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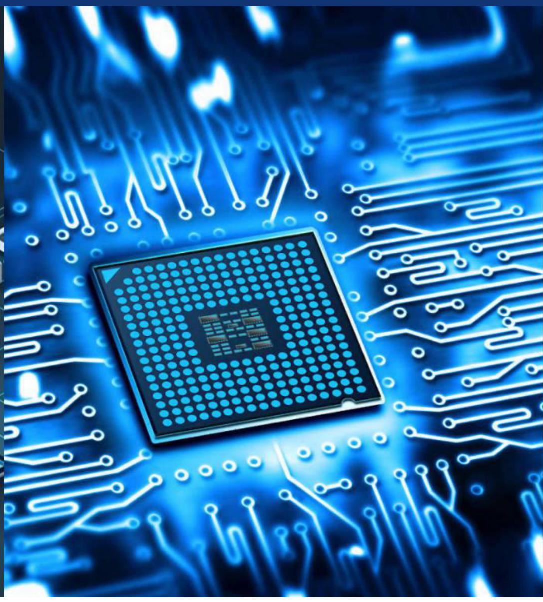


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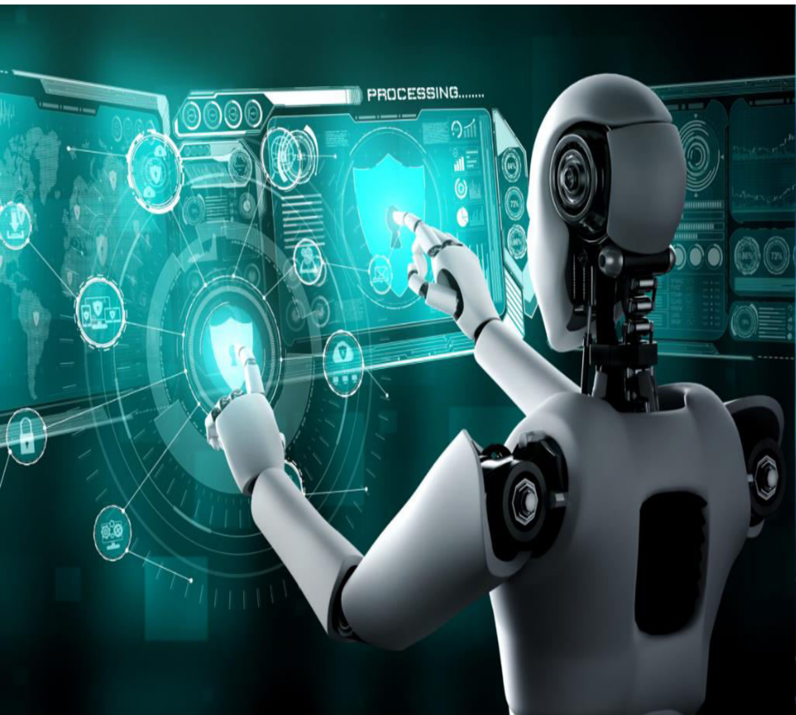

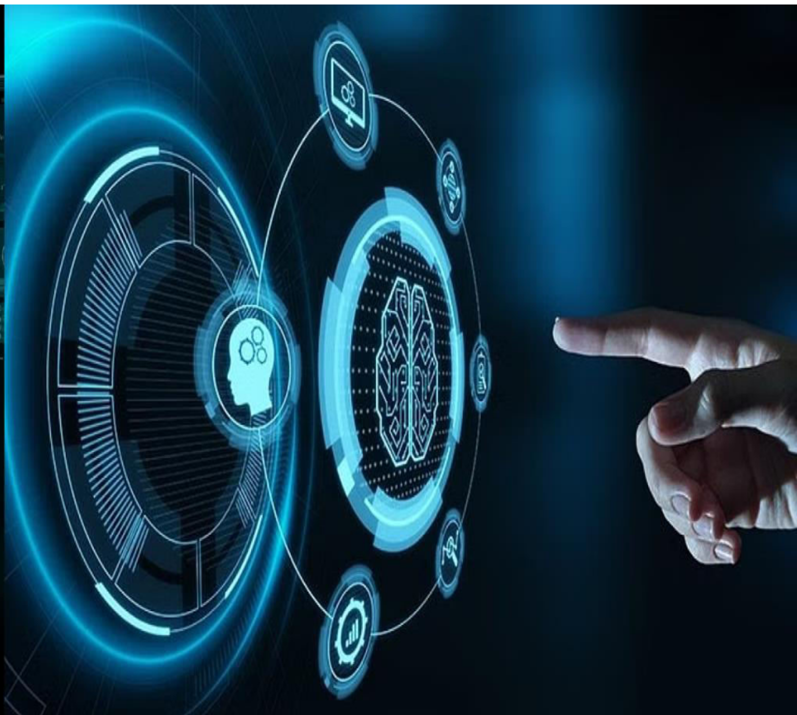

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Optimizing Wind Turbine and Standalone PV Integration in Micro grids Using Improved Droop Control Technique

