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Smart Fuzzy Energy Management for Multi-EV Charging using Hybrid PV–Wind–Fuel Cell System

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ABSTRACT: The rapid penetration of electric vehicles (EVs) has significantly increased the demand for reliable, efficient, and sustainable charging infrastructure. This paper presents a smart energy management system based on a fuzzy logic controller (FLC) for a hybrid photovoltaic (PV)–wind–fuel cell power generation system designed to support multiple EV charging stations with grid integration. The proposed system utilizes DC–DC boost converters to regulate the variable outputs of the PV array and fuel cell, while wind energy is interfaced through suitable power conditioning circuits. A common DC-link supplies power to multiple EV chargers via a grid-connected inverter. The fuzzy logic controller uses the DC-link voltage error and change in error to generate optimal control signals for regulating power flow among renewable sources, fuel cell backup, and the utility grid. The controller ensures stable DC-link voltage, balanced power sharing, and uninterrupted EV charging under varying renewable generation, grid conditions, and dynamic EV load demands. Simulation results demonstrate that the proposed FLC-based strategy improves charging reliability, reduces voltage fluctuations, enhances dynamic response, and supports scalable multi-EV charging with improved power quality.

KEYWORDS: Hybrid renewable energy system, Electric vehicle charging, Multiple EVs, Fuzzy logic controller, Photovoltaic system, Wind energy conversion system, Fuel cell, Boost converter, Smart grid integration

I. INTRODUCTION

The global transition toward electric mobility has intensified the need for sustainable and intelligent EV charging solutions. Conventional grid-dependent EV charging stations place significant stress on the utility grid, particularly during peak demand hours. Integrating renewable energy sources such as photovoltaic (PV) and wind power into EV charging infrastructure offers an environmentally friendly alternative; however, their intermittent nature poses challenges in ensuring reliable and continuous charging, especially for multiple EVs charging simultaneously.

Hybrid PV–wind–fuel cell systems provide an effective solution by combining renewable sources with fuel cells as auxiliary power units. In such systems, PV and wind sources supply primary energy, while fuel cells compensate during renewable shortages, ensuring uninterrupted EV charging. A common DC-link architecture enables efficient power aggregation and distribution to multiple EV chargers and the grid.

Efficient power management and voltage regulation are critical in multi-EV charging scenarios due to rapidly varying load demands, different charging modes (slow, fast, and ultra-fast charging), and fluctuating renewable generation. Conventional control techniques struggle under such nonlinear and dynamic conditions. Fuzzy logic controllers (FLCs), on the other hand, offer a robust control approach without requiring precise mathematical models, making them well-suited for complex EV charging environments.

In this paper, a smart fuzzy logic–based energy management scheme is proposed for a grid-integrated hybrid PV–wind–fuel cell system supplying power to multiple EV charging points. The controller maintains DC-link voltage stability, optimizes power sharing among sources, minimizes grid dependency, and ensures high-quality power delivery to EV chargers. The effectiveness of the proposed strategy is validated through simulation under varying renewable availability and multi-EV charging conditions.

II. LITERATURE SURVEY

The growing deployment of renewable energy sources and energy storage systems in residential and commercial sectors has led to the development of advanced home energy management systems. Dinh et al. presented an energy management framework that integrates renewable energy sources and energy storage while considering electricity purchase from and sale to the main grid. The study employed particle swarm optimization-based techniques to minimize energy cost and peak-to-average ratio, demonstrating that coordinated control of storage and renewable generation significantly improves economic performance and grid interaction efficiency. [1] The combined operation of variable renewable energy sources and energy storage systems has been shown to provide additional capacity value beyond individual resource contributions. Byers and Botterud investigated the portfolio effect arising from the synergy between renewable generation and storage systems using reliability-based dispatch simulations. Their results highlighted that coordinated planning and operation of renewable energy and storage resources can substantially enhance system adequacy and reliability in capacity markets. [2]

