

Stability-Oriented Power Management for Grid-Tied Hybrid Microgrid Using Fuzzy Logic Control

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Abstract - A Hybrid Microgrid is characterized by a collection of loads and distributed generation units that function collectively as a singularly manageable entity. As a cohesive energy distribution network, a microgrid possesses the capability to operate either in conjunction with or independently from the primary electrical grid. In the present work PV generating unit (PVU), wind energy system unit and energy storage unit (ESU) are used for the development of microgrid. The distributed generating (DG) units in microgrid are usually parallel connected which create bus voltage maintenance issues and load sharing among the units. Here fuzzy logic-based control strategy is implemented for power management between source and load with grid-tied operation. The power management strategy manages the power generated from DG, ESU, and Grid and same time control the voltage and frequency of the microgrid the control strategies are verified in the MATLAB/SIMULINK environment.

Keywords – MPPT, energy storage system, SOC, power Management, bi-directional converter, VDC regulator

1. Introduction

To sustain the ever-growing energy demand and to govern local area energy balance and reliability microgrids are proposed. Microgrids are conventional low or medium voltage distribution networks. The principal objective of a microgrid system is to satisfy load demand by giving preference to energy generated references over energy provided from auxiliary sources, including diesel-powered ones. When compared to typical electric utility networks, the microgrid uses renewable energy resources, it is not only more economical, flexible, and stable, but it also has a positive environmental impact. To understand the significance of DC microgrid when compared AC microgrids authors in [1] provided comprehensive analysis of DC microgrid functionality, different issues, management opportunities for grid integrations. Additionally given the option of energy storage as cost effective solution to increase the life of microgrids. The planning phase of DC microgrids involves careful selection of components and topology to ensure efficient and reliable operation. In [2] authors emphasized the importance of selecting appropriate DC/DC converters, such as boost converters and bi-directional DC/DC converters, to minimize component losses and maximize system efficiency. Similarly, authors in [3] highlights the use of DC/DC converters to connect renewable energy sources like photovoltaic (PV) arrays, fuel cells, and lithium-ion batteries (LIB) to the load, demonstrating the stability achieved through maximum power point tracking (MPPT) controllers. The integration of renewable energy sources including storage systems is given by authors in [4]-[5] with a comprehensive control strategy to manage power flow and ensure system reliability. Authors in [6] emphasized on hierarchical control structure of DC microgrids, including primary, secondary and tertiary control levels. Primary control focuses on voltage and current regulation, secondary control addresses voltage regulation and power sharing, whereas tertiary control manages power flow and grid connection. One of the control aspects is presented and examined in [7] with energy management using fuzzy logic. A real-time data is considered for their research to assess the effect of grid stability and resilience in modern power grids. Also, authors in [8] discussed the energy management option for load uncertainties with the help of MATLAB simulations. In order to provide

consumers with high-quality, secure, sustainable and ecologically friendly energy, a microgrid system needs an energy management system to control the flow of power and energy between sources and loads. To maximize the renewable energy utilization a smart power management system is introduced in [9] to address the grid failure during autonomous functioning. In addition, the microgrid resilience and redundancy is examined in the event of emergencies or grid failures. For efficient power management in microgrids, the study in [10] suggests a fuzzy logic based prescriptive analytics model. It considered load uncertainties by combining real-time data from many sources to examine operational flexibility, and maximizing energy use while maintaining grid stability. Fuzzy logic makes it easier to build robust energy management systems that can make decisions based on ambiguous or imprecise data. Rule based fuzzy logic also utilized in [11]-[12] to regulate energy flows and balance the supply and demand variations by implementing fuzzy rules. Along with control techniques, a more significant analysis on production of empirical data for energy consumption changes, battery storage conditions are discussed in [13] along with control mechanisms implemented. As per this study, the fuzzy logic-based energy management system is proved to be flexible and responsive. The deployment of energy storage system is increased for microgrid energy management, authors in [14] discussed the load balance between sources and load with SOC control strategy. This concept is implemented in MATLAB environment for the verification of the control system. Authors in [15]-[16] implemented the control logic for the microgrid power compensation with the use of fuzzy logic controller along with the charge/discharge balance of the energy storage system. The integration of renewable energy sources into smart grids is optimized in [17] by the Fuzzy logic-based mode, which leads to notable improvement in energy consumption, grid stability, storage reliability and overall efficiency. The research in [18] provided an algorithm based on fuzzy logic that was designed for the battery and load management system to support the operation of a microgrid that includes PV power generation.

