Grid-Connected Wind-Solar Cogeneration Using Back to Back Voltage Source Converters

SWATHI SANKEPALLY[1]|A.SOWMYA[2]|P.HARIKA[3]| FARHA ANJUM[4]
1 Associate Professor, Department of EEE, Bhoj Reddy Engineering College for Women, Hyderabad, TS.
2, 3 &4 UG SCHOLARS, EEE department, Bhoj Reddy Engineering College for Women, Hyderabad, TS.

ABSTRACT: This paper focuses on the design and analysis of a grid-connected solar-wind co-generation system using back-to-back voltage source converters (VSCs), aimed at enhancing power quality and system stability in hybrid renewable energy networks. a detailed investigation was carried out on the dynamic stability characteristics of the wind energy subsystem under both constant-speed and variable-speed operational conditions. To address these issues and improve the system's robustness, a fuzzy logic controller (FLC) was incorporated into the control strategy of the back-to-back VSCs. The FLC was specifically designed to mitigate harmonic distortions and enhance the system's adaptability to changing inputs, ensuring a smoother power flow and more stable grid connection. The intelligent control provided by the fuzzy logic mechanism allowed for real-time adjustments in the converter operation using a MATLAB/Simulink environment, a combined circuit of wind and solar sources was developed to simulate real-time dynamic load generation and its effect on the overall system performance. This paper provided valuable insights into the system's response to fluctuations in wind speed and solar irradiance, and how these variations impact voltage stability and power delivery to the grid. The simulation results highlighted the limitations in maintaining power quality under varying load and environmental conditions, especially the presence of harmonics and instability during dynamic transitions, thereby reducing total harmonic distortion (THD) and improving voltage and frequency regulation across the grid interface.

KEYWORDS: Grid, Wind-Solar Co-Generation, Voltage Source Converters, Total Harmonic Distortion.

I.INTRODUCTION: The growing demand for clean and sustainable energy has led to the rapid development of hybrid renewable energy systems that combine multiple sources, such as solar and wind, to ensure reliable and continuous power generation. Among these, solar-wind hybrid systems have gained considerable attention due to their complementary nature—solar energy is generally available during the day, while wind energy can be harnessed throughout the day and night depending on environmental conditions. However, integrating these variable energy sources into the grid poses significant challenges, particularly in maintaining power quality, voltage stability, and system reliability under dynamic operating conditions.

This project addresses these challenges by proposing a grid-connected solar-wind co-generation system using back-to-back voltage source converters (VSCs). The architecture allows for efficient energy conversion and flexible control of power flow between the renewable sources and the utility grid. The use of VSCs offers the added advantage of decoupling the control of active and reactive power, which is essential for stable and efficient grid integration. The system also eliminates the need for intermediate DC/DC converters, simplifying the topology and reducing losses.

The project is structured in two stages. In Stage 1, the focus is on analyzing the dynamic stability of the wind energy subsystem under constant-speed and variable-speed operational scenarios. MATLAB/Simulink simulations were used to create a combined model of the wind and solar energy sources to observe the system's dynamic load generation behavior. This stage helps in understanding the interaction between both sources and their individual contributions to system performance under varying environmental and load conditions. It also highlights the limitations in power quality due to harmonics and transient disturbances.

To address these limitations, Stage 2 introduces a fuzzy logic controller (FLC) into the system. Fuzzy logic, a form of intelligent control, is known for its ability to handle non-linear systems and uncertain inputs effectively. The controller is implemented to regulate the operation of the VSCs, aiming to reduce harmonic distortion, improve voltage regulation, and enhance the overall dynamic response of the hybrid system. With the inclusion of fuzzy logic control, the system demonstrates improved power quality and grid compliance, making it more suitable for real-time grid-connected applications. Through the integration of advanced control strategies and optimized system architecture, this project contributes to the development of more efficient, stable, and intelligent renewable energy systems, paving the way for a more sustainable and resilient energy future.

III. PROPOSED SYSTEM:

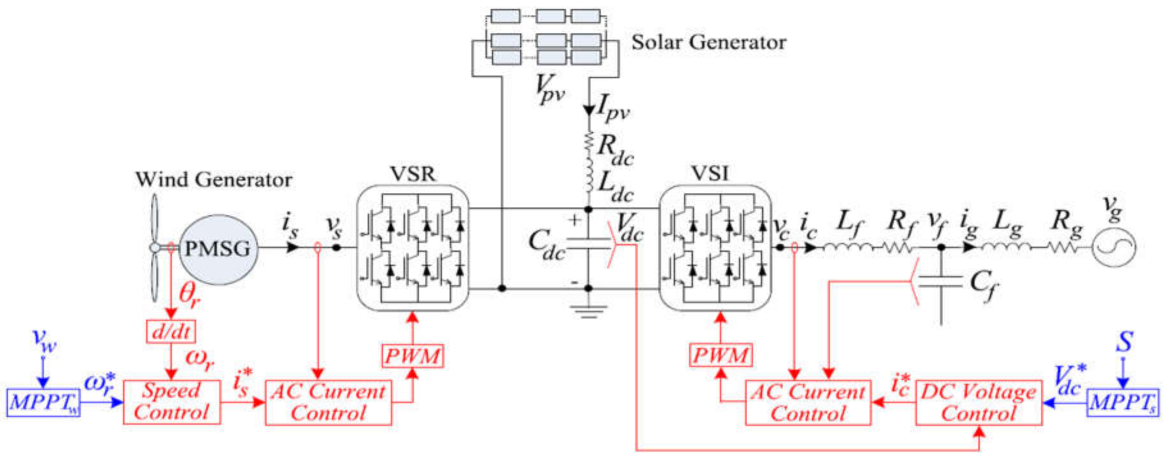


Fig.1 Proposed Block Diagram

This paper presents the grid-connected solar-wind cogeneration system integrates renewable energy sources solar and wind using a back-to-back voltage source converter configuration. The system starts with the wind turbine, which converts wind energy into alternating current (AC) electricity. Due to variations in wind speed, the AC output has fluctuating frequency and amplitude. This variable AC power is fed into an

AC-DC rectifier, which converts it into direct current (DC) and ensures a stable output that is fed into the common DC link. Simultaneously, the solar PV array generates DC electricity by capturing sunlight. The solar output, which varies with changes in sunlight and temperature, is processed by a DC-DC converter. This converter incorporates a Maximum Power Point Tracking (MPPT) algorithm to maximize power extraction from the PV array, and it also steps up the voltage to meet the system's requirements before feeding the stabilized output into the DC link.

