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Enhancing Microgrid Performance of Fuzzy MPPT-Controlled Energy Management for Small-Scale Hybrid Wind-Solar-Battery System

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ABSTRACT: This paper presents for "Enhancing Microgrid Performance of Fuzzy MPPT-Controlled Energy Management for Small-Scale Hybrid Wind-Solar-Battery Systems" is as follows: In the rapidly evolving landscape of renewable energy sources and micro grid technologies, the integration of hybrid wind, solar, and battery systems holds immense potential for sustainable and reliable power generation. This research presents an innovative approach to optimize the energy management of small-scale micro grids by incorporating a Fuzzy Maximum Power Point Tracking (MPPT) control strategy. The proposed system aims to efficiently harness the available renewable resources by dynamically adjusting the power generation from wind turbines and solar panels, while effectively managing energy storage in batteries. The Fuzzy MPPT algorithm, with its adaptability and robustness, proves to be a valuable tool for tracking the maximum power points under varying environmental conditions. By uing mat lab Simulink software 2018a

Key words : Energy management system, hybrid system, microgrid, solar energy, standalone system, wind energy fuzzy mppt controller

I. INTRODUCTION

Global efforts have been made to promote self-sufficient renewable energy systems, leading to the development of power generating systems that combine multiple renewable energy sources for self-sufficient power generation [1], [2]. Among these, hybrid systems utilizing solar and wind energy are the most common [3], [4]. Since both solar and wind energy are intermittent, energy storage systems (ESS) are typically used in stand-alone applications [5], [6]. Various control techniques are employed in hybrid renewable energy systems to ensure efficient power transfer. The design of these systems requires careful consideration of the energy conversion methods and the types of converters used at different points, prompting significant research in this field [7] [9]. One study simulated a hybrid energy system to analyse performance under different practical load demands and weather conditions [10]. Another discussed the simulation of coordinated control for microgrid energy management in both standalone and grid-connected modes [11]. A hybrid wind-solar-battery ESS system was simulated to test state of charge (SOC) control [12]. Additionally, a scaled hardware prototype with a battery SOC control scheme was developed to enhance DC grid voltage control in a stand-alone DC microgrid [13], and a low-cost hybrid stand-alone power generation system prototype was created [14]. the goal of this research is to design and develop a small-scale microgrid based on wind, solar, and battery renewable energy sources. An energy management system is proposed to maintain power balance in the microgrid, offering configurable and flexible control for varying load demands and renewable energy source variations. The proposed system can be tested in real-time using rapid control prototyping, which allows for the validation of control algorithms and the development of efficient renewable energy management systems. the paper is structured as follows: Section II details the complete system design, converter topologies, and control techniques. Section III covers the hardware setup and rapid control prototyping. Section IV discusses experiments on the microgrid and presents various results. The paper concludes with discussions and conclusions in Section V.

II. Literature Review:

X. Song, Y. Zhao, J. Zhou, and Z. Weng highlight the critical importance of reliability in microgrids (MGs), particularly those based on photovoltaics (PV) and energy storage systems (ESS). Their study models the microturbine (MT), PV, ESS, and comprehensive load (CL) — which consists of hourly time-varying, stochastic, and controllable components. These are combined with a load shedding minimization model and a sequential Monte Carlo (SMC) simulation algorithm to develop a reliability assessment framework, which is then applied to comprehensive case studies.Firstly, they examine the variability of reliability indices, such as loss of load probability (LOLP), average service availability index (ASAI), system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI), and customer average interruption duration index (CAIDI), in relation to PV penetration. They particularly focus on and study the surge effect of SAIFI (SE-SAIFI) and propose a principle for PV capacity decision-making based on SE-SAIFI. Secondly, they analyze the reliability profiles associated with different ESS sizes, introducing a novel method for determining reasonable ESS sizes based on the concept of expected hourly redundant power (EHRP). Lastly, they calculate reliability indices for multiple scenarios with varying percentages of controllable load and analyze the benefits of load management from the perspective of standalone MG reliability. The results from these case studies underscore the necessity of reliability assessment in MG planning and size optimization, confirming the validity of the developed methodologies.

A. Jamali, N. M. Nor, and T. Ibrahim, propose that the growing integration of renewable energy sources into electrical grids necessitates the use of energy storage systems (ESS) to manage the fluctuations of intermittent power outputs. These technologies aid in balancing generation and demand by storing excess electricity and supplying it back to the grid as needed. In future grids, ESS is anticipated to become a primary source of electricity, complementing distributed generation (DG) resources. Their research aims to review various ESS and their sizing techniques within power systems, focusing on Mechanical Energy Storage (MES), Electric and Magnetic Energy Storage (EMES), and Electro-Chemical Energy Storage (ECES) systems. The review reveals that most research on energy storage sizing for large photovoltaic (PV) plants employs techniques similar to those used for standalone PV systems. Additionally, some energy models proposed by authors consider only daily or yearly energy demand without accounting for specific network constraints. Estimating energy storage capacity without considering these constraints can jeopardize future energy balance predictions, potentially leading to significant financial losses due to improper storage sizing. Consequently, the authors recommend that current energy models for ESS sizing be reconsidered and redesigned to incorporate network constraints accurately.