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ABSTRACT: the majority of electric power networks now rely on hybrid renewable power production. The low-voltage direct current microgrid has arisen as a new trend and intelligent solution for the smooth integration of distributed energy resources and battery storage system. The unpredictable and stochastic volatility of wind energy, as well as the unexpected fluctuations in load demand, require the incorporation of both high-power and high-energy density storage devices in microgrids. This research investigates the use of a droop control approach in a wind-PV-based microgrid to provide stable and autonomous power sharing across distributed energy resources. The suggested system takes use of the complimentary characteristics of wind and solar energy, as well as battery storage, to assure consistent energy delivery under changing environmental and load situations. Droop control is used to adjust voltage and frequency in the microgrid, allowing for decentralized coordination without relying on sophisticated communication networks. It ensures that the control of all microgrid subsystems runs smoothly under a wide range of power production and load situations.

KEYWORDS: microgrids, wind turbines, batteries, energy management, PV, Droop control

I. INTRODUCTION

Energy consumption is expected to rise by 53% by 2035, fueling a steady growth in the use of renewable energy resources (RESs) during the last decade to address severe sustainability challenges, environmental concerns, and dependable energy difficulties [1]. The integration of photovoltaic (PV) and wind energy into hybrid microgrid systems is becoming more important in solving energy availability, sustainability, and grid resilience issues. These systems take use of the complimentary nature of solar and wind resources, resulting in a more constant and stable power supply. Economically, hybrid PV-wind microgrids provide considerable cost savings [2]. For example, a research on a university campus deployed a PV/wind/diesel generator/grid system without energy storage, reaching a cost of energy (COE) of $0.0172/kWh, a return on investment (ROI) of 8.8%, and a payback time of 7.64 years. This arrangement achieved 94.8% renewable energy penetration and lowered yearly CO_2 emissions to 7,460 kg [3]. The market patterns reflect this expanding relevance. The worldwide hybrid solar-wind systems market was valued at USD 1.26 billion in 2024, and it is expected to increase at a 7.8% CAGR from 2025 to 2030. This expansion is being driven by rising environmental concerns, technical improvements that reduce prices, and the desire for dependable power supplies in off-grid locations [4]. In India, co-locating wind and solar PV projects has been suggested as a technique for lowering transmission infrastructure costs and power production volatility. Studies indicate that hybrid plants may reach a lower levelized cost of electricity (LCOE) than stand-alone plants, particularly in places with complimentary wind and solar profiles [5].

The intermittent and unpredictable nature of renewable energy sources necessitates good management in PV-wind hybrid microgrids. Solar irradiance and wind speed vary during the day and seasons, resulting in variable power outputs that may jeopardize grid stability and electricity quality. To guarantee consistent and efficient functioning, sophisticated control techniques must be used to monitor energy flow, balance supply and demand, and keep voltage and frequency within acceptable ranges. In hybrid systems, where multiple distributed energy resources (DERs) are operating concurrently, control methods such as droop control, model predictive control (MPC), and adaptive control are critical in coordinating power sharing and enabling seamless transitions between grid-connected and islanded modes. Furthermore, energy storage systems must be intelligently controlled to reduce unpredictability and increase

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dependability. Without effective supervision, PV-wind microgrids run the danger of overloading components, frequent outages, and poor energy consumption. As a result, complex, real-time control mechanisms are required to realize hybrid microgrids' full promise in providing clean, decentralized, and steady electricity.