The DC link acts as the central interface, connecting the wind and solar systems to the voltage source converters. It stabilizes the voltage using capacitors, filters out ripples, and temporarily stores energy, ensuring a smooth and reliable power supply to the converters. From the DC link, the power is delivered to the source-side voltage source converter (VSC), which converts DC power back to AC. This VSC synchronizes the output voltage, frequency, and phase with the grid and regulates active and reactive power flow. To ensure power quality, the AC output from the source-side VSC is passed through LC filters, which eliminate high-frequency harmonics generated during the conversion

The filtered AC power is then managed by the grid-side voltage source converter (VSC). This converter ensures precise synchronization of the system with the grid and maintains voltage and frequency stability. It also compensates for reactive power and handles any disturbances in the grid, such as voltage sags or surges, to maintain a stable connection. The control system governs the entire operation, managing MPPT for solar, speed control for the wind turbine, and power sharing between the two sources. It ensures seamless synchronization with the grid, regulates power quality, and includes protective mechanisms to handle faults like overvoltage, overcurrent, or short circuit.

DYNAMIC STABILITY ON WIND SYSTEM:

The dynamic wind stability was analyzed by simulating two operating conditions for the wind turbine one with constant wind speed (12 m/s) and the other with variable wind speed to mimic realistic wind behaviour. Under constant speed, the power generation from the wind turbine remains steady, allowing the back-to-back voltage source converters to operate in a stable mode with minimal fluctuations in DC-link voltage and output power. This provides a baseline for system performance. In contrast, the variable wind speed condition introduces dynamic changes in wind power input, challenging the control system's ability to maintain stability.

These variations affect the generator output, causing corresponding fluctuations in the DC-link voltage and inverter output. The system's response under these conditions was observed using scope waveforms, which Showed how effectively the control loops—such as MPPT, voltage regulation, and inverter synchronization handled the disturbances. The results highlight the importance of robust control strategies to ensure dynamic stability in real-world scenarios where wind speed is constantly changing.

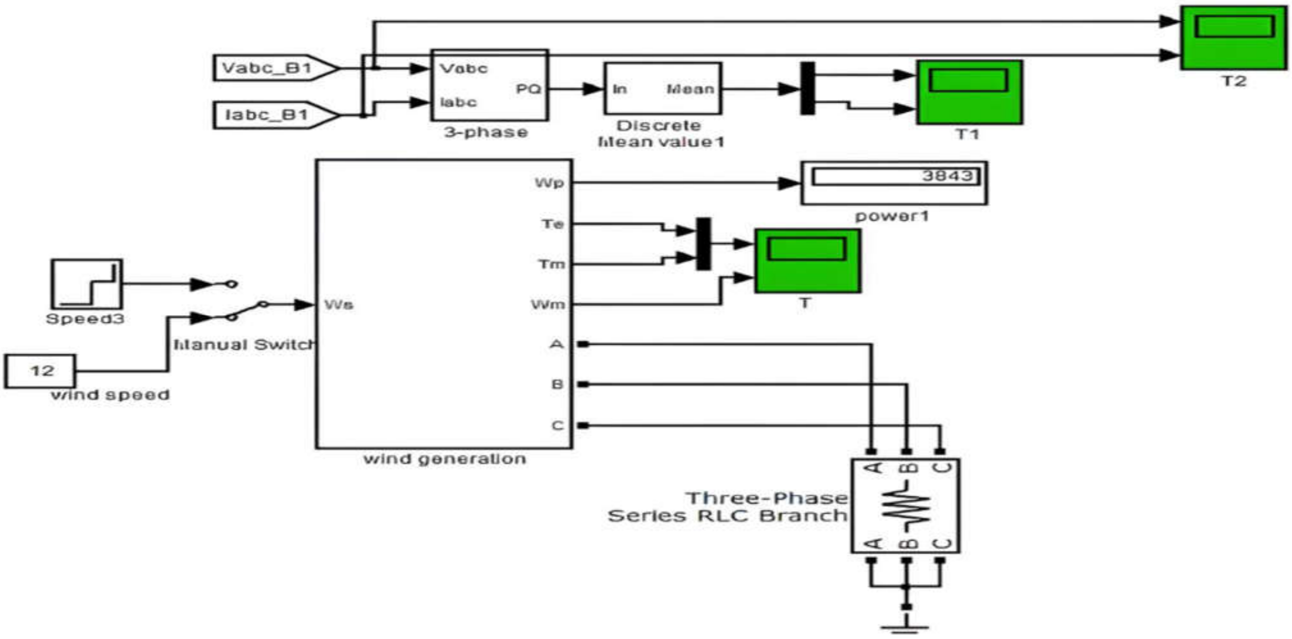


Fig.2 Simulation Diagram for Dynamic Stability On Wind System

DYNAMIC LOAD GENERATION:

The dynamic load generation is implemented using a purely resistive load to evaluate the system's performance under varying power demands. A resistive load is chosen because it draws only active power and does not introduce any reactive component, making the analysis of system behaviour more straightforward and focused on real power dynamics. At 5 seconds into the simulation, the resistive load is increased to simulate a sudden rise in power demand, similar to connecting an additional appliance or machinery in a real-world scenario. This triggers a transient response in the system, where the DC-link voltage may initially dip due to the increased current drawn by the inverter. The control systems of the wind and solar converters, along with the battery through the bidirectional DC-DC converter, work together to stabilize the power flow and restore the DC-link voltage. Because the load is purely resistive, the voltage and current remain in phase, reducing the complexity of phase synchronization and easing the burden on the phase-locked loop (PLL). This setup effectively demonstrates the system's small signal stability and its ability to maintain smooth and stable operation under active power fluctuations. A pure resistive load is used to focus solely on the system's active power response, avoiding complexities related to reactive power. At t = 5 seconds, the resistive load is increased to simulate a sudden rise in consumer demand, similar to switching on large appliances or industrial equipment in a real grid scenario.