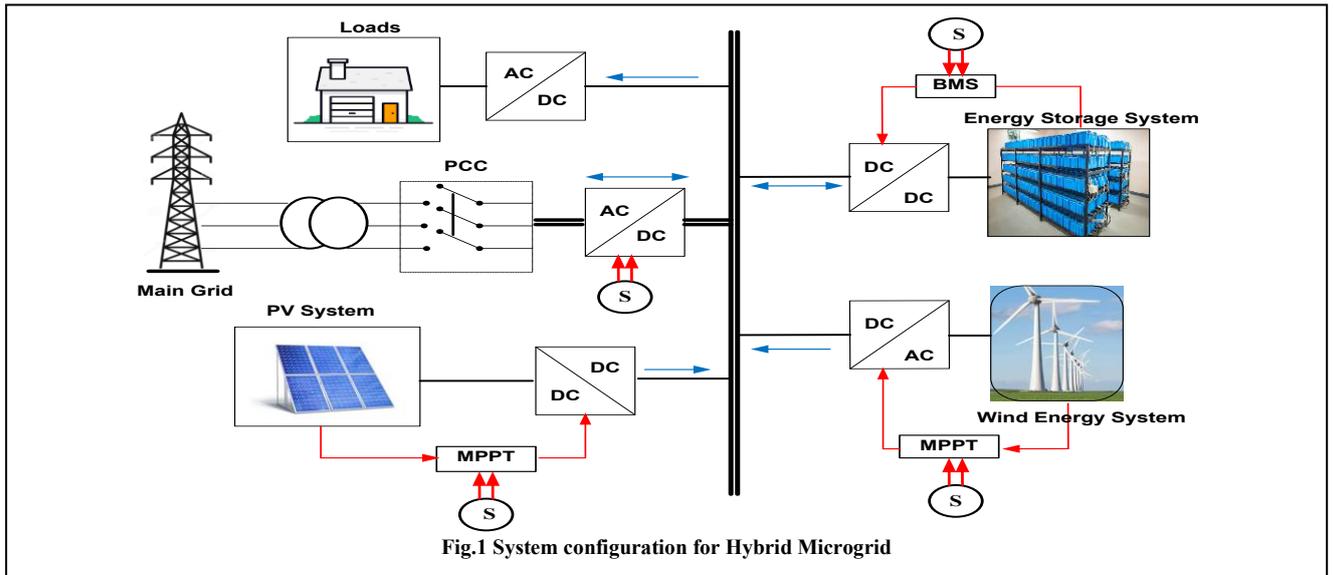
The reviewed literature on microgrid modelling and power management indicates that the success of microgrid control system depends on the reliability and accuracy of the microgrid model and control strategies, which are still being enhanced through research. The majority researchers employ droop control as conventional method. But selection of droop coefficient is crucial in this approach, sometimes improper droop coefficients result inadequate voltage regulation. To overcome this limitation, in this paper a fuzzy based primary control is proposed to ensure appropriate load sharing across sources, enhance the accuracy of current sharing and voltage regulation in the hybrid microgrid (HMG). In order to accomplish the above-mentioned objective, the scope of this work covers:

- The integration of photovoltaic and wind energy sources, along with DC-DC boost converters, the battery energy storage system (BESS), and the three-phase parallel inverters, offered enhanced scalability, modularity, and improved power management capacity.
- The designed Fuzzy controller optimizes the VSC-based interlinking bidirectional converters for Q-V and P-V control for equal distribution of power between grid and microgrid.