DC microgrids have gained increasing attention due to their high efficiency and compatibility with renewable energy sources. Kakigano et al. proposed a voltage control strategy for DC microgrids that integrates fuzzy logic control with gain-scheduling techniques to achieve both DC bus voltage regulation and balanced energy sharing among multiple storage units. Experimental validation demonstrated that the proposed approach maintains stable distribution voltages while ensuring uniform utilization of storage devices under islanded operating conditions. [3] Effective control of DC microgrids under both grid-connected and islanded modes is essential for ensuring uninterrupted power supply. Kumar et al. developed a coordinated control strategy using dual proportional-integral controllers combined with feed-forward and feedback loops. The proposed method maintained DC-link voltage stability and ensured robust performance during load variations, fault conditions, and mode transitions, highlighting the effectiveness of linear control approaches under structured operating conditions. [4] To address voltage regulation challenges under rapidly changing load and generation conditions, Hajebrahimim et al. introduced an adaptive droop-based energy management control scheme for DC microgrids. The proposed nonlinear droop characteristics enabled tight DC bus voltage regulation across a wide range of operating scenarios. Simulation and experimental results confirmed improved stability and dynamic performance compared to conventional droop controllers. [5] Optimal control techniques have also been explored to manage multiple energy storage systems in microgrids. Xu and Shen proposed an optimal energy management strategy that minimizes adjustment costs while maintaining supply-demand balance. The method incorporated time-varying renewable generation, load demand, and electricity pricing, demonstrating effective coordination of multiple storage units and improved economic performance through rigorous theoretical and simulation analysis. [6]

Seamless transition between grid-connected and islanded microgrid modes requires robust and high-bandwidth control strategies. Mohamed et al. presented a direct-voltage control approach with optimized dynamic power sharing to minimize disturbances during mode transitions. The proposed control architecture improved voltage stability and disturbance rejection while reducing switching actions, making it suitable for practical microgrid implementations. [7]

Nonlinear adaptive control techniques have been employed to address the uncertainties inherent in renewable-based DC microgrids. Roy et al. designed an adaptive backstepping controller based on Lyapunov stability theory to regulate the DC bus voltage under varying operating conditions. The controller accounted for unknown system parameters and ensured voltage stability, with both simulation and experimental results validating its robustness. [8]

To enhance renewable integration and enable ancillary services, Iovine et al. developed nonlinear control strategies for DC microgrids capable of providing voltage and power stability while supporting AC grid frequency regulation. The proposed controllers outperformed conventional proportional-integral methods, particularly under dynamic operating conditions, as demonstrated through theoretical analysis and simulation results. [9] The stability of DC microgrids can be adversely affected by constant power loads due to their negative impedance characteristics. Li et al. proposed a novel nonlinear stabilizer for DC-DC multilevel boost converters supplying constant power loads. By integrating a disturbance observer with an adaptive backstepping controller, the approach ensured large-signal voltage stability and improved dynamic response, as confirmed through experimental validation. [10]

The primary objectives of this research are:

1. To design a fuzzy logic-based energy management system for a hybrid PV-wind-fuel cell DC microgrid.

2. To regulate the common DC line voltage within acceptable limits under fluctuating source and load conditions.
3. To prioritize renewable energy sources and minimize dependence on auxiliary or non-renewable sources.
4. To reduce power fluctuations and improve power quality for EV and DC loads.
5. To enhance the reliability, stability and economic performance of the hybrid microgrid.
6. To suggest practical implementation solutions and improvement measures for enhancing the stability, efficiency, and real-time applicability of the proposed fuzzy logic-based energy management system in hybrid DC microgrids.

Problem Statement:

The high penetration of renewable energy sources in DC microgrids introduces challenges such as power intermittency, voltage fluctuations, and inefficient power sharing among hybrid sources. Conventional linear controllers with fixed gains are inadequate to handle the nonlinear dynamics and uncertainties caused by variable generation and dynamic loads, particularly in systems supplying electric vehicle loads. Therefore, an intelligent and flexible energy management strategy is required to regulate the DC bus voltage, maximize renewable energy utilization, and ensure stable and reliable microgrid operation under varying operating conditions.