II. LITERATURE SURVEY

When it comes to ensuring a consistent, predictable, and effective power supply in the face of variable renewable energy sources, controlling strategies in hybrid microgrids that combine photovoltaic and wind power are very essential. In a general sense, these methods may be categorized as centralized, decentralized, and distributed control techniques. A single control unit is responsible for managing all of the components in a centralized management system. This allows for optimal coordination, but it also creates the risk of a single point of failure and requires a complex communication network. Through the use of decentralized control, such as droop control, individual generators are able to operate independently depending on local measurements. This results in increased reliability and scalability while also reducing the amount of transmission that is required. By enabling controllers to interact with one another and to make choices in a cooperative manner, distributed control incorporates the benefits of each of these approaches. There has also been a significant amount of research conducted on advanced control methods, such as Model Predictive Control (MPC), Fuzzy Logic Control, Sliding Mode Control (SMC), and AI-based control. The MPC algorithm is able to forecast the behavior of the system and maximize its performance over a certain time horizon. On the other hand, fuzzy logic and SMC are able to give resilience against uncertainties and nonlinearities in the system. Methods of artificial intelligence (AI), such as neural networks and machine learning algorithms, are increasingly being used in complex hybrid systems for the purposes of adaptive control, defect detection, and energy management.

We propose an energy management and control system for a laboratory-scale microgrid that makes use of hybrid energy resources such as wind, solar, and batteries. This system was developed by A. Merabet and colleagues [6]. Using voltage-source inverters, A. Khalil and colleagues [7] investigated the modeling and control of a photovoltaic (PV) and wind (Wind) microgrid. In order to construct the controller, the dq reference frame is used, and the Space Vector Pulse Width Modulation technique is utilized. The second inverter just contains a power control loop, but the first inverter has both an outer voltage control loop and an interior current control loop. Both of these loops are contained inside the inverter. A two-degree-of-freedom fractional order proportional integral derivative+proportional integral controller (2-DOF FOPID+PI) was developed by Patel et al. [8] for voltage-controlled loops. This controller was able to efficiently stabilize dc bus voltage and power flow in both grid-connected and islanded modes.

A study conducted by B. Papari and colleagues [9] investigates the growing significance of renewable energy and distributed generation, highlighting the relevance of implementing intelligent control systems in order to optimize the advantages and performance of networks.

The control tactics that are used on a PV-wind powered autonomous DC microgrid that is equipped with a hybrid storage system are taken into consideration by T. Thomas et al. [10]. An Enhanced Exponential Reaching Law (EERL)-based sliding mode control (SMC) is used in a wind energy system that is based on a Permanent Magnet Synchronous Generator (PMSG) in order to extract the highest amount of power possible.

In their study, Yizhen Wang and colleagues [11] evaluate the possibility of integrating wind turbines with microgrids in order to enhance the generation of electricity and its transfer to distribution networks. The focus is on doing a comprehensive study of the design of the microgrid that is linked to a wind turbine. This analysis should include the wind power producing system, the determination of variable-speed wind energy, the estimation of faults for stability analysis, and the control of the microgrid via fault detection. An example of a coordinated regulated power management strategy (PMS) for wind-solar powered systems is provided by P. Behera and colleagues [12]. A microgrid that operates at low voltage and is coupled with a hybrid energy storage system (HESS) that is actively created. In an effort to improve the reliability of microgrid systems, G. Wang [13] proposed the use of a photovoltaic hybrid power grid control system that makes use of renewable energy. P. Behera and colleagues [14] present a novel power distribution control system (PDCS) that is designed for a low-voltage direct current (LVDC) microgrid that is fueled by wind energy on a much smaller scale. Three innovative protection algorithms are presented by A. Adewole and colleagues [15] for active distribution networks that have a large penetration of inverter-based distributed energy resources (DERs). An adaptive differential protection algorithm, incremental transient energy-based directed protection, and rate-of-change current protection are some of the protection strategies that are included in this category. In a nutshell, the complexity of the system, the communication infrastructure, the cost, and the required level of performance and flexibility are the factors that define the optimal control technique for photovoltaic-wind microgrids

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respectively. In order to attain optimal performance throughout a wide range of operational conditions, modern hybrid microgrids often make use of a control structure that is layered or hierarchical. This structure integrates a number of different different techniques.

III. METHODOLOGY

The Droop Control Technique is a decentralized control approach often used in microgrids to govern power distribution across numerous distributed energy resources (DERs) such as photovoltaic (PV) systems, wind turbines, and battery storage units. Droop control, modeled after the behavior of traditional synchronous generators, adjusts an inverter's output frequency and voltage in response to variations in active and reactive power. Specifically, P-f droop regulates frequency based on active power production, whereas Q-V droop regulates voltage based on reactive power. This approach allows numerous inverters to share load without needing real-time communication, hence increasing system stability and scalability. Droop control is a reliable and easy approach for maintaining voltage and frequency stability in hybrid PV-wind systems with intermittent generation and fluctuating load demand. Although it may not offer ideal power sharing or dynamic response in severe situations, it is often used with secondary and tertiary control layers to increase accuracy and restore normal operating conditions. Overall, droop management is a fundamental strategy for self-contained operation and flexible renewable integration in current microgrids.

