A Novel Fuzzy Logic EMS for Hybrid Microgrids with Photovoltaic, Wind, Fuel Cell, and Energy Storage Integration

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Abstract. This paper presents an innovative Energy Management Strategy (EMS) for a hybrid microgrid that combines two main renewable energy sources (RESs), photovoltaic (PV) and wind turbine (WT) generators working at the maximum power point (MPP) to extract the maximum available energy, and an energy storage system (ESS) based Lithium batteries to ensure DC-bus stability. This system includes a backup device based on Fuel Cell (FC) to assure system dependability and minimize blackouts, as well as power electronic converters for flexible system parts and a residential community as DC loads. The proposed EMS is based on the advanced Fuzzy Logic Controller (FLC), which regulates voltage and manages power flow inside the microgrid. MATLAB/Simulink simulations were conducted to assess the performance of innovative microgrid stability strategy. A comparative analysis with conventional EMS approaches demonstrates the superior effectiveness and viability of the proposed FLC technique in energy management within microgrids. The simulation-based comparison indicates that the proposed optimization method enhances system performance and DC-bus stability.

1 Introduction

In recent years, the growing demand for power has been driven by significant environmental challenges, including greenhouse gas emissions, depletion of fossil fuel resources, and the energy imbalances caused by conflicts. These issues have heightened global awareness of the need for sustainable energy solutions. As a result, renewable energy sources have gained considerable attention. To address these challenges, hybrid energy systems that integrate renewable resources have emerged as a promising solution [1]. Among these, PV system and WT are the most widely adopted due to their ease of installation and cost-effectiveness in relation to power generation. These sources are widely adopted in various configurations around the world, as they do not require fuel for power generation, unlike technologies such as fuel cell (FC) stacks or biogas systems[2, 3].

Energy sources such as PV systems and WT are highly sensitive to climatic fluctuations, including changes in wind, temperature, and solar radiation. These variations can lead to grid instability. To mitigate this issue, energy storage systems (ESS) are crucial for maintaining stability in microgrids. The ESS systems allow the storage of excess energy produced by renewable energy sources and provide power during times when consumer demand is higher than the capacity of power sources, or during nighttime periods. Storage systems also help maintain energy stability within the overall energy system.

The literature highlights several energy storage technologies, such as FC, batteries, and other devices, that are important for dealing with the challenges presented by intermittent renewable energy sources and unforeseen changes in load demand [4, 5]. An efficient Energy Management System (EMS) is crucial for the supervision, tracking, and regulation of energy systems, specifically for the integration of distributed energy resources (DERs). Additionally, it enhances the efficiency of decentralized energy sources like PV, WT, and energy storage systems, while also overseeing the allocation of electricity between the primary power grid and power exchanges within microgrids. Various sophisticated AI algorithms have been used to achieve a balance in economic distribution and load changes, while also improving the effectiveness and efficiency of microgrids (MGs). Artificial neural networks (ANN) and fuzzy logic controllers (FLC) are extensively employed for energy management and control in MGs. These techniques guarantee a streamlined transfer of energy between the system and the grid, simultaneously enhancing the performance of the battery [6,] [7] [8].

This paper presents a novel EMS that uses artificial intelligence based on fuzzy logic control to enhance the stability of microgrids. The proposed EMS aims to improve stability by simplifying the controller's inputs and rule base. The single-input FLC incorporates units of RES and energy storage systems to achieve this. The FLC has one output and operates based on three rules, the input is the difference between the load terminal voltage and a reference voltage fixed at 400 V.

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The paper also includes a simulation-based comparison of the FLC and proportional-integral-derivative (PID) control technique.

2 System description

Fig. 1 illustrates the proposed system, which includes PV and WT as the primary sources, a lithium-ion battery, and a fuel cell (FC) that is utilized only in emergencies when the power from PV and WT is insufficient to meet the load's requirements and the state of charge (SoC) drops below the minimum threshold (20%). All energy sources are dimensioned to meet the power requirements of the system loads. The total of DC loads can range from 2 kW to 25 kW. As a result, each source will be dimensioned to account for all possible scenarios in the microgrid.