Q. Jiang, M. Xue, and G. Geng, are proposed to There are two operation modes of microgrids: grid-connected mode and stand-alone mode. Normally, a microgrid will be connected to the main grid for the majority of time, i.e., operates in the grid-connected mode. In the stand-alone mode, a microgrid is isolated from the main grid; the highest priority for microgrids is to keep a reliable power supply to customers instead of economic benefits. So, the objectives and energy management strategies are different in two modes. In this paper, a novel double-layer coordinated control approach for microgrid energy management is proposed, which consists of two layers: the schedule layer and the dispatch layer. The schedule layer obtains an economic operation scheme based on forecasting data, while the dispatch layer provides power of controllable units based on real-time data. Errors between the forecasting and real-time data are resolved through coordination control of the two layers by reserving adequate active power in the schedule layer, then allocating that reserve in the dispatch layer to deal with the indeterminacy of uncontrollable units. A typical-structure microgrid is studied as an example, and simulation results are presented to demonstrate the performance of the proposed double-layer coordination control method in both grid-connected mode and stand-alone mode.

X. Li, D. Hui, and X. Lai, propose that the battery energy storage system (BESS) is a key solution for smoothing the intermittent power generation from wind and solar sources. BESS hybrid power systems require effective control strategies to regulate power output levels and manage the battery state of charge (SOC). This paper presents a simulation analysis of a wind/PV/BESS hybrid power system aimed at enhancing the smoothing performance of wind and photovoltaic (PV) power generation, as well as improving battery SOC control. The authors introduce a wavelet-based power smoothing method designed to reduce power output fluctuations in wind/PV hybrid power systems and to regulate the battery SOC. The effectiveness of this proposed method was validated through simulations using MATLAB/SIMULINK software.

N. P. Subramaniam, D. Divyalakshmi, and C. Kalaivani, suggest building a small, independent hybrid power plant that uses solar and wind energy. This system is intended to be installed beside national highways, where ambient solar energy can be harvested and wind energy can be produced by fast-moving vehicles. In order to cover the electrical needs of rural and residential areas, batteries are charged using a combination of solar and wind energy. A DC generator and power supply line are also incorporated into the system to provide the highest level of continuous power supply for factories and businesses. When the wind-solar system is unable to meet the demand, these other systems come online in priority order. This hybrid system's adaptability is one of its main advantages,

III. SYSTEM DESCRIPTION (PROPOSED METHOD)

The proposed system, depicted in Fig. 1, is divided into three main components:

1. **Renewable Energy Sources and Battery Storage**: This part includes solar and wind-based renewable energy sources supported by a battery storage system. These sources, along with their converters, are connected to a DC bus. The wind energy conversion system utilizes a permanent magnet synchronous generator (PMSG) based wind

turbine. The solar photovoltaic (PV) panel operates with maximum power point tracking (MPPT). When the combined power generated by the PV and wind sources is less than the load demand, the MPPT ensures optimal power generation. When the power generated exceeds the demand, the excess power charges the battery. If the battery reaches its safe charging limit, the MPPT is turned off.

2. **Load Side Inverter and Single-Phase Load**: This part includes an inverter that converts DC power to AC to supply a single-phase load.
3. **Real-Time Controller**: This component implements the energy management system, which controls the power flow under various conditions to ensure a stable supply to the load through the single-phase inverter. The battery storage system maintains energy balance within the system.

The overall system is designed to efficiently manage power generation, storage, and distribution, ensuring continuous and reliable power supply.

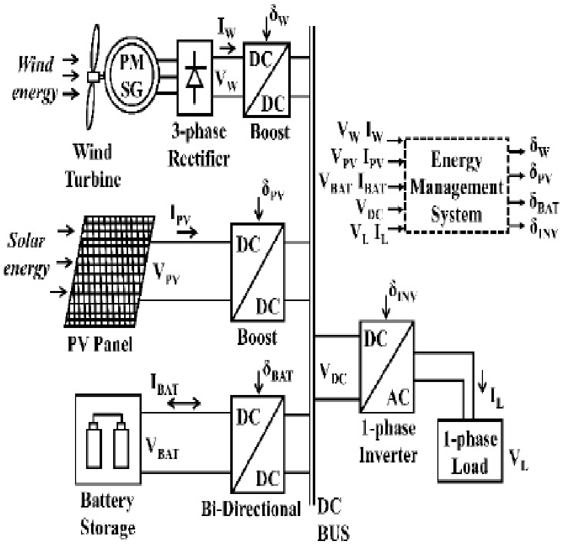


FIGURE 1. Components of small-scale wind-solar-battery microgrid with EMS.