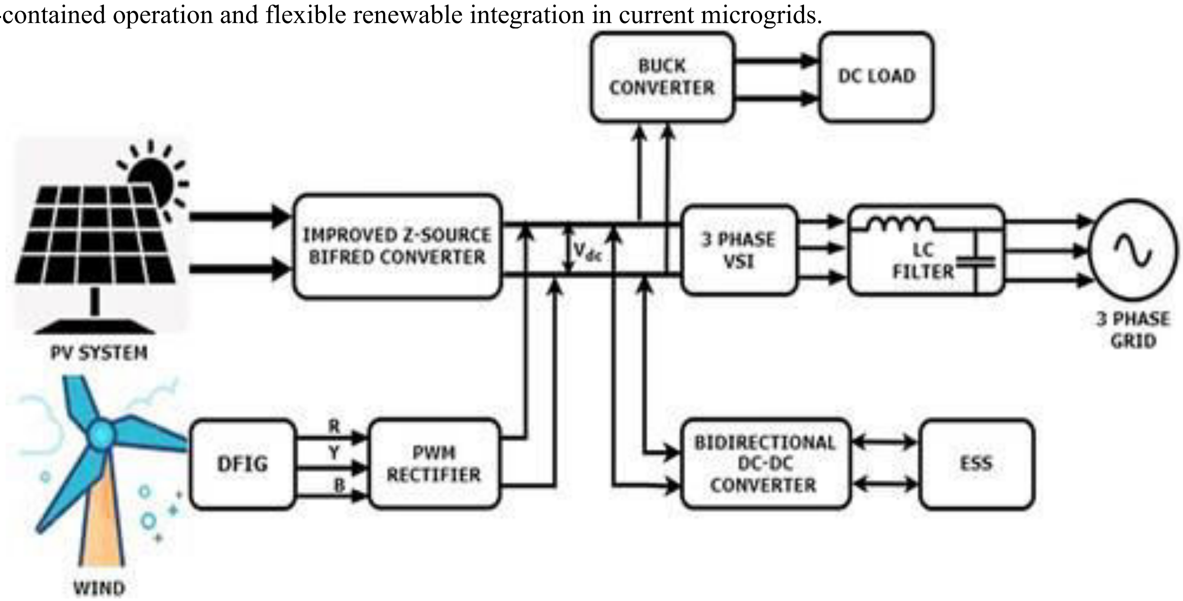

Fig 1: Proposed System Architecture

The figure 1 depicts a hybrid PV-wind microgrid system that includes an energy storage system (ESS) and is linked to both DC and AC loads, as well as the 3-phase utility grid. The PV system delivers electricity to an Improved Z-Source Bidirectional Converter, which improves voltage flexibility and supports both step-up and step-down functions. The wind turbine converts AC to DC using a Doubly Fed Induction Generator (DFIG) coupled to a PWM rectifier. The total DC connection from both sources is connected to a 3-phase Voltage Source Inverter (VSI), which transforms DC power into AC for grid supply after passing through an LC filter to smooth the voltage and current waveforms. A buck converter separates from the PV converter to serve DC loads directly. Meanwhile, a Bidirectional DC-DC Converter links the DC connection to an Energy Storage System (ESS), enabling charging and discharging depending on excess generation or demand. This adaptable bidirectional flow guarantees load balancing, voltage management, and dependability in the face of changing renewable inputs or grid outages.

This arrangement allows for multi-directional power flow, allowing for effective integration of renewable sources, load management, and grid support, all while ensuring system stability using sophisticated power electronics and control tactics such as droop control, MPPT, and ESS management. In inverter-based distributed generating systems, the droop

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control approach emulates the behavior of synchronous generators by using linear relationships between frequency (or voltage) and power output. The following are the basic design equations for active and reactive power droop control.

a) Active Power–Frequency (P–f) Droop Control
This determines the frequency depending on the active power output of the inverter.

$$f = f_0 - K_p(P - P_0) \qquad (1)$$

f: Output frequency of the inverter (Hz)
f_0 : Nominal system frequency (e.g., 50 or 60 Hz)
P : Measured active power output
P_0 : Reference active power (usually set to 0 or nominal value)
K_p : Active power droop coefficient (Hz/W or Hz/kW)

b) Reactive Power–Voltage (Q–V) Droop Control:
This determines the voltage magnitude depending on the reactive power output.