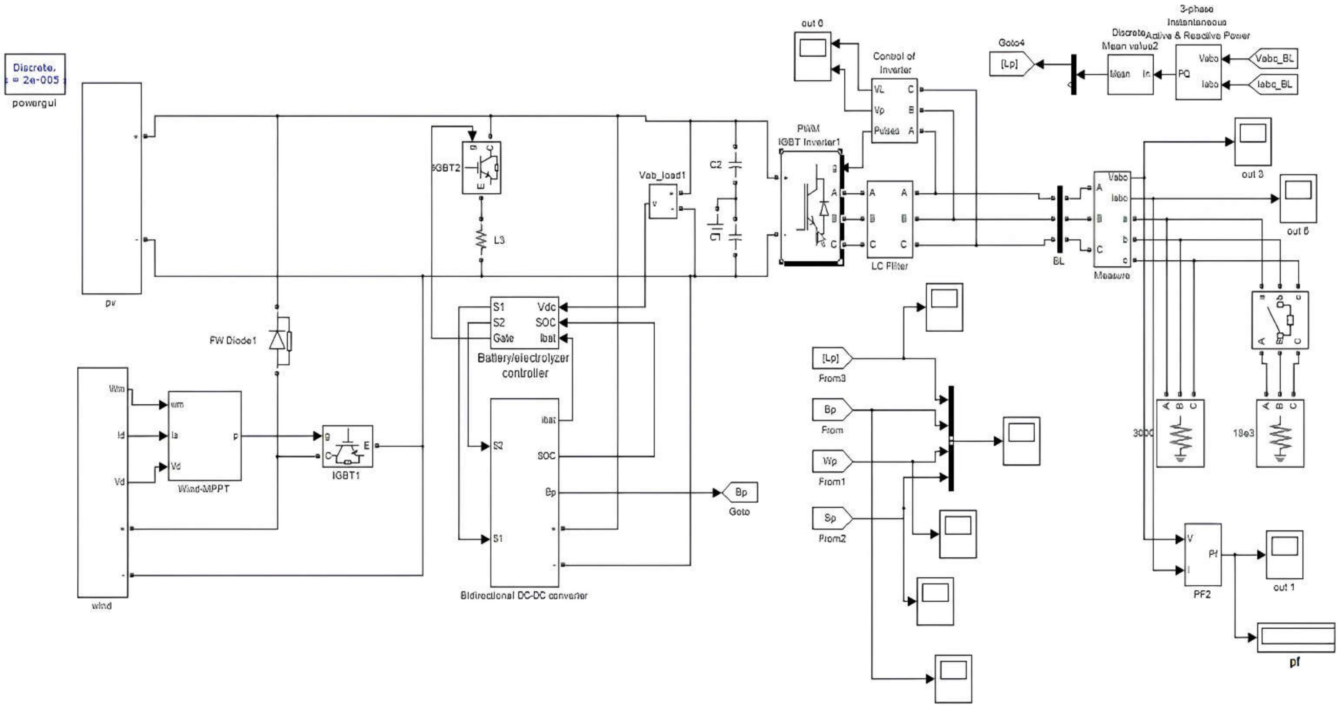


Fig.3 Simulation Diagram for Dynamic Load Generation

A pure resistive load is used to focus solely on the system's active power response, avoiding complexities related to reactive power. At t = 5 seconds, the resistive load is increased to simulate a sudden rise in consumer demand, similar to switching on large appliances or industrial equipment in a real grid scenario. This deliberate disturbance introduces a temporary mismatch between power generation and load demand, which challenges the system’s control architecture. The DC-link voltage—shared by the back-to-back voltage source converters—experiences a transient dip due to increased current flow. To maintain stability, the system must react rapidly by adjusting the output from the wind turbine generator (via the rectifier) and solar PV (via MPPT and converter). If necessary, the battery storage unit, connected through a bidirectional DC-DC converter, compensates for the shortfall by discharging power into the DC bus.

The grid-side inverter, synchronized through a phase-locked loop (PLL), must also respond efficiently to keep the output power quality stable and prevent phase mismatch with the grid. Since only a resistive load is used, the voltage and current remain in phase, which reduces the control complexity and provides a clean test condition for observing the system’s transient and steady-state performance. The waveforms observed in the simulation scopes provide visual confirmation of the system’s response, showing how quickly the voltage, current, and power levels settle after the disturbance. These results confirm whether the control loops (current, voltage, and PLL) are correctly tuned and whether the system can handle typical variations in demand without becoming unstable. Overall, this test highlights the importance of dynamic load generation in validating the robustness, reliability, and responsiveness of renewable energy-based power systems under practical grid conditions.