A. SOLAR ENERGY CONVERSION SYSTEM (SECS):

The Solar Energy Conversion System (SECS) comprises a solar photovoltaic (PV) panel, a DC-DC boost converter, and a maximum power point tracking (MPPT) controller, as illustrated in Fig. 2. The operation of the MPPT depends on the state of charge of the battery storage system, functioning either in MPPT mode or off-MPPT mode. The power-voltage (P-V) characteristics of the solar panel under different levels of irradiance are depicted in Fig. 3. These characteristics are shown for irradiance values ranging from 400 W/m² to 1200 W/m² at a constant temperature of 25°C. At an irradiance of 1000 W/m², the power reaches its maximum of 66 Wp at 17.6 V. The power (P) at the PV panel is given by the product of the voltage (V) across the terminals of the PV panel and the current (I) through it:

P=V×IP = V \times IP=V×IThe flow chart of the MPPT algorithm is illustrated in Fig. 4, showing the process of tracking the maximum power point to optimize the power output from the solar PV panel.

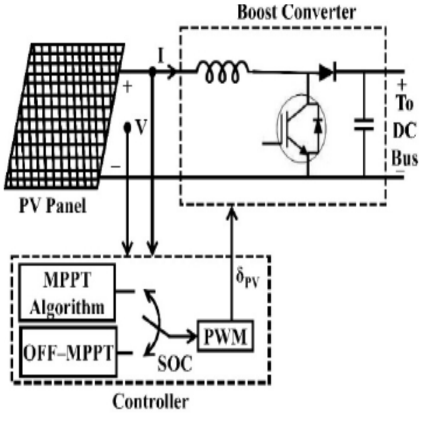


FIGURE 2. Solar energy conversion system with controller.

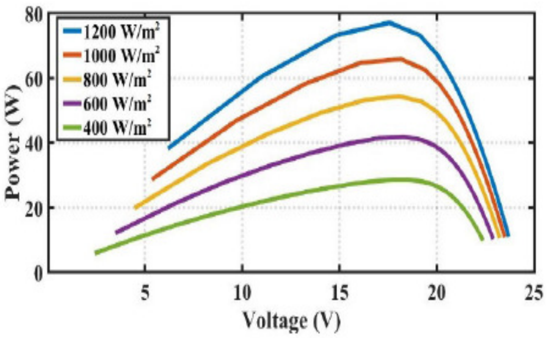


FIGURE 3. Effect of irradiance on PV array performance at T D 25 ^{0}C.

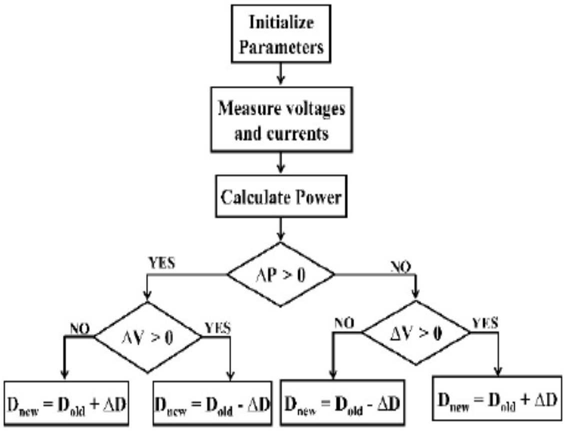


FIGURE 4. MPPT algorithm flow chart.

The MPPT algorithm in the PV system ensures that the PV panel voltage remains close to the maximum power point (MPP) voltage. The Perturb and Observe (P&O) method is employed for this purpose. Here's how it works:

1. **Perturbation and Calculation**: Initially, the voltage (V) of the PV panel is perturbed, and the corresponding output power (P) is calculated.
2. **Decision Making**:
   - If the power (P) increases as a result of the voltage perturbation, the voltage is further increased in the next step.
   - If the power (P) decreases, the voltage is decreased.

The required change in the duty cycle (ΔD) is calculated based on the changes in power (ΔP) and voltage (ΔV). The flow of the P&O method can be summarized as:

1. Measure the current voltage (V) and power (P) of the PV panel.
2. Perturb the voltage slightly (increase or decrease).
3. Measure the new power (P') after the voltage perturbation.
4. Compare the new power (P') with the previous power (P):
   - If P′>PP' > PP′>P, the perturbation is in the correct direction, so continue perturbing the voltage in the same direction.
   - If P′<PP' < PP′<P, the perturbation is in the wrong direction, so reverse the direction of perturbation.
5. Repeat the process to continuously track the MPP.
6. This iterative process helps in keeping the PV panel operating close to its MPP, thus optimizing the power output. The P&O method is simple and widely used due to its ease of implementation.

B. WIND ENERGY CONVERSION SYSTEM (WECS)

The WECS consists of a wind turbine, a PMSG, a DC-DC boost converter and controller. The power extracted from the wind is [15]

$$P_w = \frac{1}{2}\rho A v^3 C_p(\lambda, \theta) \tag{2}$$

where ρ is the air density in kg/m3, A is the area swept by the rotor blades in m^2, and v is the wind velocity in m/s. Cp is the power coefficient and is a function of tip speed ratio (TSR, λ) and pitch angle (θ).