III. METHODOLOGY

The proposed work focuses on the design and implementation of a hybrid DC microgrid integrated with renewable energy sources and an intelligent energy management controller. The system primarily consists of a Wind Energy Conversion System (WECS), a photovoltaic (PV) system, a battery energy storage system (BESS), power electronic converters, and a fuzzy logic-based energy management system (EMS), all interconnected through a common DC link voltage.

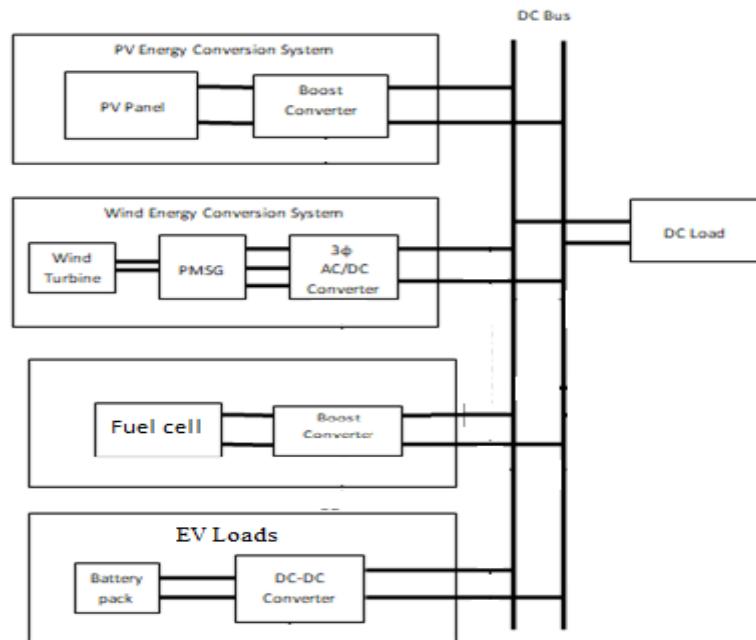


Fig. 1 PV Wind Fuel Cell BESS based Hybrid DC Microgrid for Multiple EV fast charging Infrastructure

[1] Hybrid Microgrid Structure

The hybrid microgrid integrates wind and solar energy sources to supply DC loads and electric vehicle loads through a regulated DC-link. Wind energy is converted into electrical energy using a permanent magnet synchronous generator (PMSG), while solar energy is harvested using a PV array. Both sources are interfaced to the DC bus through controlled DC-DC boost converters to ensure voltage compatibility and maximum power extraction. A battery storage system is connected via a bidirectional DC-DC converter to balance power mismatches and enhance system reliability.

[2] Wind Energy Conversion System Modelling

The wind energy system captures kinetic energy from wind using a turbine and converts it into electrical power through a PMSG. The aerodynamic power depends on air density, turbine swept area, wind speed, and the power coefficient. The PMSG is modelled in the synchronous rotating d-q reference frame, which enables effective control of electromagnetic torque and generator speed. This modelling approach allows accurate representation of generator dynamics and efficient integration with power electronic converters.

[3] Photovoltaic System Modelling

The PV array is modelled using a single-diode equivalent circuit consisting of a current source, diode, series resistance, and shunt resistance. The PV output current is influenced by solar irradiance and temperature variations. Mathematical relations based on semiconductor theory are used to describe the PV characteristics under standard test conditions and varying environmental conditions. This model helps in analysing PV behaviour and implementing effective maximum power point tracking (MPPT).