The subsequent sections of the paper are structured as follows: Sections 2 & 3 present a comprehensive overview of the Hybrid Microgrid configuration and elaborate on the Methodology for the modeling and control of the PV, Wind & Energy storage unit integrated microgrid system employing the Fuzzy controller. Section 4 have Results with Discussions and Section 5 present the Conclusions, respectively.

2. Hybrid Microgrid (HMG) Configuration:

In the hybrid microgrid (HMG), power management is the primary concern. It means that under all circumstances, power must be distributed evenly among grid, load, energy storage devices, and renewable energy sources (REs). Therefore, the bus voltage must be maintained constant at all loads. A distinct mode of operation should be used for power management in microgrids. The proposed hybrid microgrid (HMG) with four power units: a grid unit, PV generating unit, wind energy system unit, load unit, and energy storage unit are illustrated in Figure 1. The grid power unit uses a transformer and a bidirectional AC-DC converter to link the utility grid to the DC bus. On the other side wind turbine power unit was connected to the DC bus through a three-phase doubly fed induction generator and a unidirectional AC-DC converter. The energy storage unit with a bidirectional DC-DC side converter integrates battery to DC bus. The load unit consists of DC loads directly connected to the bus, whereas AC loads are connected with the converter. The battery and grid power units in



this HMG system can transfer power in both directions, either by absorbing power off the DC bus or delivering power into it.

The proposed hybrid microgrid parameters are listed below in Table 1.

Table .1 Microgrid system parameters

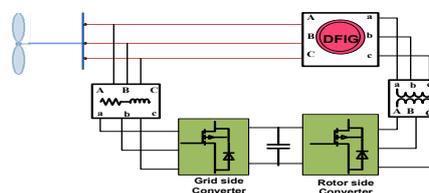
System Parameters	Rating
PV Generating Unit power (DG 1)	300 KW
Wind energy system unit (DG 2)	50 KW
Energy Storage Unit Power rating	3.5 KW
Power level of AC Grid	0.5MW
Connected Load Units	350 KW
DC Link voltage (DLV)	400V

2.1 Mathematical Modelling of Hybrid Microgrid Grid (HMG) system:

The proposed Hybrid Microgrid has wind and solar energy along with battery storage system as the primary components connected through respective converters to the DC-link. To model the individual system mathematical modelling is given in the subsequent section to design the appropriate control model to implement proposed fuzzy controller for power management.

2.1.1 Wind Energy System (WES) Modelling:

Wind generators are induction units that absorb reactive power while delivering real power. A wound rotor induction generator is typically used in DFIGs. The power electronic system bridges the DC control link between the generator and the grid to efficiently regulate the whole WECS. Since the DC-link is essential to the transmission of generated power from the generator to the grid, any grid-connected WECS needs a strong DC-link voltage controller to avoid frequent DC-link fluctuation caused by sudden swings in wind power, which could ultimately lead to complete system failure. To achieve this objective a vector control approach with proportional integral control is implemented for DC voltage regulation.



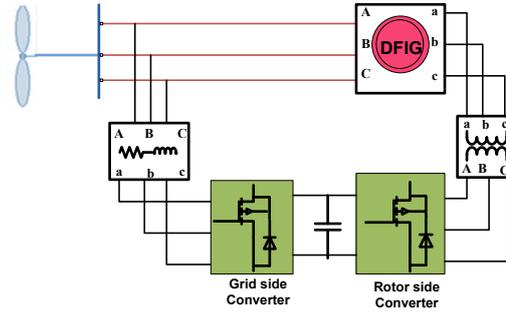


Fig .2 System block diagram for WECS

The rotor circuit is connected to an external converter, which supplies the rotor voltage and also transforms the shaft's mechanical power into electrical power as per the given equations from [1]-[2] as