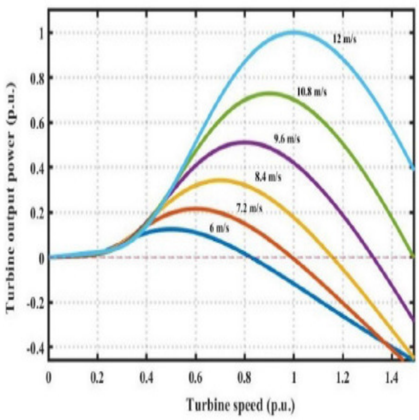


FIGURE 5. Mechanical characteristics of wind turbine for different wind speeds.

A variable speed wind turbine is used in this system. The characteristics of the wind turbine is shown in Fig. 5; the Cp for various wind speeds at different pitch angles. A permanent magnet synchronous generator is selected for its low maintenance and low operational cost. The generator output is dependent on the wind speed. The three-phase output of the generator is rectified using a diode rectifier and then the voltage level is increased with the help of a DC-DC boost converter as shown in Fig. 6.

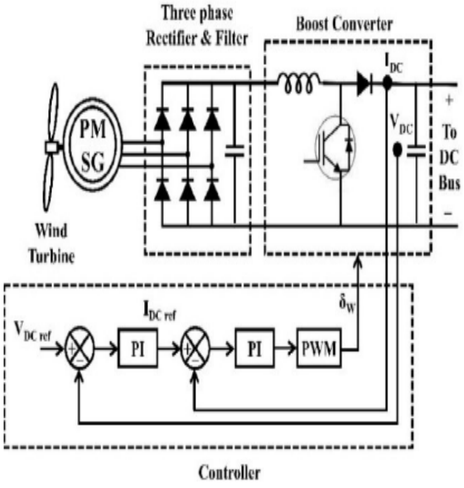


FIGURE 6. Wind energy conversion system with controller.

C. BATTERY STORAGE SYSTEM (BSS) The Battery Storage System (BSS) consists of a lead-acid battery and a bidirectional DC-DC buck-boost converter. This converter maintains the DC bus voltage through a Proportional-Integral (PI) controller, as illustrated in Fig. 7.

The state of charge (SOC) of the battery is a crucial parameter and is given by:

$$SOC_{min} \leq SOC \leq SOC_{max} \qquad (4)$$

The battery operates in two modes: charging and discharging. The mode of operation depends on the power generated by both solar and wind sources. The battery also operates based on energy constraints determined by the SOC limits. When the generated power exceeds the demand, the battery charges, and when the generated power is insufficient, the battery discharges to supply the required power.

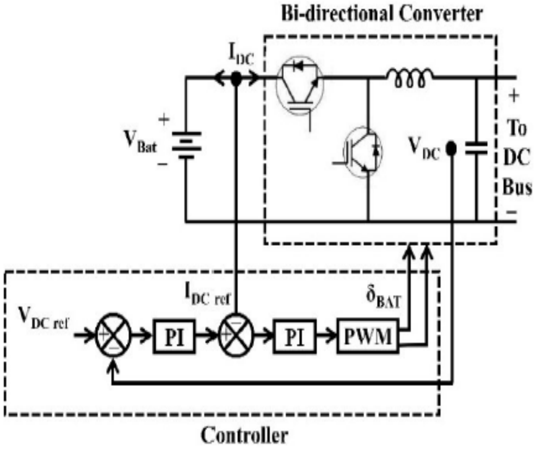


FIGURE 7. Battery energy storage system with controller.

D. LOAD SIDE CONTROL

In the DC microgrid system connected to a single-phase resistive load through a single-phase inverter, the control architecture is illustrated in Fig. 8. Here's how it operates:

1. **Single-Phase Inverter**: Converts DC power from the microgrid to

AC power suitable for the single-phase resistive load.

2. **Controller Architecture**:
    - **Outer Loop PI Controller**: This controller regulates the output voltage of the inverter. It compares the reference voltage with the actual measured voltage at the inverter output and adjusts the inverter's duty cycle to maintain the desired voltage level.
    - **Inner Loop PI Controller**: This controller regulates the output current of the inverter. It compares the reference current with the actual measured current flowing into the resistive load. Based on this error signal, it adjusts the inverter's switching frequency or duty cycle to control the current output accurately.
3. **R-L Filter**: Installed at the output of the inverter, this filter is designed to reduce and smooth out any undesired harmonic content present in the AC waveform. It typically consists of a resistor (R) and an inductor (L) to attenuate high-frequency components.

