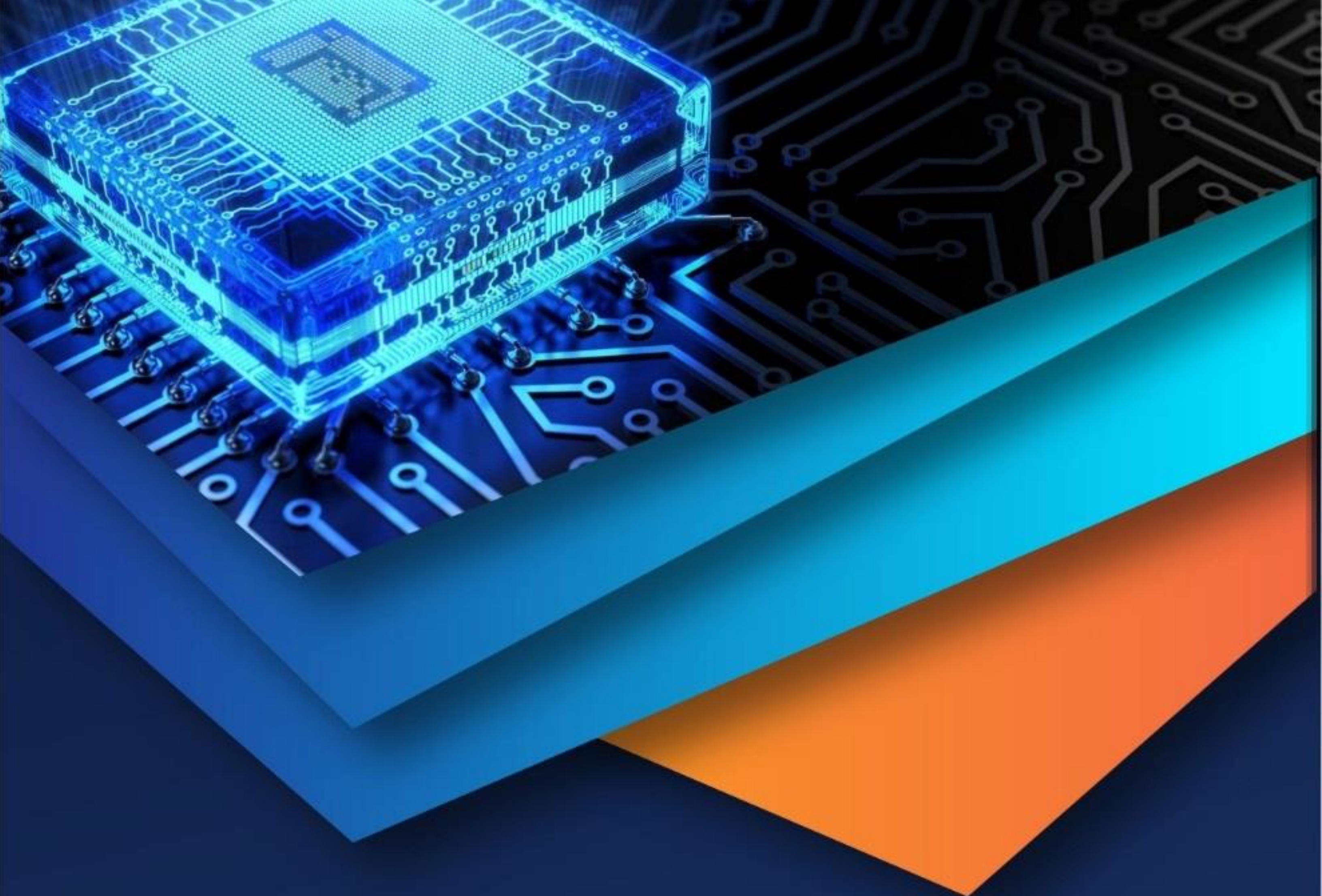

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