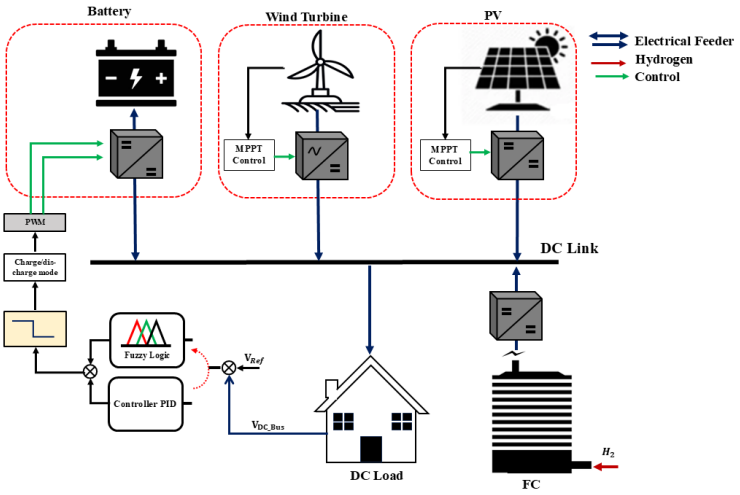

Fig. 1. Proposed microgrid system architecture.

2.1 PV cells

The PV array used in this system consists of N parallel strings, each containing M series-connected modules to achieve the desired power rating. The model employed in this research includes a current source that generates the current due to light incidence, a diode, and two resistances, as shown in Fig. 2. The resistance represents leakage current caused by ground losses, while accounts for internal losses due to the flow of current through the solar cell.

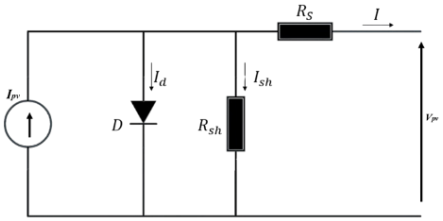

Fig. 2. Equivalent circuit of the solar cell.

$$I_{pv} = I_{ph} - I_d - I_r \quad (1)$$

$$\text{With} \qquad I_d = I_s\left(e^{\frac{V_{pv}+R_{sh}*I_{pv}}{n*V_T}} - 1\right) \quad (2)$$

$$I_r = \frac{V_{pv} - R_s*I_{pv}}{R_{sh}} \quad (3)$$

The electric current delivered by photovoltaic cells is determined by the operating temperature T and the irradiation G, which is proportional to the amount of light. As a result, the (1) becomes:

$$I_{pv} = I_{ph} - I_s\left(e^{\frac{V_{pv}+R_{sh}*I_{pv}}{n*V_T}} - 1\right) - \frac{V_{pv} - R_s*I_{pv}}{R_{sh}} \quad (4)$$

V_T: The thermal voltage.

n: The diode ideality constant.
I_d: Reverse saturation currents of the diode.
I_{ph}: Photocurrent.

2.2 Wind Turbine

The power output of a wind turbine is influenced by several factors, including its rated power, cut-in wind speed, cut-out wind speed, and rated wind speed [9]. The generated power of a wind turbine is governed by the (5):

$$P_{Wind} = \frac{1}{2}\rho S {V_{Wind}}^3 C_p(\lambda) \quad (5)$$

Where:
C_p(>0): Coefficient of performance of the turbine.
ρ: Density of air (m3)
S: Area traversed by the rotor blades ($m2$)
V_{Wind}: Wind speed (m/s)

2.3 Battery

Lithium batteries are preferred in storage systems due to their benefits over other battery types. To safeguard the battery from overcharging and over discharge, the energy management approach takes into account the state of charge (SOC) [10]. The battery's state of charge (SOC) is defined by (6):

$$\text{SoC}\ (\%) = 100\left[1 - \left(\frac{1}{Q_{bat}}\int_0^t i_{batt}(t)dt\right)\right] \quad (6)$$

Where:
i_{batt} is the battery's current (A), and Q_{bat} (Ah) is the battery capacity.