$$V = V_0 - K_q(Q - Q_0) \qquad (2)$$

V : Output voltage magnitude of the inverter (V)
V_0 : Nominal voltage (e.g., 400 V, 230 V, etc.)
Q : Measured reactive power output
Q_0 : Reference reactive power
K_q : Reactive power droop coefficient (V/VAR or V/kVAR)

The values of K_p *and* K_q are designed based on the allowable frequency and voltage deviations for a given power range.
The frequency can vary ±0.5 Hz for a 100 kW power variation:

$$K_p = \frac{0.5}{100} = 0.005\ Hz/kW \qquad (3)$$

In practice, low-pass filters are used to smooth power measurements:

$$P_{avg}(s) = \frac{1}{1+sT}P(s) \qquad (4)$$

where T is the filter time constant.
Secondary control is often added to restore frequency and voltage to nominal values over time.

IV. EXPERIMENTAL RESULTS

Proposed system is design and simulated in MATLAB & Simulink.

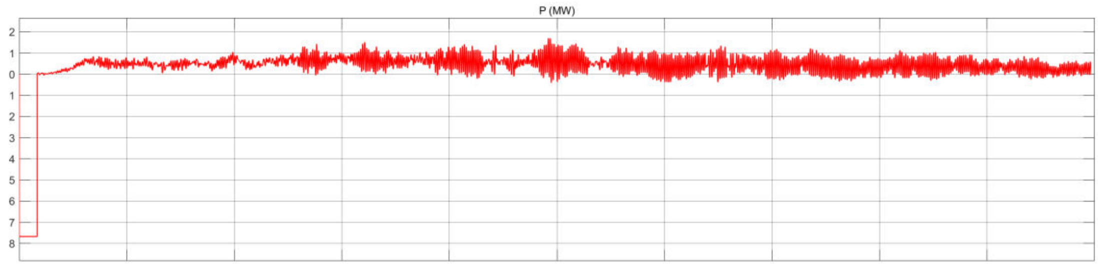

Fig 2: Active Power (P in MW)

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This graphic depicts the wind turbine's actual power production over time, measured in megawatts (MW). The power swiftly increases from 0 to roughly 1 MW at the start (during the first 0.05 units of time). Then it stabilizes with slight oscillations of 1-1.5 MW throughout the remainder of the simulation. This is normal wind turbine behavior; once wind conditions are suitable, it accelerates and begins producing electricity. P fluctuations are caused by variations in wind speed, changes in turbine blade angle, or generator control operations.

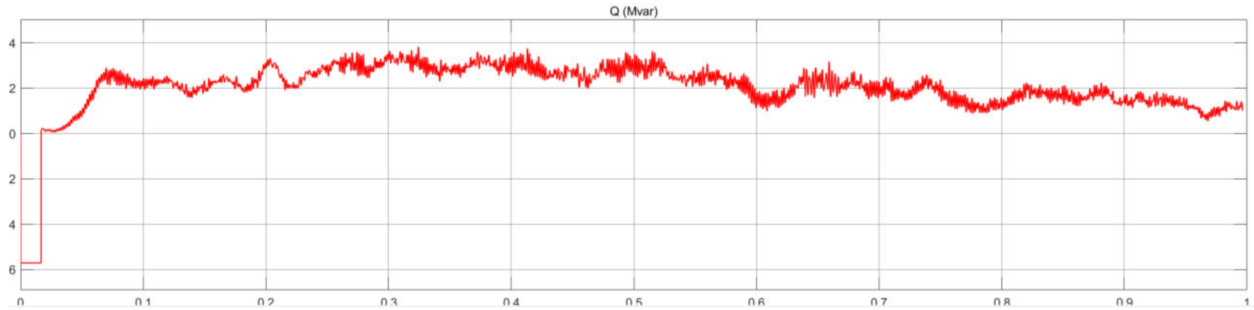

Fig 2: Reactive Power (Q in Mvar)

This graph depicts reactive power, measured in megavolt-amperes reactive (Mvar), which is required for voltage control. Q begins at zero, then rises to around 2.5 to 3 Mvar, fluctuates, and then gradually drops over time, with minor oscillations. Wind turbines equipped with power electronic converters (DFIG or complete converter types) may inject or absorb reactive power to help maintain grid voltage levels. The first spike in Q might be caused by the system attempting to stabilize voltage at startup. The progressive drop might be attributed to controller modifications or changing grid/load circumstances.