$$P_w = \frac{1}{2} \rho C_p(\alpha, \delta) a u^3 \quad (1)$$

$$T_w = \frac{P_w}{\omega_t} \quad (2)$$

Where u denotes the wind speed, α represents the pitch angle, ω_t denotes turbine speed. C_p is the power coefficient, δ denotes the tip-speed ratio, a represents the area of blades. The proposed control model of source side converters needs to be expressed as

$$\frac{dV_{rw}}{dt} = \frac{I_{rw}}{C_w} - \frac{I_w}{C_w} \quad (3)$$

$$\frac{V_{rw}}{L} = \frac{dI_{rw}}{dt} + (1 - U_1) \frac{V_{Dc}}{L} - D_1 \quad (4)$$

$$\frac{dV_{Dc}}{dt} = (1 - U_1) \frac{I_w}{C_{Dc}} - \frac{I_{ow}}{C_{Dc}} + D_2 \quad (5)$$

The equations [3]-[5] are the equations to model the proposed source side converter control model, where V_{rw} represents the rectified input voltage, I_{rw} is the rectified wind current, L denotes the inductance and V_{Dc} is the associated dc link voltage. D_1 & D_2 are the parameters depending on state of the storage system. The WES operates under MPPT for maximum power extraction.

2.1.2 PV Generating unit Modelling:

The PV Generating unit is constituted by the PV array & MPPT controller connected to the DC-link through DC-DC boost converter. The mathematical equations for the control logic are given in equations. [6]-[7] as

$$\frac{d(V_p)}{dt} = \frac{I_p}{C_p} - \frac{I_{LP}}{C_p} \quad (6)$$

$$\frac{V_p}{L_p} = \frac{dI_p}{dt} + [1 - U_2] \frac{V_{Dc}}{L_p} - D_3 \quad (7)$$

Where I_p & V_p are the PV array current and voltage respectively, V_{Dc} is dc link voltage and D_3 is dynamic value based on the state of charge of the battery depending on the operating condition. When operating in grid-connected mode, the main grid regulates the microgrid's load power as well as voltage and frequency variations to meet load needs. For the stable operation, it is essential to maintain a constant DC voltage on the DC link of the inverter.

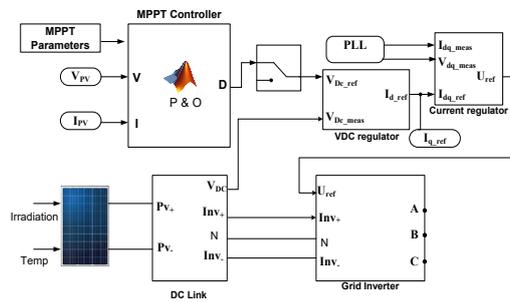


Fig. 3 system block diagram for PV MPPT

The VDC regulator makes sure the solar panels always run at their maximum power point by modifying the duty cycle of the Maximum Power Point Tracking (MPPT) controller. Whereas current regulator controls the current that the inverter injected into the grid to ensure the current is in phase with the grid voltage for the good commitment of power quality requirements. Adjusts the inverter's switching signals to maintain the required current level by comparing the observed grid current with a reference current using a feedback loop.

2.1. Battery unit Control Approach:

The battery unit is connected to the DC link of microgrid through bidirectional DC-DC converter. This converter is needed to maintain Dc link voltage constant irrespective of power variation in the sources and load. The battery is a nonlinear voltage source, and its output voltage is dependent on both the current and the battery's state of charge (SOC), which is a nonlinear function of both time and current. The SOC is modelled as described below in equation [8]-[9].

$$SOC = 100 \left\{ 1 + \frac{[\int I_B dt]}{Q} \right\} \quad (8)$$

The battery charge-discharge condition is based on available power, demand and SOC limits. The ESU converter modeled based on the below mentioned equations

$$\frac{V_B}{I_B} = \frac{dI_B}{dt} + U_3 \frac{V_{DC}}{L_B} - D_5 \quad (9)$$

Therefore, when the battery is completely discharged and there is no current flowing, the battery's voltage will be almost zero. During charging when current starts flowing again, the voltage drops sharply. Essentially serving as a dynamic energy buffer to level out variation in power supply or demand, a battery controller regulates the charging and discharging of a battery to maintain a steady voltage on both the DC link and grid voltage by modifying its power flow with respect to instantaneous voltage measurements.