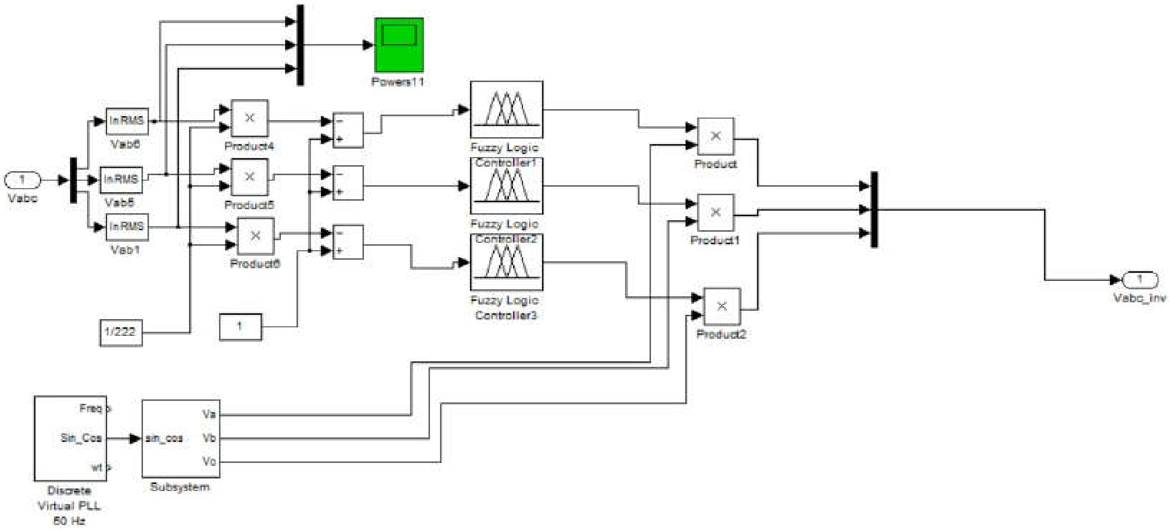


Fig 4 Block diagram for Total Harmonic Distortion

There are blocks on the far left that act as the system's inputs. One looks like a "Constant" block (often used for setting a fixed input value or reference).Another block seems to be a "Scope" or a display block, possibly to visualize the input signal.Several circular blocks with + and - signs are visible, indicating summing junctions where signals are added or subtracted. These are fundamental in control systems for calculating errors or combining signals.Rectangular blocks with a number or variable inside are likely gain blocks, which multiply the input signal by a constant factor. The most distinctive elements are the diamond-shaped blocks. These are characteristic of Fuzzy Inference Systems (FIS) or Fuzzy Logic Controllers in Simulink's Fuzzy Logic Toolbox. Each diamond block likely representsConverting crisp (numerical) input values into fuzzy sets. A set of IF-THEN rules that define the system's logic. Applying the rules to the fuzzified inputs to derive fuzzy outputs.Converting the fuzzy outputs back into crisp numerical values that can be used by other parts of the system.There appear to be at least three or four distinct fuzzy logic blocks, suggesting a multi-variable fuzzy control strategy or different stages of fuzzy processing.Lines feeding back from later stages of the diagram to earlier summing junctions indicate feedback loops. This is crucial for regulating the system's behavior and ensuring stability. For example, the output might be compared to a reference input to generate an error signal that drives the controller.Signals eventually lead to the right side of the diagram, where they likely represent the system's controlled outputs. A "Scope" block is also visible on the output side, used for visualizing the output signals over time.This block diagram could represent a fuzzy logic-based control system for various applications, such as Controlling temperature, pressure, flow, etc., in industrial processes.For motion control, path planning, or decision-making.Engine control, cruise control, or stability control. Fuzzy logic is often preferred for systems that are difficult to model precisely with traditional mathematical equations.

IV.SIMULATION RESULTS:

Simulation Results of Dynamic Stability on Wind System (Constant Speed):

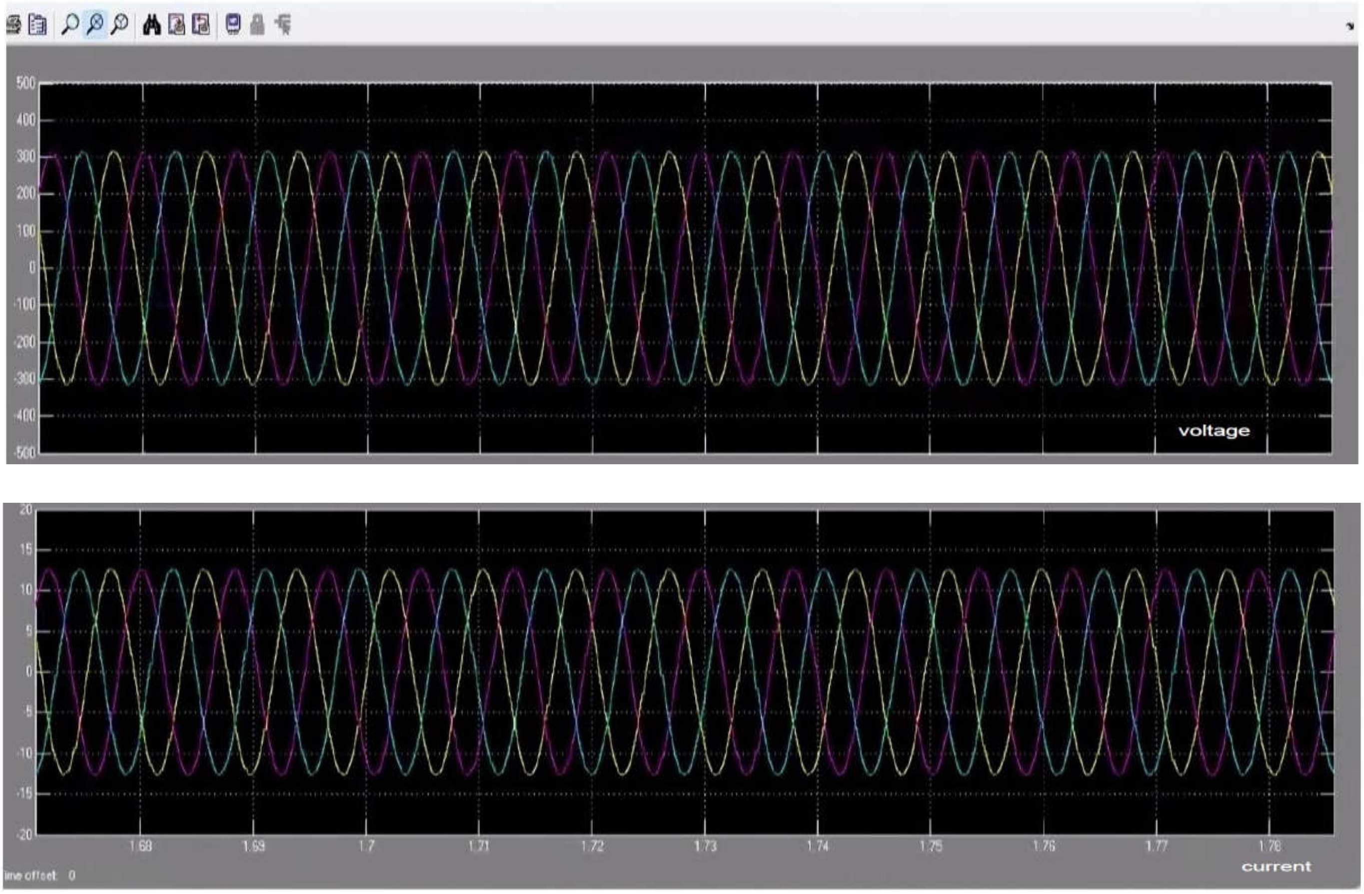


Fig.5 simulation graphs of voltage and current for dynamic stability on wind system(constant)