2.3 Fuel Cell Model

A Proton Exchange Membrane Fuel Cell (PEMFC) is a device that converts fuel's chemical energy directly into electrical energy. A single cell's output voltage is given in [4], and can be described as follows:

$$V_{Cell} = N_{Cell}.E_{Cell} \quad (7)$$

Where E_{Cell} is the output voltage of a single cell is determined by the following (8) [10]:

$$E_{Cell} = E_{Nernst} - V_{Act} - V_{Const} - V_{Ohm} \quad (8)$$

Where:

$$E_{Nernst} = \frac{\Delta G°}{zF} + \frac{\Delta S}{zF}(T - T_0) + \frac{RT}{zF}\ln\left(\frac{{P_{O_2}}^{\frac{1}{2}}.P_{H_2}}{P_{H_2O}}\right) \quad (9)$$

$$V_{Act} = \frac{RT}{azF} ln\left(\frac{I}{I_0}\right) \quad (10)$$

$$V_{Ohm} = I.R_{ohm} \quad (11)$$

$$V_{Const} = \frac{-RT}{azF} ln\left(1 - \frac{I}{I_{lim}}\right) \quad (12)$$

$\Delta G°$ is an electrical work called Gibbs free energy.
ΔS is the specific entropy.
z is the number of electrons.
F is Faraday's constant.
R is the universal perfect gas constant (J/K.mol).
P_{O_2}, P_{H_2}, P_{H_2O} The pressure of pure Oxygen, Hydrogen and H_2O respectively.
V_{Act} signifies the activation-related voltage drop at the anode and cathode.
V_{Ohm} represents the ohmic voltage drop caused by proton and electron conduction.
V_{Const} denotes the mass concentration voltage drop.

3 Energy Management System

The EMS serves as the primary controller, coordinating and managing all control actions within the microgrid system. All the controllers for the converters operate according to the EMS control mode. The boost converter in the solar energy conversion system uses Maximum Power Point Tracking (MPPT) modes to generate maximum power. The battery is connected to the microgrid via a bidirectional converter, which controls the charging and discharging modes and maintains a constant DC bus voltage. Meanwhile, the wind energy conversion system's DC-DC boost converter operates in boost mode. To ensure the stability of the microgrid, the power generated must be balanced with load demand across various power generation scenarios from renewable energy sources. Additionally, the EMS is responsible for monitoring and managing the power generated by fuel cells according to the load demand.
The system effectively combines power generated from renewable energy sources with that produced by fuel cells, guaranteeing a consistent supply even when there are fluctuations in load demands. The EMS diligently regulates the battery's state of charge, ensuring it remains between 20% and 80% to prevent excessive charging and discharging, therefore prolonging the battery's longevity. Fig. 3. depicts the various operational modes of the EMS under these situations.

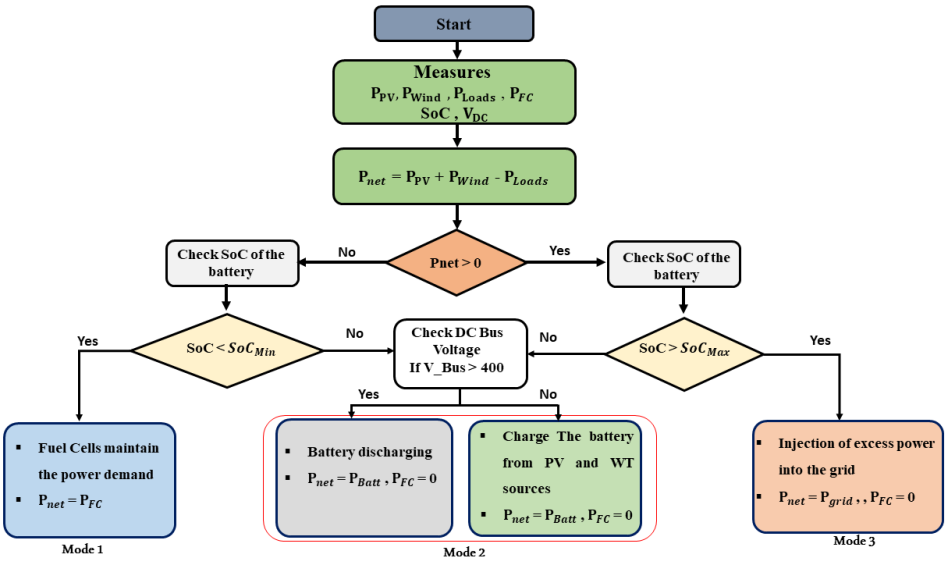

Fig. 3. Energy management strategy

4 Results and Discussion

The efficacy of the proposed EMS was evaluated by simulating the DC microgrid system as shown in Fig. 1. in MATLAB/Simulink. The parameters of the microgrid elements, along with their respective converter and control settings used in the simulation studies, are detailed in Table 1.