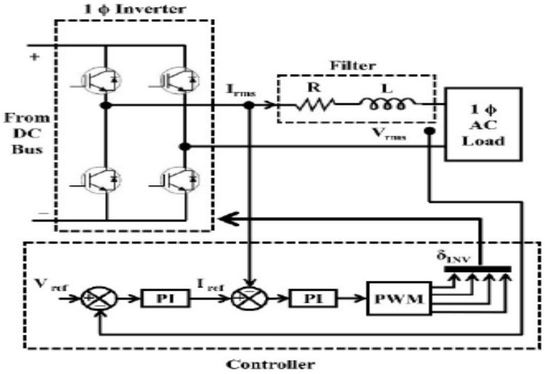


FIGURE 8. Single phase inverter with filter for AC load control.

E. ENERGY MANAGEMENT SYSTEM (EMS)

The microgrid system's main controller, the EMS, is in charge of coordinating and managing all control actions. The EMS control mode is the foundation for how all of the converter controllers in the earlier sections function. Depending on the amount of power generated, the solar energy conversion system's boost converter runs in either MPPT mode or off-MPPT mode.

While the DC-DC boost converter of the wind energy conversion system runs in boost mode, the battery bidirectional converter runs in charging or discharging mode and keeps the DC bus voltage constant. Under various load demand scenarios and power output from renewable energy sources, the microgrid's power must be balanced. Here is the equation for the power balance conditions. The power balance equation is given as follows.

$$P_{w} + P_{pv} = P_{L} + P_{bat} \tag{5}$$

The various modes of operation of the energy management system are presented in the flowchart in Fig. 9.

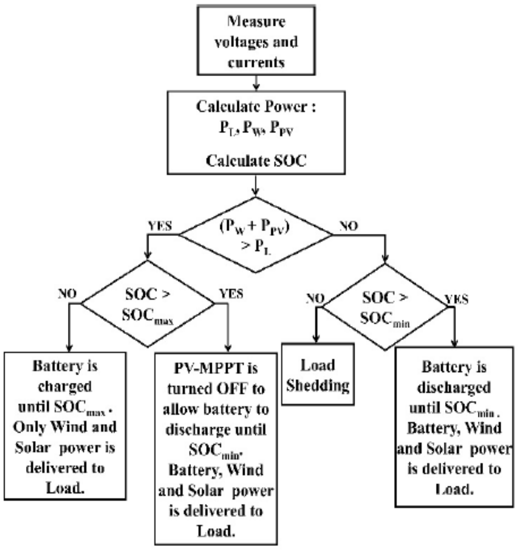


FIGURE 9. Energy management system.

The energy management system can function in four different ways. Every operating mode is contingent upon two factors: the first is the creation of power, and the second is the battery's level of charge. When the electricity generated by the SECS and WECS exceeds the load demand, this is the desired mode of operation. The battery is charged to its SOCmax during this operation. If the battery's SOC reaches SOCmax, the MPPT controller is turned to off-mode, which lowers the amount of solar power generated because the total power generated exceeds the demand, the excess power generated cannot be used to charge the battery, and the battery now supplies any additional power needed at the load.

SOFTWARE REQUIREMENTS

Software Configuration:

Operating System : Windows 7/8/10
Application Software: Matlab/Simulink

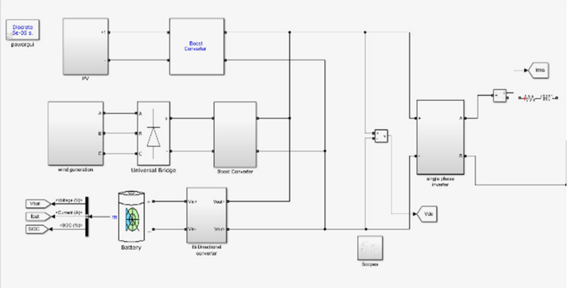
Hardware Configuration:

RAM : 8 GB / 4 GB (Min)
Processor : I3 / I5 (Mostly prefer)

SIMULATION RESULTS:

The microgrid for hybrid renewable energy was used to test two case scenarios. The solar and wind energy were changed while the first scenario was performed under a constant load state. Variations in load demand with consistent renewable energy sources were used in the second example. The simulation results for the two scenarios have a runtime of the 70s.

Simulation Block Diagram:



A. VARIATIONS IN RENEWABLE ENERGY SOURCES WITH A CONSTANT LOAD

Providing a steady power supply to the load under various generating conditions is the aim of the first scenario. By turning the lights on and off, you may change the solar irradiance and provide varying levels of light. Altering the fan blower's speed allows you to change the wind speed. Figure 12 illustrates how the irradiance was varied by 1000W/m2, 800W/m2, 400W/m2, and 600W/m2 at the start, 20s, 30s, and 50s, respectively, and how the wind speed was varied by 12M/s, 8M/s, 11M/s, 7M/s, and 11M/s at the start, 10s, 20s, 40s, and 60s, respectively. Although the differences in sun irradiance and wind speed are merely small fluctuations, real-world weather conditions are constantly changing, thus these variances cannot occur.