In the constant wind speed condition (set at 12 m/s), the wind energy system demonstrated stable dynamic behaviour, as evidenced by the smooth and consistent waveforms observed in the simulation. The voltage and current signals maintained steady sinusoidal shapes with minimal distortion or oscillation, indicating effective control and synchronization with the grid through the back-to-back voltage source converters. This stable response under constant wind input highlights the system's ability to maintain proper power delivery and voltage regulation without inducing instabilities in the electrical network. The absence of transients or harmonics further confirms that the control strategies—including MPPT and inverter control—are well-tuned for constant speed operation. Overall, the wind system operates reliably and efficiently under steady wind conditions, validating the design's robustness in terms of dynamic stability.

Simulation Results of Dynamic Stability on Wind System (Variable Speed):

The simulation results for dynamic load generation under variable speed conditions indicate a system with strong stability and effective transient response. In the upper graph, an initial transient spike is observed, which quickly settles to a steady-state value, demonstrating that the system can handle sudden changes and stabilize efficiently. This suggests that the dynamic control mechanisms in place are robust and capable of maintaining consistent performance despite variations.

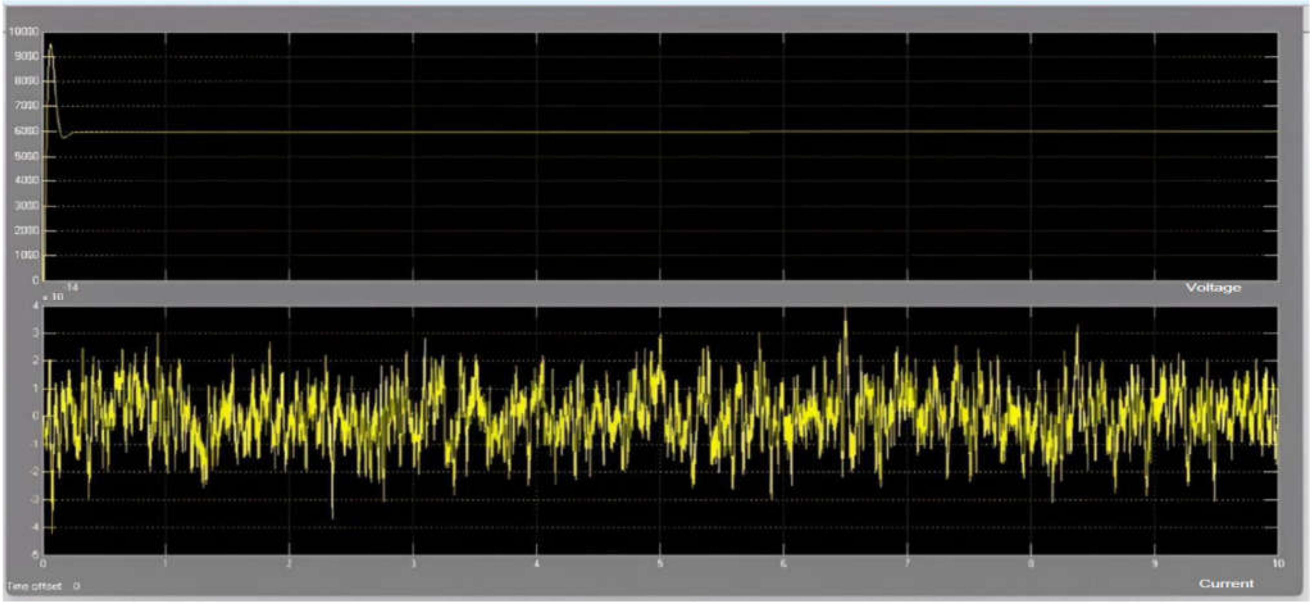


Fig.6 simulation graphs of voltage and current for dynamic stability on wind system(variable)

The lower graph shows significant high-frequency fluctuations, likely representing variable speed or stochastic load input. Despite this variability, the fluctuations remain within a bounded range, indicating that the system is resilient and capable of operating reliably under continuously changing conditions. Overall, the results confirm that the system performs well in dynamic environments, making it suitable for applications such as renewable energy systems or smart grid scenarios where load and speed can vary unpredictably.

Simulation Results of Dynamic Load Generation :