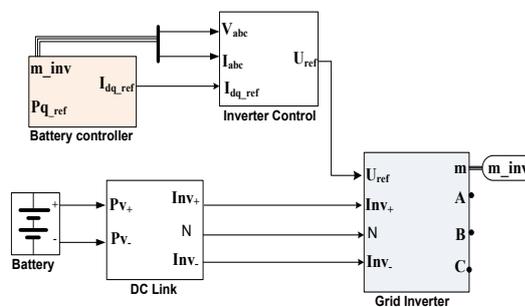


Fig. 4 Control logic for battery & grid inverter

3. Proposed Fuzzy Control Systems:

The basic control over power management in an microgrid is maintaining equilibrium between energy supplied and load demand throughout the system, ensuring that it can be met at any instant during the system's operation. The control strategy has only primary controller which regulates voltage and current to reduce computational burden. To monitor the uncertainties, all power units estimate the DC link voltage (DLV) and compares with the measured DLV. Under normal circumstances the proposed control strategy achieves both balance in power and voltage regulation with the help of estimated DLV. When there is uncertainty with any of the power unit, the operation of the DG unit are changed based on the algorithm to ensure a continuous power management even in the presence of DLV variation. As per the control objectives, this paper considered a fuzzy controller that has multi-dimensional structure with five fuzzy variables. The five variables are the battery SOC percentage, the distributed generated power i.e., PV and Wind energy unit, load power, battery power and operation mode switching, while M is a fuzzy output variable. The basic range of the SOC is [0,1], with a fuzzy domain of [0,1,2,3,4,5]. [NP, NM, NE, ZE, PP, PM, PE].

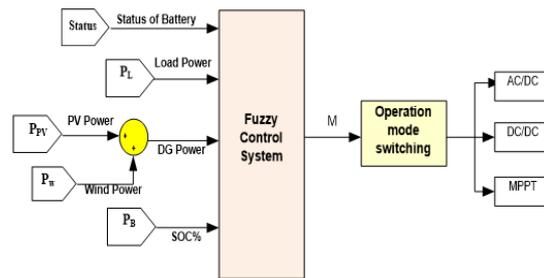


Fig .5 Fuzzy control system block diagram

Mode Power Management	PV Power	Wind Power	Battery Power	Load Power	Grid Power
$P_{DG} = P_L$	P_{PV}	P_W	Battery neither discharge/charge	$P_L = P_{DG}$	Grid neither absorbed/Supplied
$P_{DG} < P_L$ $SOC > 0.8$	P_{PV}	P_W	$+P_B$ Deliver/Discharge	$P_L = P_{DG} + P_B$	$+P_G$
$P_{DG} < P_L$ $SOC < 0.2$	P_{PV}	P_W	$-P_B$ Charge/Absorbed	$P_L = P_G$	$+P_G$
$P_{DG} > P_L$ $SOC < 0.2$	P_{PV}	P_W	$-P_B$ Charge/Absorbed	$P_L = P_{DG}$	Grid neither absorbed/Supplied
$P_{DG} > P_L$ $SOC > 0.8$	P_{PV}	P_W	Battery neither discharge/charge	$P_L = P_{DG}$	$-P_G$

The fundamental selection signal M of the system's operational mode is [-2, -1, 0, 1, 2]. quantization factor Ke1 is 5, and the corresponding fuzzy subset is [Z, VS, S, M, B, VB]. The basic domain of Pd is defined as [-1200,1200], the fuzzy domain consists of the values [-3, -2, -1, 0, 1, 2, 3], the quantization factor Ke2 is 3/1200, and the associated fuzzy subset is [NP, NM, NE, ZE, PP, PM, PE].