SIMULATION RESULTS:

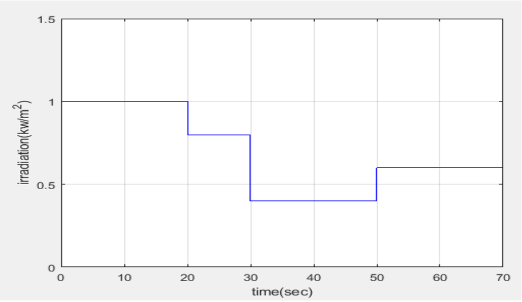


FIG 1: Solar irradiance(kw/m$^{2)}$

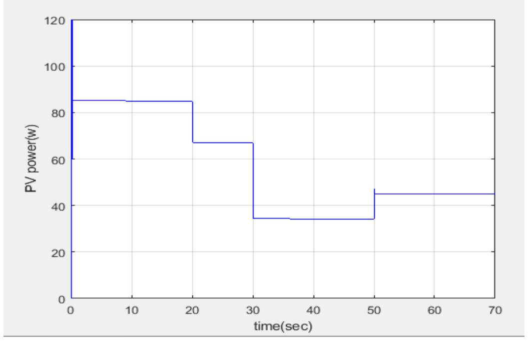


FIG 2: PV Power (w)

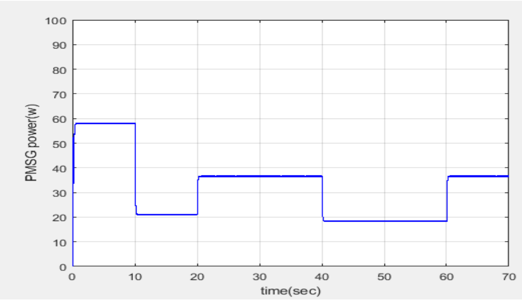


FIG 3: PMSG Power (w)

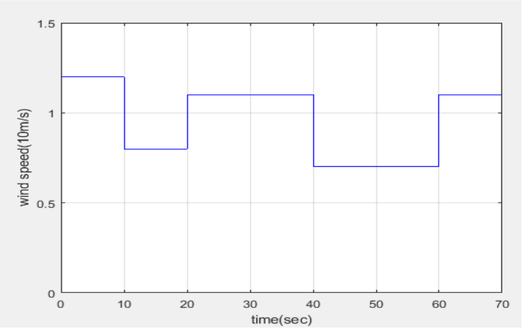


FIG 4: Wind speed (10m/s)

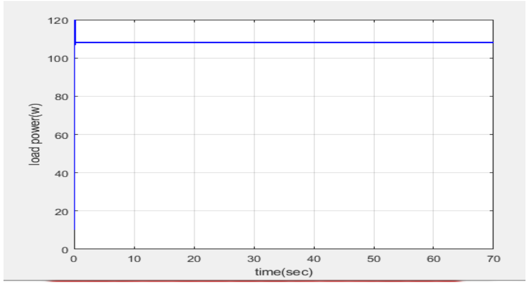


FIG 5: Load power (w)

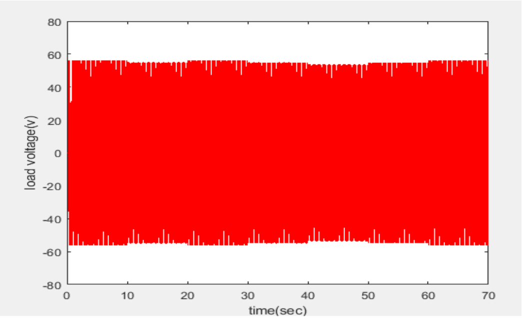


FIG 6: Load voltage (v)

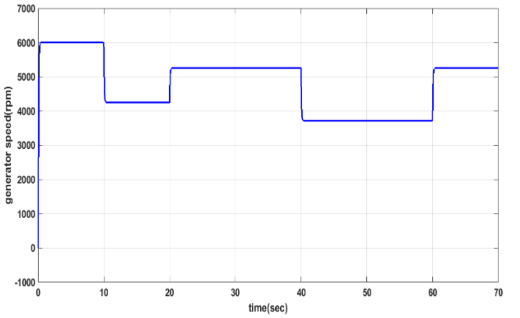


FIG 7: Generator speed (rpm)

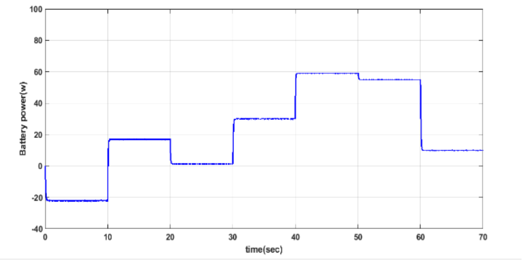


FIG 8: Battery power (w)