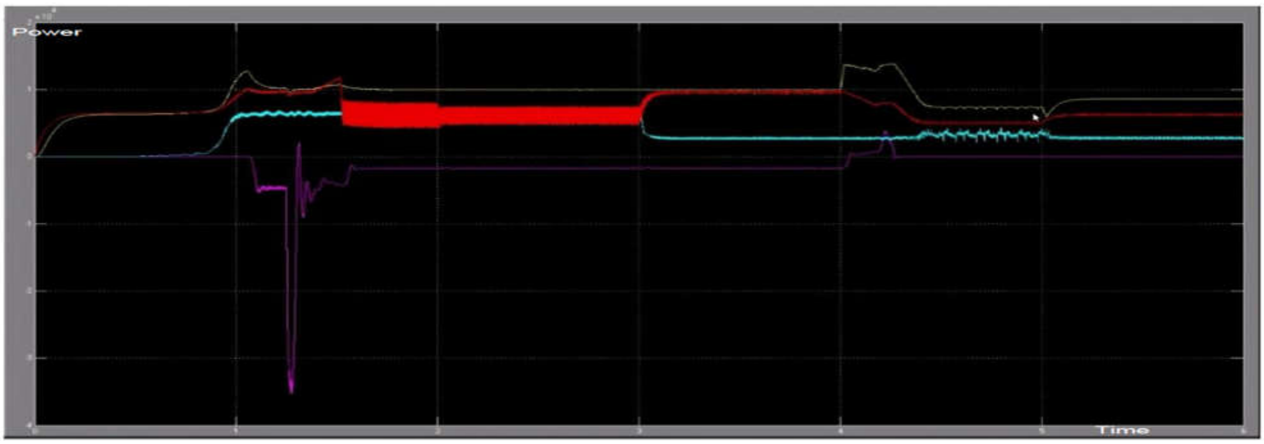


Fig.7 Simulation Results of Dynamic Load Generation

The graph illustrates the dynamic power behaviour of a hybrid energy system over time, with the x-axis representing time and the y-axis indicating power. The yellow line represents the load demand, which varies continuously, showing that the system is dealing with a dynamic and fluctuating load. The red line corresponds to solar power generation, which typically changes smoothly over time depending on sunlight availability. The blue line shows wind power generation, which is more irregular and fluctuates rapidly due to variable wind speeds. The purple line indicates the battery's charging and discharging activity—positive values represent charging when excess power is available, and negative values represent discharging when there is a shortfall in generation. Together, these plots demonstrate how the hybrid system balances power supply and demand in real time, with the battery playing a crucial role in maintaining system stability under varying load and generation conditions.

TABLE 2: RESULTS OF DYNAMIC LOAD GENERATION

Load(watts)	Wind Generation(watts)
100%(load)=14000w(1.3in graph)	5384w
50%(load)=7000w(1 in graph)	9800w
25%(load)=350w(0.5 in graph)	1400w

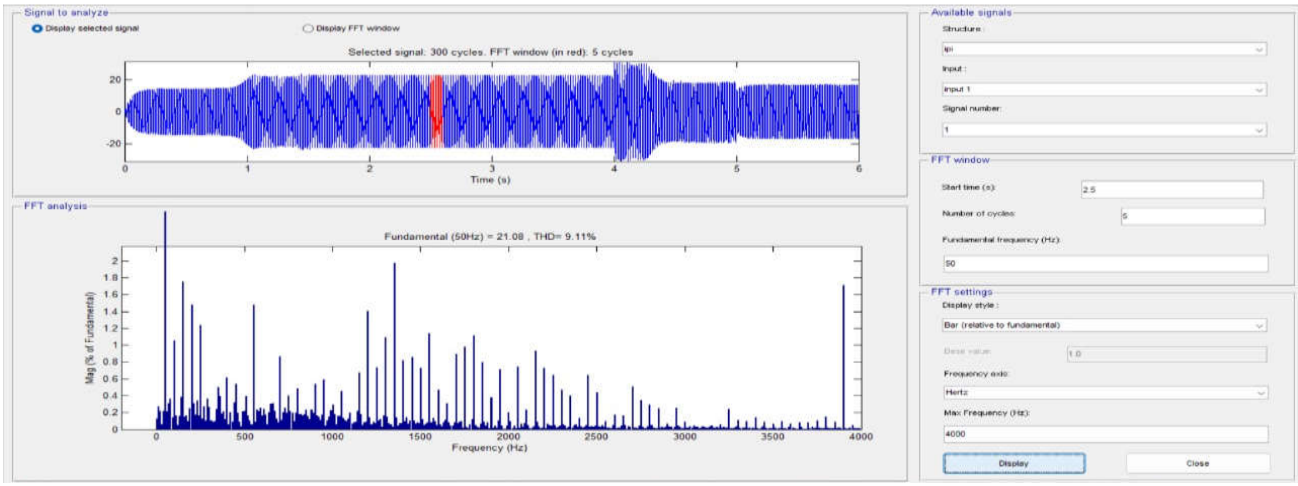
Case1: When the load demand is at 100% (14,000 W), the wind power generation is 5,385 W. In the corresponding graph, a load of 14,000 W is represented as 1.3 on the scale. At this point, the wind power generation is marked as 0.5. This indicates that when the load is scaled to 1.3, the wind generation output corresponds proportionally to 0.5 on the graph. The relationship between the load demand and wind generation is depicted through these scaled values for better visualization and comparative analysis.

Case2: When the load demand is at 50% (7000 W), the wind power generation is 9800 W. In the corresponding graph, a load of 7000 W is represented as 1.0 on the scale. At this point, the wind power generation is marked as 0.7. This indicates that when the load is scaled to 1.0, the wind generation output corresponds proportionally to 0.7 on the graph. The relationship between the load demand and wind generation is depicted through these scaled values for better visualization and comparative analysis.

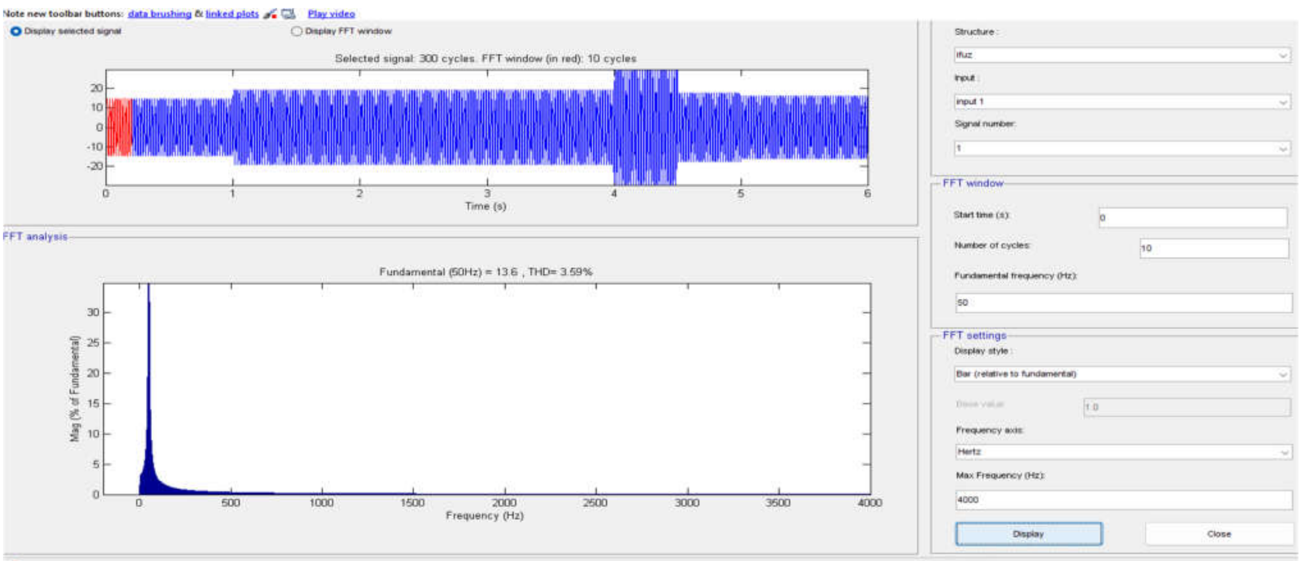
Case:3 When the load demand is at 25% (3500 W), the wind power generation is 1400 W. In the corresponding graph, a load of 3500 W is represented as 0.5 on the scale. At this point, the wind power generation is marked as 0.2. This indicates that when the load is scaled to 0.5, the wind generation output corresponds proportionally to 0.2on the graph. The relationship between the load demand and wind generation is depicted through these scaled values for better visualization and comparative analysis.