Table 1. Parameters of the microgrid

Element	Parameters	Value
PV array	Maximum current at MPP (A)	7.98
	Maximum voltage at MPP (V)	37
	Short circuit current (A)	8.32
	Open circuit voltage (V)	45.2
	Temperature coefficient of short-current (mA/°C)	3
Wind Turbines	L_d (d-axis leakage inductance)	4,988 10^{-4}
	L_q (q-axis leakage inductance)	5,513 10^{-4}
	Ψm (leakage inductance)	0.1119
	P (number of poles of machines)	4

Li-ion Battery	Nominal voltage (V)	230
	Maximum capacity (Ah)	300
	Internal resistance (Ohms)	7,7 10^{-3}
Fuel cell system	Type of fuel cell	PEMFC
	No of cells	65
	Nominal voltage (V)	45
	Nominal current (A)	65
	Operating temperature (Celsius)	33

The simulation runs for 1 s with a 1e^{-5} s sampling time. To show the robustness of the fuzzy logic controller against the change in meteorological conditions. A scenario was selected that includes multiple changes in solar irradiation and wind speed to represent a range of possible conditions. Fig. 4 and Fig. 5 depict the solar irradiation and wind speed, respectively.

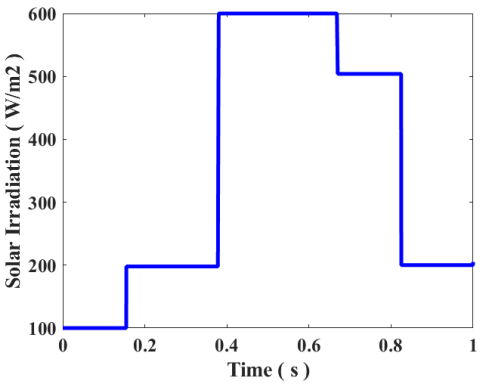

Fig. 4. Solar irradiation (W/m²)

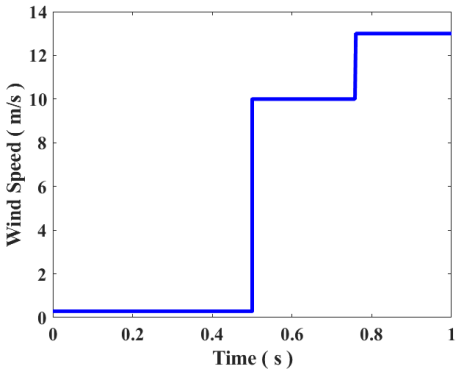

Fig. 5. Wind speed (m/s)

At the start of the simulation, the power generated from renewable sources $P_{gen} = P_{pv} + P_{WT}$ is less than the load demand power P_{loads} as shown in Fig 6. As a result, the battery discharge provides the requested power, and the EMS disconnects the fuel cell. The battery maintains system balance by discharging when the produced power is less than the requested load power (between t=0 s and t=0.4 s), and by charging when the produced power exceeds the load demand (between $t = 0.4\ s$ and $t = 1\ s$). Fig. 6 and Fig. 7 illustrate the variation in the state of charge and the power of the microgrid units, respectively, during this scenario.

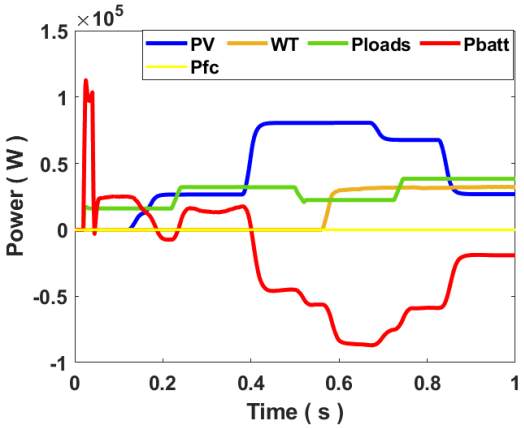

Fig. 6. Power output of the microgrid units during the scenario.