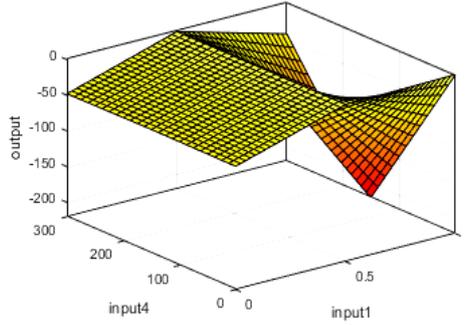


Fig .6 Fuzzy Control map

The fundamental selection signal M of the system’s operational mode is [-2, -1,0,1,2]. The fuzzy domain is the same as this. The scale factor Ku is set to 1. The fuzzy subset consists of [NM, NE, ZE, PP, PM]. Once the membership function has been designed, fuzzy control rules must be set based on requirement.

The energy storage system not only for uninterrupted power source, but also proper charge and discharge to maintain life of the battery. The SOC is set between 0.8 and 0.2 as maximum and minimum limit for charge and discharge battery power. specific control modes are as shown in Table .2. The bidirectional DC-to-AC converter and battery power are crucial control parameters for keeping the power balance in the system. The output power reference value for bidirectional DC/AC converter operated in parallel when $P_{DG} < P_L$ & $P_{DG} > P_L$ in the above-mentioned Table .2. The operational mode of power management in a grid-tied HMG system indicates at every moment; load power is equated with grid power. As per the distributed power generation and load power requirements, the grid power will be exchanged.

4. Results and Discussion

The hybrid microgrid (HMG) is implemented with renewable PV and Wind energy sources and a energy storage unit in grid-tied operation as per the ratings mentioned in Table .3.

Table .3 design parameters of HMG system

S.No	HMG Connected Units	Ratings
1	PV Generating Unit Power (DG 1)	SPR-15E-WHT-D 300KW 7 Modules in parallel strings.
2	Wind energy system unit (DG 2)	DFIG-50KW Nominal Voltage Line-Line=400V
3	Energy Storage Unit output Power	Capacity=300Ah Nominal Voltage =480V
4	Power of AC Grid	154 MW, 33KV Grid connected T/F=33KV/0.4KV
5	Load Unit	Dynamic Loads of 1KW each $V_{rms}=400V$ Variable Load -300KW to 350KW

6	DC Link voltage (DLV)	400V
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To confirm the accuracy and effectiveness of the proposed fuzzy control-based power management strategy for the Hybrid microgrid (HMG) system, simulations were conducted within the Simulink modelling environment.

The PV and Wind operates via an MPPT block to extract the most power. The amount of power produced current and voltage response of the distributed generating units (DG's) are shown in figures.[8]-[11].

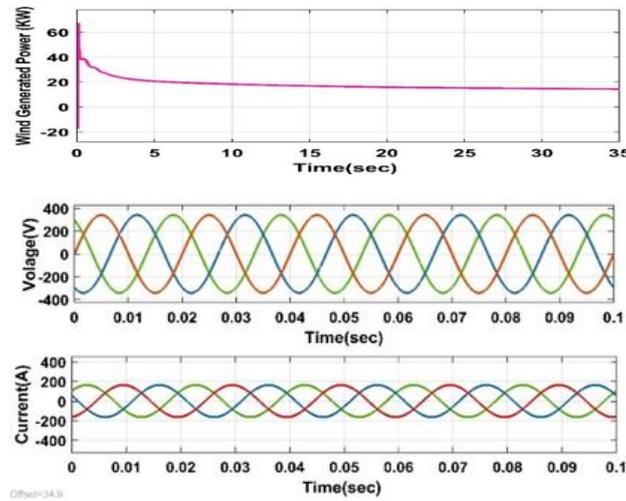


Fig .7 Wind generating unit V,I and Power curves

The microgrid has a total load requirement of 355 kW. The power generated of DG units is not always constant it varies dynamically at all times. When the total power produced by DG sources exceeds 355 kW, indicating a surplus of power in the microgrid bus, which is represented by an increase in the battery power graph as shown in Figure .7.