The results indicate a non-linear relationship between load demand and wind power generation across different operating conditions. At full load (14,000 W), wind generation is relatively low (5,384 W), covering only a portion of the demand. Interestingly, at 50% load (7,000 W), wind generation increases significantly to 9,800 W, exceeding the load and suggesting surplus power that could be stored or redirected. At 25% load (3,500 W), wind generation drops to 1,400 W, which is less than half of the demand. This variation shows that wind generation does not scale linearly with load demand; instead, it depends on external factors like wind availability. The scaled graph values help visualize and compare this mismatch, making it clear that system balance requires the integration of other sources or storage (like batteries) to maintain reliability across varying load levels.

Waveform of The Current Before Implementing the Fuzzy Controller:



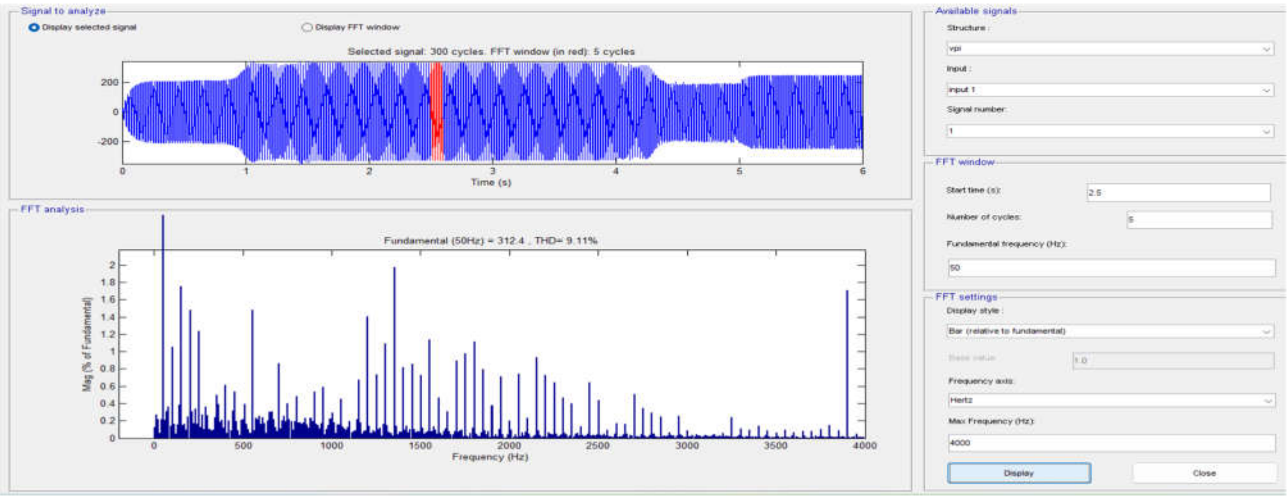
Waveform of the Current After Implementing the Fuzzy Controller:



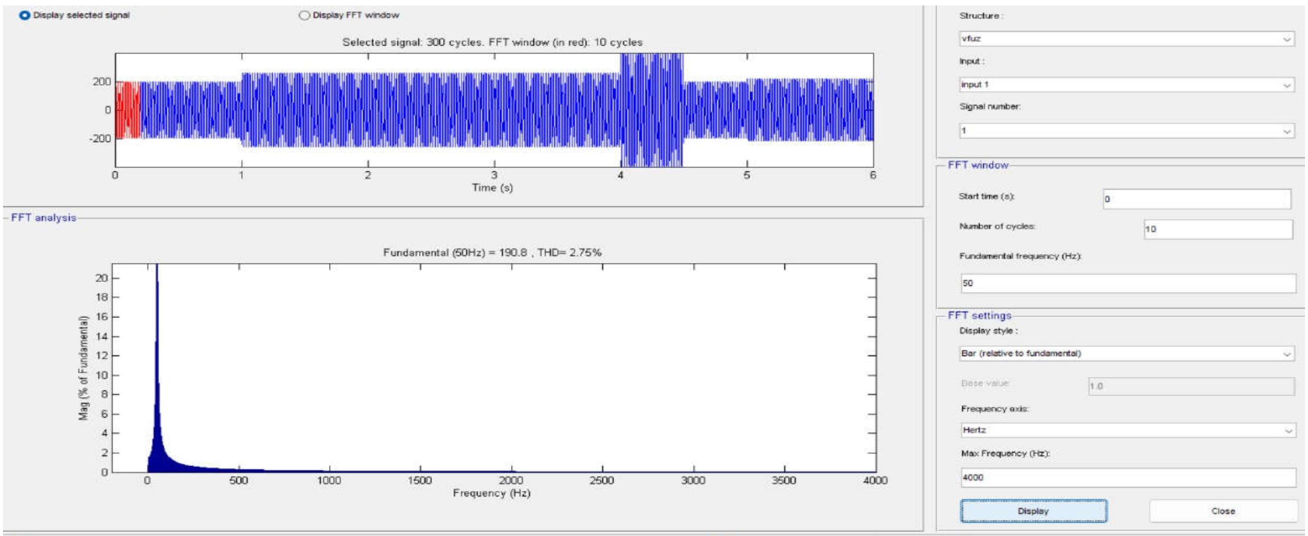
The analysis, a fuzzy logic controller was implemented to improve power quality by reducing Total Harmonic Distortion (THD) in the current waveform. The first image shows the waveform before applying the fuzzy logic controller, where the signal exhibits noticeable harmonic distortions with a Total Harmonic Distortion