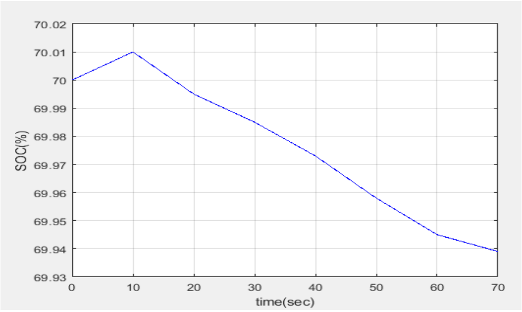


FIG 9: SOC (%)

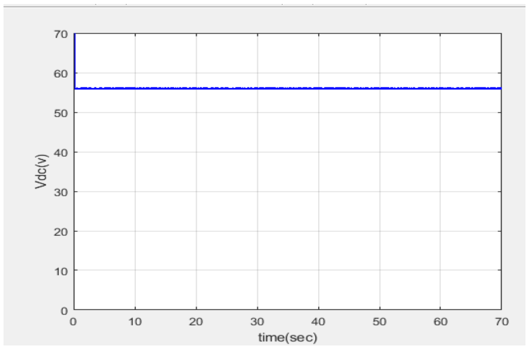


FIG 10: DC bus voltage (v)

TABULAR FORM:

	PI Controller	**Fuzzy MPPT**
Irradiation (kw/m^{2})	**1**	**1.1**
PV Power (w)	**70**	**85**
PMSG Power (w)	**55**	**58**
Wind speed (10m/s)	**1**	**1.2**
Load power (w)	**100**	**110**
Battery power (w)	**-30**	**-20**
SOC (%)	**70**	**70**
Load voltage (v)	**50**	**56**
DC Bus voltage (V$_{dc}$)	**50**	**55**
Generator speed (rpm)	**6000**	**6100**

B. VARIATIONS IN LOAD WITH CONSTANT RENEWABLE ENERGY SOURCES

As illustrated in Fig. 18, in the second case scenario, both solar and wind power generation are maintained at constant levels, with the solar irradiance remaining constant at 800W/m2 and the wind speed being constant at 11 m/s. As seen in Fig. 19, the energy storage device maintains a steady DC bus voltage at 50V to achieve power balancing. As the wind speed is kept constant, as seen in Fig. 20, the generator speed remains constant at 5280 rpm.

Every ten seconds, the load is changed, and the microgrid's performance is evaluated with a variable load demand. In Fig. 21, the power at various microgrid locations is displayed. At first, a 100W load is required, and the electricity produced from

SIMULATION RESULTS:

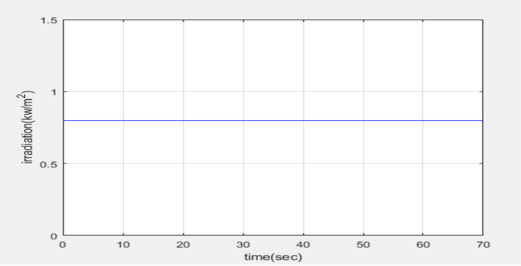


FIG 11: Solar irradiance (kw/m^{2})

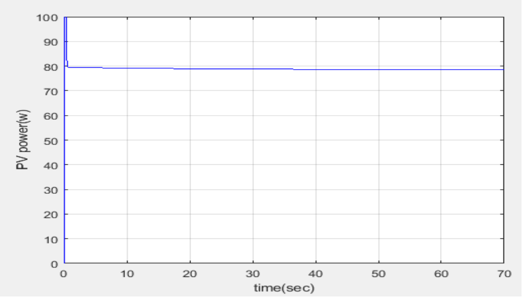


FIG 12: PV Power

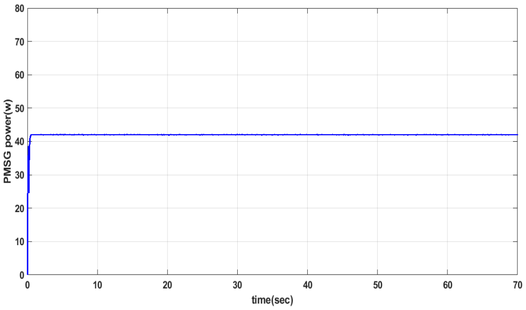


FIG 13: PMSG Power (w)

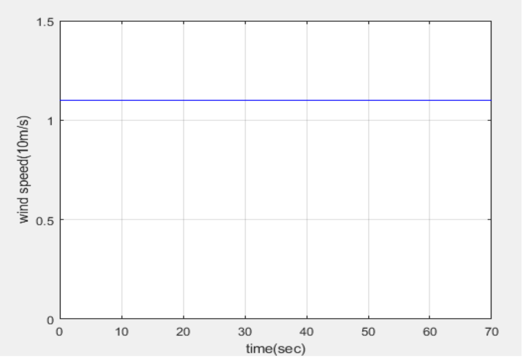


FIG 14: Wind speed (10m/s)