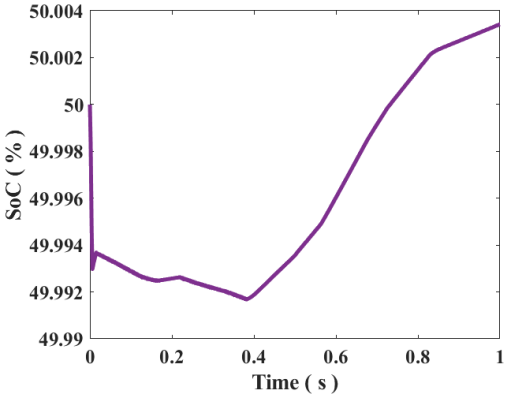

Fig. 7. State of charge the battery

Fig. 8 illustrates the comparison of variations in reference voltage and DC bus voltage for both fuzzy logic and PID control strategies. The simulation results demonstrates that the FLC-based energy management system provides superior voltage regulation and stability compared to the PID controller. Specifically, FLC effectively reduces voltage deviations and improves response time, resulting in a more stable and reliable performance in managing voltage fluctuations.

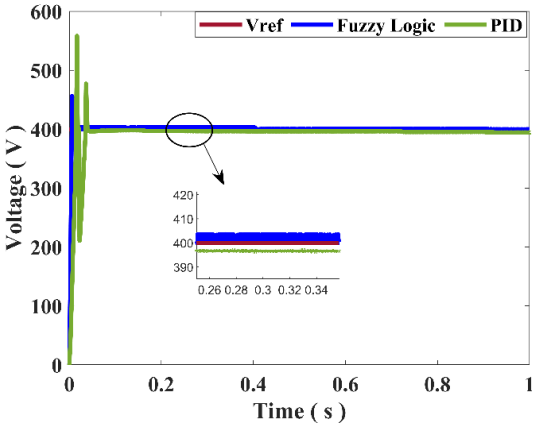

Fig. 8. Measured voltage at the DC bus (V) for both fuzzy logic and PID control strategies.

Fig. 9 compares the error signals between the fuzzy logic and PID control strategies. It shows the difference between the measured DC bus voltage (V_{DC_Bus}) and the desired reference voltage (V_{Ref}) for each controller. The Figure demonstrates that the FL-based system results in a smaller and more consistent error signal compared to the PID controller, indicating better accuracy and stability in maintaining the desired voltage level.

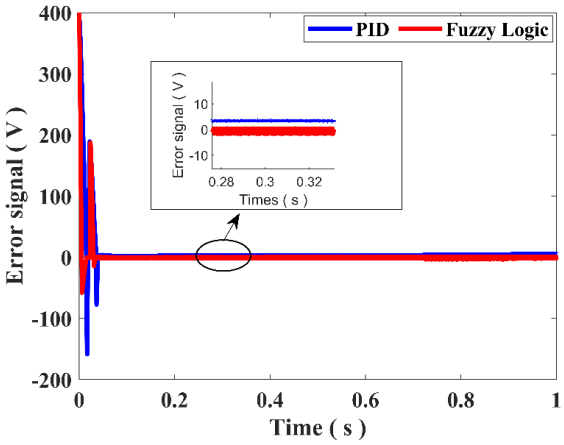

Fig. 9. Difference between the V_{DC_Bus} and V_{Ref}

5 Conclusion

The proposed energy management strategy for renewable energy based microgrids effectively balances power supply and demand on the DC bus using PV and WT as primary sources, with battery and FC systems as backups. The fuzzy logic controller (FLC)-based EMS outperforms conventional methods, demonstrating faster convergence, improved accuracy, and enhanced system stability. The approach proves to be robust and reliable for managing complex scenarios, making it a viable solution for efficient energy management in renewable energy microgrid systems.

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