[4] Maximum Power Point Tracking (MPPT)

To maximize energy extraction from both wind and solar sources, a perturb and observe (P&O) MPPT algorithm is employed. The MPPT controller continuously adjusts the duty cycle of the boost converter by observing changes in DC-link voltage and power. This approach eliminates the need for mechanical sensors such as wind speed sensors, thereby reducing system cost and complexity. The algorithm ensures that the operating point converges to the maximum power point under changing environmental conditions.

[5] Boost Converter Design

DC-DC boost converters are used to step up the low and variable DC voltages obtained from renewable sources to a stable DC-link voltage. The converter output voltage is controlled by regulating the duty cycle. Proper design of inductors and capacitors ensures reduced current ripple and stable voltage output. The boost converter serves as a key interface between renewable sources and the DC microgrid.

[6] Battery Energy Storage System

A lithium-based battery energy storage system is integrated into the DC microgrid through a bidirectional DC-DC converter. The battery operates in both charging and discharging modes depending on power availability and load demand. The state of charge (SOC) of the battery is monitored to prevent overcharging and deep discharging. The BESS helps in mitigating power fluctuations caused by intermittent renewable generation and improves overall system stability.

[7] Energy Management System (EMS)

The proposed EMS operates in multiple modes based on the balance between generated power and load demand. When renewable generation exceeds load requirements, surplus power is stored in the battery. During power deficit conditions, the battery supplies energy to maintain DC bus voltage stability. If both renewable sources and storage are insufficient, grid support is enabled. Priority is always given to renewable sources to minimize operational cost and emissions.

[8] Fuzzy Logic Controller Design

A fuzzy logic controller (FLC) is developed to regulate power flow and manage the energy storage system. The controller uses DC bus voltage error and rate of change of error as input variables. These inputs are fuzzified using membership functions and processed through a rule base designed using expert knowledge. Mamdani inference and centroid defuzzification methods are employed to generate control signals. The FLC provides robust performance under nonlinear and uncertain operating conditions without requiring an accurate mathematical model[11].

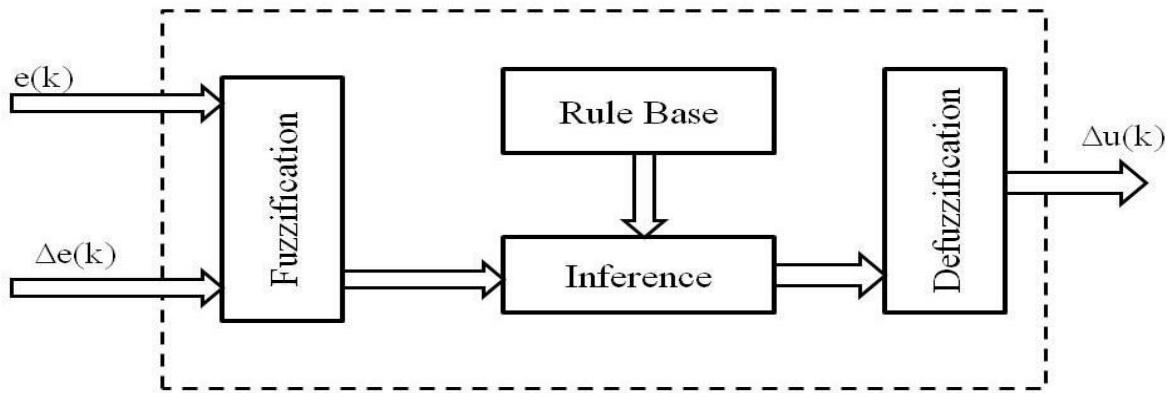


Fig.2 Fuzzy Logic Controller design for PV Wind Fuel Cell based BESS and Grid connection

[9] PWM Control and Inverter Operation

Pulse width modulation (PWM) techniques are used to control inverter switches and regulate output voltage. Sinusoidal PWM is adopted due to its simplicity and effectiveness in reducing harmonic distortion. The modulation index controls the output voltage amplitude, while the carrier frequency determines the switching frequency. Proper selection of PWM parameters ensures efficient power conversion and improved power quality[12].