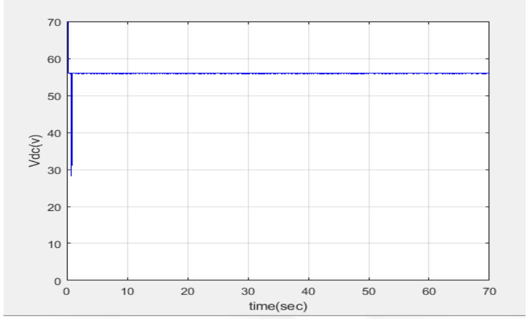


FIG 15: DC bus voltage (v)

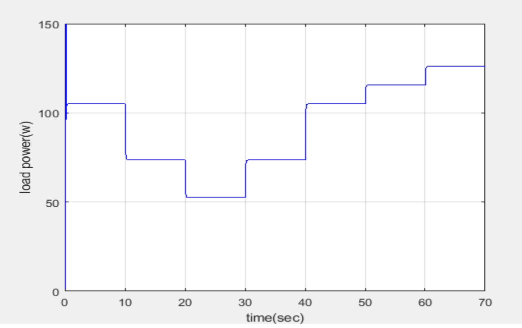


FIG 16: Load power (w)

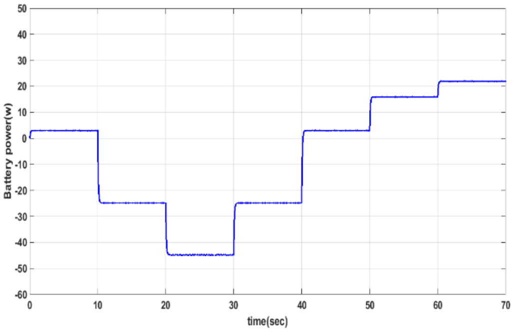


FIG 17: Battery power (w)

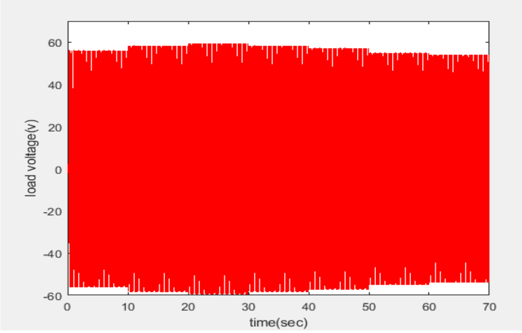


FIG 18: Load voltage (v)

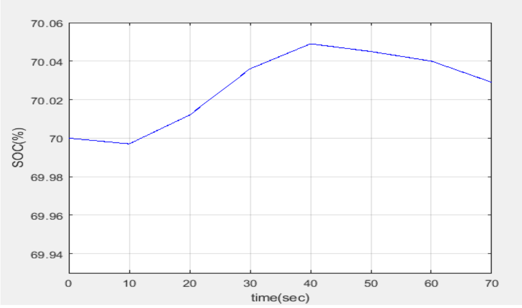


FIG 19: SOC (%)

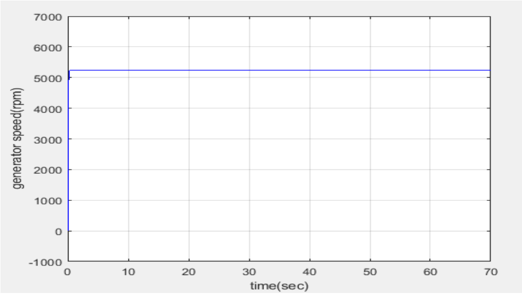


FIG 20: Generator speed (rpm)

TABULAR FORM:

	PI Controller	Fuzzy MPPT
Irradiation (kw/m$^{2)}$	0.2	1
PV Power (w)	56	80
PMSG Power (w)	42	42
Wind speed (10m/s)	1.1	1.1
Load power (w)	100-50	105-55
Battery power (w)	-55	-45
SOC (%)	69-70	70-71
Load voltage (v)	50	55
DC Bus voltage (V$_{dc)}$	50	56
Generator speed (rpm)	5200	5250

CONCLUSION:

A hybrid microgrid powered by renewable energy sources, including solar, wind, and batteries, is created and put into operation on a small scale. It includes an energy management system. To evaluate the suggested energy management system's efficacy for varying load demands and renewable energy source fluctuations, experiments were carried out. Using simulation, the control algorithms and energy management system were put into place. Empirical findings from the simulation demonstrate the system's adaptability to various fluctuations in the load and renewable energy sources. An efficient energy management system can be implemented thanks to the controller. For future testing of various case scenarios and control algorithms for the study of hybrid renewable energy microgrid systems, this test bench offers a platform.

FUTURE SCOPE: Despite focusing on Fuzzy MPPT, acknowledging the existence and potential benefits of other techniques broadens the understanding and applicability of renewable energy systems. Highlighting potential areas for future research, such as hybrid approaches combining multiple controllers or integrating machine learning techniques for adaptive MPPT control.

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