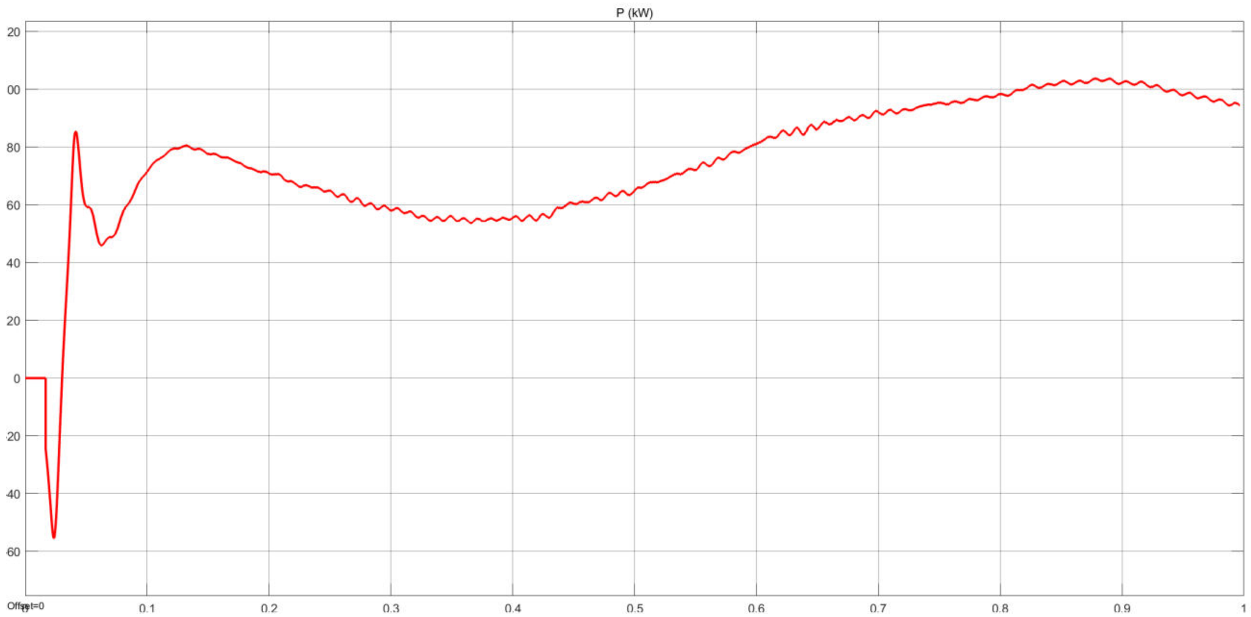

Fig 4: active power (P in kW) across a load in a hybrid microgrid system

This graph depicts the active power (P in kW) across a load in a hybrid microgrid system over time, demonstrating the dynamic behavior of power sharing across diverse sources such as PV, wind, and perhaps battery storage. In a hybrid microgrid system, active power provided to the load is an important characteristic that indicates the coordinated functioning of numerous distributed energy resources (DERs). The graph below shows how the power throughout the load reacts dynamically during a 1-second period. Initially, there is a strong transient — a spike followed by a drop — which is most likely the system's reaction to a quick load connection or source synchronization event. Following this initial oscillation, the power stabilizes at roughly 70 kW, with obvious oscillations caused by source variability such as changes in solar irradiation or wind speed dynamics. Around 0.5 seconds, a continuous rise in power is noticed, which might indicate higher output from PV or wind sources, or the discharge of energy storage to meet growing load demand. By 0.9 seconds, the power has risen to about 90 kW, indicating that the hybrid sources are working together well. The smooth climb and controlled oscillations suggest successful load management and power sharing, which is often achieved by droop control or other hierarchical control systems. This behavior highlights the hybrid microgrid's capacity to offer reliable electricity under a variety of generating and load scenarios.

V. CONCLUSION

Direct current microgrids are a new trend and a clever option for smoothly combining renewable energy sources (RES) and energy storage systems (ESS) to promote a sustainable energy ecology. The control algorithms are designed to ensure power compatibility and energy management across the microgrid's various resources. Simulation findings demonstrate the control scheme's efficacy in balancing power flow, ensuring voltage and frequency stability, and improving the microgrid's overall resilience. This research shows that droop-controlled wind-PV microgrids are a flexible and effective way to achieve energy sustainability in both grid-connected and islanded modes of operation.

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