Overall Implementation

The entire system is modelled and simulated using MATLAB/Simulink. The proposed control strategy is evaluated under varying wind speed, solar irradiance, and load conditions. Performance metrics such as DC bus voltage regulation, power sharing, battery SOC, and system stability are analysed to validate the effectiveness of the proposed fuzzy logic-based energy management approach.

IV. DEVELOPMENT OF SIMULINK MODEL

The developed Simulink model is tested under steady-state and dynamic operating conditions. The connection of the second EV load at $t = 0.4s$ introduces a sudden increase in demand, allowing validation of the controller's dynamic response. Simulation results demonstrate effective voltage regulation, proper power sharing among sources, and stable operation of the hybrid microgrid under varying load conditions, confirming the practical feasibility of the proposed system. The Simulink model is developed to implement and validate a hybrid DC microgrid integrating photovoltaic (PV), wind energy conversion system (WECS), and fuel cell (FC) sources with a common DC link voltage for high-power load and electric vehicle (EV) charging applications. The overall objective of the model is to achieve regulated DC bus voltage, coordinated power sharing among multiple sources, and stable operation under dynamic load variations. In this, PV, wind energy and fuel cell are the three sources used for power generation. The PV voltage is 400V and power is 500KW, Wind energy conversion system voltage is around 400V and power is 400KW and fuel cell voltage is 400V and power is 100KW. Each source is connected with dc-dc converter in order to get regulated dc voltage, so that it can be connected in parallel to for dc bus. It is connected to load of 300KW and with EV load1 of 350KW and EV load2 (connected at $t=0.4s$) of 350KW.