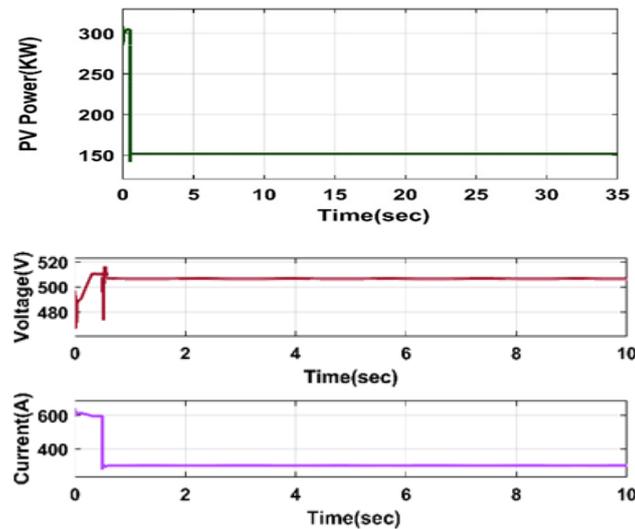


Fig .8 Battery operating curves for power, v and I

During some time when the total of DG power units is below 355 kW, indicating that energy is required in the microgrid bus; thus, the battery serves as a power source during this period to supply energy to the microgrid, resulting in a reduction of the battery power curve illustrated in Figure .8.

As noted above, the battery serves as the primary component in maintaining microgrid balance. The battery's state of charge is configured at 85%, while the battery current fluctuates from -200 to 200A, and the battery voltage is approximately 480V.

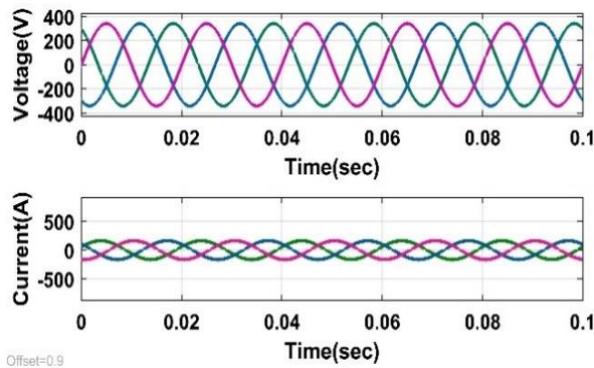
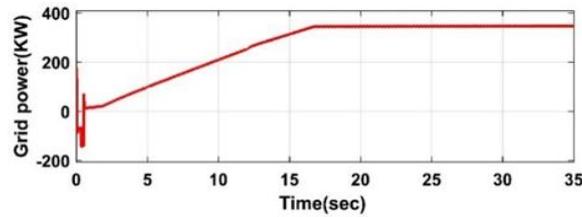
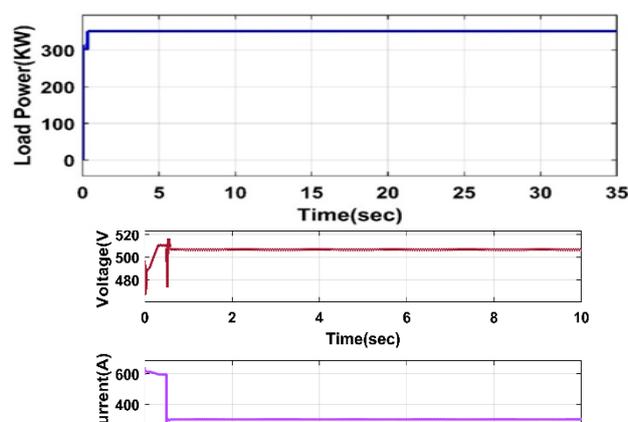