(THD) of 9.11%. This high THD value indicates a significant presence of harmonic components beyond the fundamental frequency (50 Hz), which can negatively affect system performance and equipment lifespan.After implementing the fuzzy logic controller, as shown in the second image, the current waveform becomes more sinusoidal and stable, with a significantly reduced THD of 3.59%. The reduction in harmonics is clearly visible in the FFT (Fast Fourier Transform) spectrum, where the magnitudes of higher-frequency components have decreased considerably. This demonstrates the effectiveness of the fuzzy logic controller in filtering out unwanted harmonic content and improving the overall quality of the current signal. The result is a cleaner waveform, improved power efficiency, and reduced stress on electrical equipment.

Waveform of the Voltage Before Implementing the Fuzzy Controller:



Waveform of the Voltage After Implementing the Fuzzy Controller:



The project, focused on improving the quality of the voltage waveform by implementing a Fuzzy Logic Controller (FLC). Initially, the voltage waveform (as shown in the figure labeled vpi) exhibited significant distortion with a Total Harmonic Distortion (THD) of 9.11%. This high THD indicates the presence of substantial harmonic components, which can negatively impact sensitive equipment and overall power quality. The waveform was irregular, and the FFT analysis showed numerous frequency components beyond the fundamental 50 Hz, confirming poor waveform purity.

After introducing the FLC, the voltage waveform (shown in the figure labeled vfuz) became much cleaner and more sinusoidal. The THD was significantly reduced to 2.75%, demonstrating the effectiveness of the fuzzy control strategy. The controller dynamically adjusted the output of the power converter based on real-time error and change in error, following a rule-based decision-making approach without requiring an exact mathematical model. This led to a substantial suppression of higher-order harmonics, as evident in the FFT spectrum where the magnitude of non-fundamental components decreased sharply. Overall, the application of the FLC in Stage 2 resulted in a significant improvement in voltage waveform quality and a major reduction in harmonic distortion.

TABLE: RESULTS OF FUZZY LOZZY CONTROLLER:

PARAMETER	BEFORE FLC	AFTER FLC	IMPROVEMENT
Current THD	9.11%	3.59%	Reduced by ~60%
Voltage THD	9.11%	2.75%	Reduced by ~70%

V. CONCLUSION: In this paper the combination of the wind and solar systems using vector-controlled grid-connected BtB VSCs. The VSR at the wind generator side is responsible for extracting the maximum wind power following the wind velocity variations. On the utility-grid side, the roles of the VSI are to extract the maximum PV power from the PV generator, achieve the balance between the input and output powers across the dc-link capacitor, and to maintain a unity PCC voltage under different modes of operation. A small-signal linearization analysis has been conducted where the entire state-space model is developed to investigate the system stability. The proposed system features the following advantages; 1) the increased reliability and efficiency due to the combined wind and solar generators. 2) the independent MPPT extraction as the VSR and VSI are solely responsible for extracting the wind and PV powers, respectively. 3) the regulation of the dc-link voltage under all operating conditions is maintained by the VSI and hence a better damped performance is yielded. 4) Simple system structure and controllers design. 5) fault-ride through can be achieved using existing protection schemes. A well-damped performance and an efficient operation have been revealed from the time-domain simulations results under the Matlab /Simulink environment under different operational scenarios.Incorporating a Fuzzy Logic Controller (FLC) into the control strategy of back-to-back Voltage-Source Converters (VSCs) in a hybrid wind-solar power system significantly enhances its performance. The FLC effectively mitigates harmonic distortions and improves voltage and frequency regulation, ensuring a more stable grid connection. Simulation results demonstrate a substantial reduction in Total Harmonic Distortion (THD) and improved dynamic response under both steady-state and transient conditions.

REFERENCES:

1. Bubalo, M., Bašić, M., Vukadinović, D., & Grgić, I. (2023). *Hybrid Wind-Solar Power System with a Battery-Assisted Quasi-Z-Source Inverter: Optimal Power Generation by Deploying Minimum Sensors*. Energies, 16(3), 1488. https://doi.org/10.3390/en16031488

2. Harrabi, A., & Ben Hamed, M. (2018). *Intelligent Control of Grid-Connected AC–DC–AC Converters for a WECS Based on T–S Fuzzy Interconnected Systems Modelling*. IET Power Electronics, 11(5), 820–828. https://doi.org/10.1049/iet-pel.2017.0174

3. Sharma, S., Chauhan, B. K., & Saxena, N. K. (2023). *Grid Connected Fuzzy Logic Control-Based MPPT Techniques for Hybrid Photovoltaic Wind with Battery System*. International Journal of Power and Energy Conversion, 14(3), 280–309. https://doi.org/10.1504/IJPEC.2023.134873

4. Xu, D., & Cen, H. (2021). *A Hybrid Energy Storage Strategy Based on Multivariable Fuzzy Coordinated Control of Photovoltaic Grid-Connected Power Fluctuations*. IET Renewable Power Generation, 15(8), 1826–1835. https://doi.org/10.1049/rpg2.12152

5. Simhachalam, R., & Goswami, A. D. (2023). *Fuzzy Induced Controller for Optimal Power Quality Improvement with PVA Connected UPQC*. Energy Harvesting and Systems, 10(1), 1–12. https://doi.org/10.1515/ehs-2022-0146

6. Teekaraman, Y., Kuppusamy, R., Baghaee, H. R., Vukobratović, M., Balkić, Z., & Nikolovski, S. (2020). *Current Compensation in Grid-Connected VSCs Using Advanced Fuzzy Logic-Based Fluffy-Built SVPWM Switching*. Energies, 13(5), 1259. https://doi.org/10.3390/en13051259