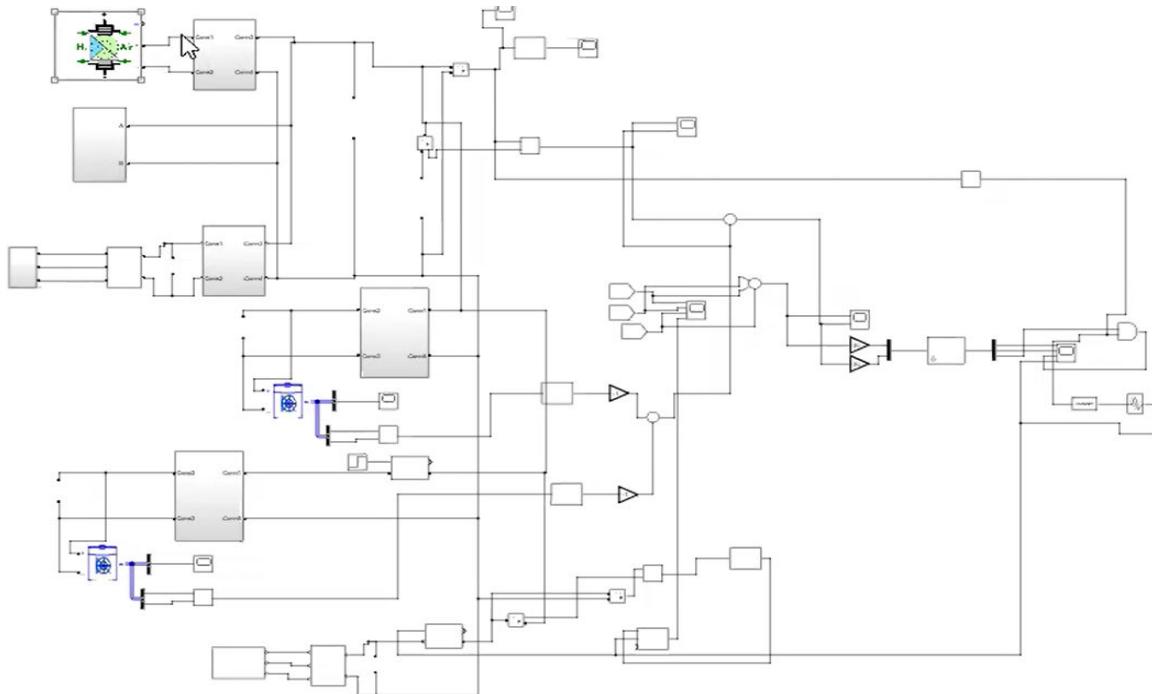


Fig. 3 PV Wind BESS Hybrid DC Microgrid for EV fast Charging infrastructure

In the proposed hybrid DC microgrid, a fuzzy logic controller (FLC) is implemented to regulate the common DC link voltage and manage power flow among renewable sources, energy storage systems, and loads under nonlinear and uncertain operating conditions. The controller uses two inputs: the DC link voltage error, defined as the difference between the reference and actual DC link voltages, and the change in voltage error, which indicates the dynamic variation of the voltage deviation. These inputs enable the FLC to assess both the magnitude and trend of voltage imbalance in the microgrid. Based on a predefined set of linguistic rules and membership functions, the FLC generates a control output that adjusts the duty cycle or reference current of the associated DC-DC converters. When the DC link voltage falls below its reference value, the controller increases power injection into the bus, while excess voltage results in reduced power delivery or energy absorption. This intelligent, model-free control approach ensures stable DC link voltage, smooth transient response, and effective power sharing among sources during load and generation fluctuations.

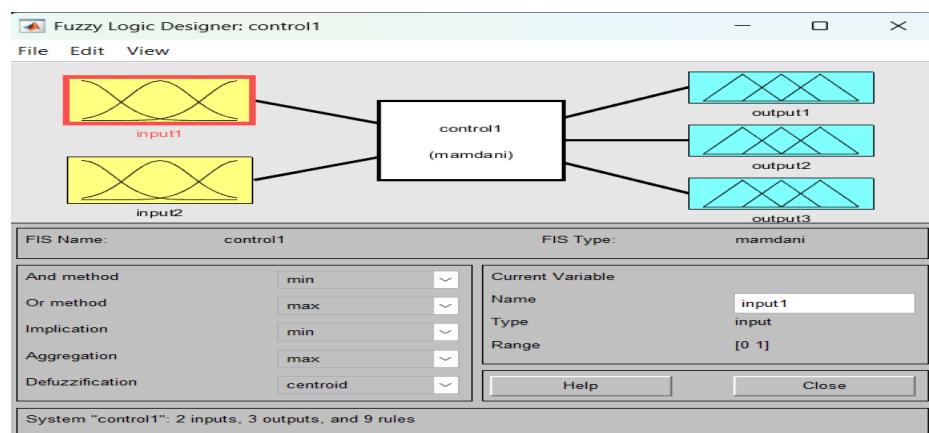


Fig. 4 Fuzzy Logic Controller Implementation to choose proper sources depending upon power demand

V. RESULT AND DISCUSSION

In this work, the power generated from PV is reduced at $t=0.3s$ and excess loads are connected at $t=0.4s$ and hence grid is connected and provides required power to the loads. The PV power reduced from 500KW to 260KW during $t=0.3s$ due to the reduction in irradiation from $1000W/m^2$ to $400W/m^2$. The grid is disconnected from $t=0$ to $t=0.4s$ and it starts to provide power at $t=0.4s$ as the load demand is increased from 650KW to 1200 KW.