Fig .9 Grid voltage, current and Power curve

The fuzzy logic toolbox is employed to implement the fuzzy logic controller (FLC). The loads are regarded as dynamic and variable loads. Upon execution of the simulation, the results showed in Figure .9 that the Fuzzy controller can maintain a constant voltage at the grid level. As per the distributed power generation and load power requirements, the grid power will be exchanged. Figure.10 illustrates the output characteristics of AC load voltage and current.

The operation is accomplished for the grid-connected mode. The performance of the load characteristics and the grid power is examined alongside that of the hybrid microgrid. The AC load has a phase-to-phase voltage of 400V and a current of 200A. Figure. 10 illustrate the voltage and current responses at the AC side of the main converter. Figure.[6]–[10] illustrate the different characteristics of the hybrid microgrid. In this work microgrid functions in a grid-tied mode here. In this mode, the primary converter functions in Q-V and P-V control for equal distribution of power between grid and microgrid, with power being balanced by the utility grid. The battery has been completely charged. The utility grid keeps the AC bus voltage stable, while the main converter does it for the DC bus voltage.



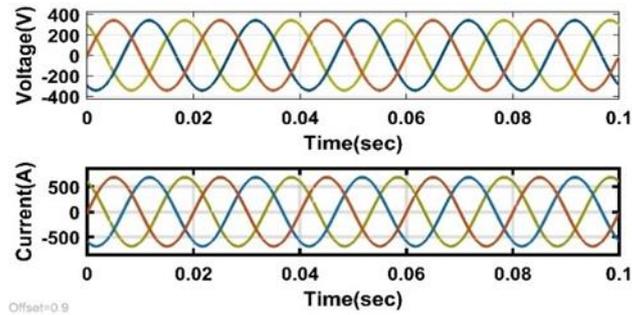


Fig .10 Load voltage, current and power curve

5. Conclusion

This work presents, development and management of a hybrid microgrid system that combines photovoltaic (PV) generating unit, wind energy system, and an energy storage unit (ESU). The hybrid microgrid system is capable of functioning as a single, controllable energy network in connection with main utility grid. A key challenge addressed in this study is parallel operation of DG units, which often gives inconsistent bus voltage and so inappropriate load sharing among the sources. To resolve the above-mentioned challenges, an intelligent control strategy based on fuzzy logic was implemented. The proposed intelligent control strategy ensured efficient power sharing among DG units, the ESU and the grid, maintaining both voltage and frequency within desired limits. The effectiveness of the control strategy is verified through simulation in MATLAB/SIMULINK, which reveals the following

- The successful integration of DG units supported by DC-DC boost converters and a battery energy storage system (ESU). Enhanced the overall sustainability of the microgrid.
- The use of modular DC-DC converters and three-phase parallel inverters improves scalability and enables efficient power management, making the system adaptable to different load and generation scenarios.
- The implementation of a fuzzy logic controller effectively manages the operation of voltage source converter (VSC)-based interlinking bidirectional converters, enabling dynamic and intelligent control of real (P) and reactive (Q) power flows.
- The control strategy ensures balanced power sharing between the grid and the microgrid by regulating voltage (V) and reactive power (Q), thereby supporting grid stability and optimal resource utilization.

The proposed power management system employed fuzzy logic, which is among the most effective controllers for safeguarding the battery system against overcharging damage by regulating battery cycles and balancing demand with consumption. The system detailed in this study is simpler, more efficient in maintaining power balance, and easier to update. Future research procedures will focus on empirically validating the proposed strategy across different power levels

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