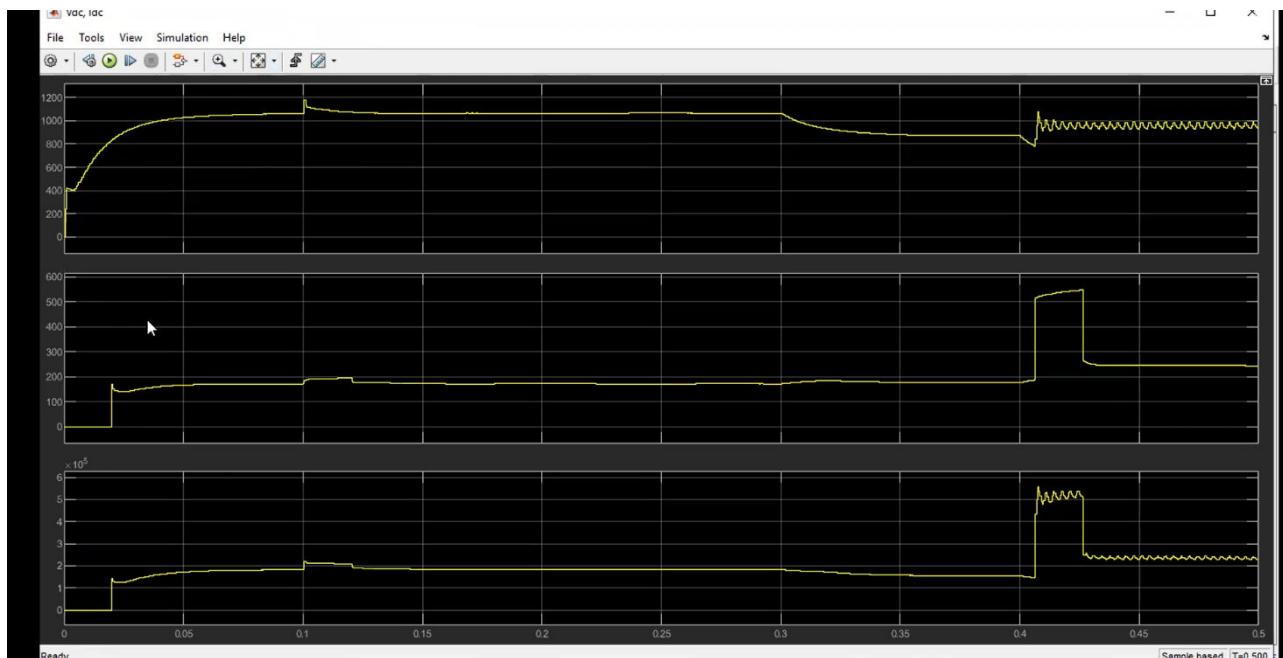


Fig. 5 Power generation curves from PV, Wind, Fuel cell and Grid

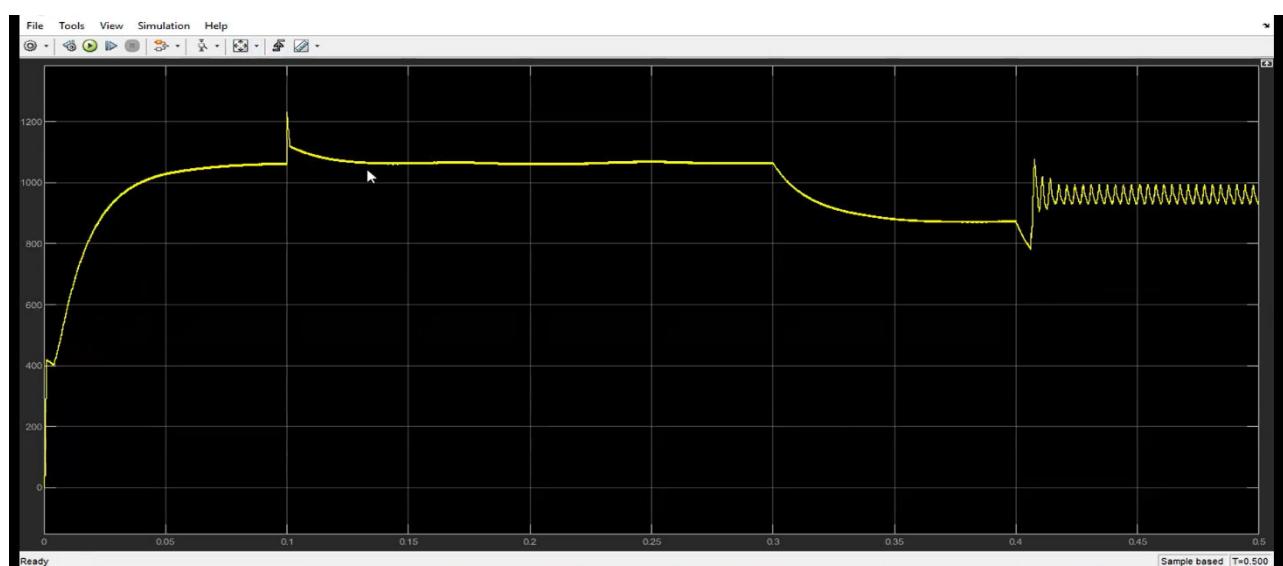


Fig. 6 The dc voltage waveform from the dc link

The dc voltage is regulated at 1000V even when the load is increased at $t=0.4s$ and a voltage sag occurs and recovers due to the grid



Fig. 7 Power Source Availability Waveform

The PV and wind energy sources are available initially and when PV energy is reduced, Fuel cell is connected and when extra EV load is connected at $t=0.4s$, grid is connected.

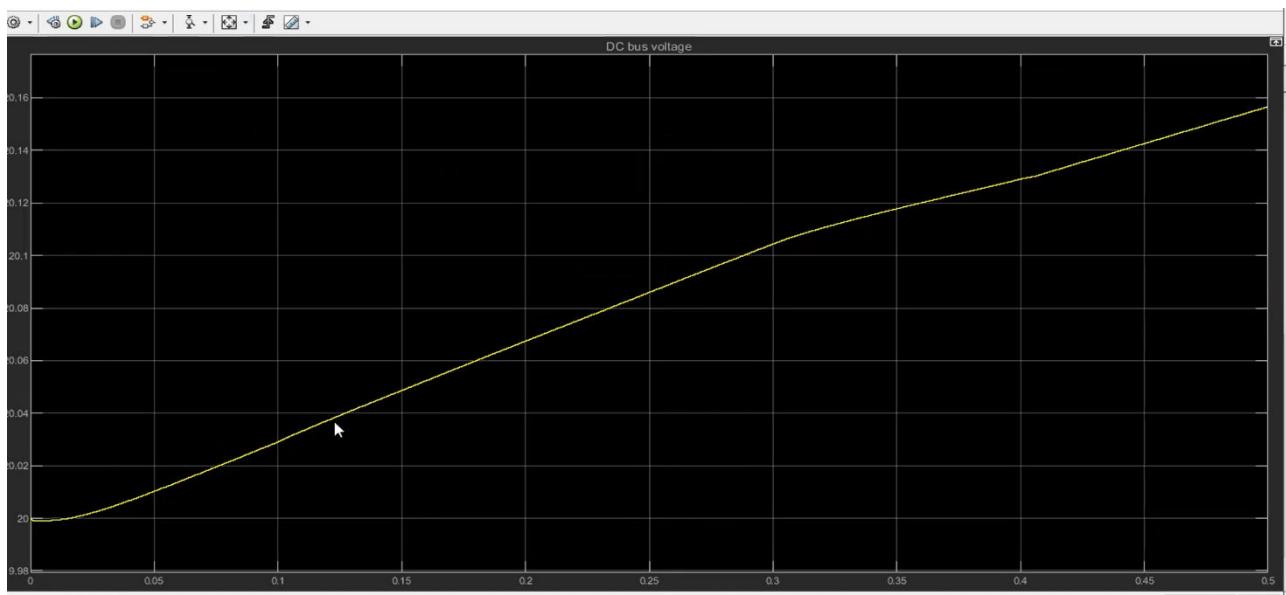


Fig .8 State of Charge of Electric Vehicle Battery 1

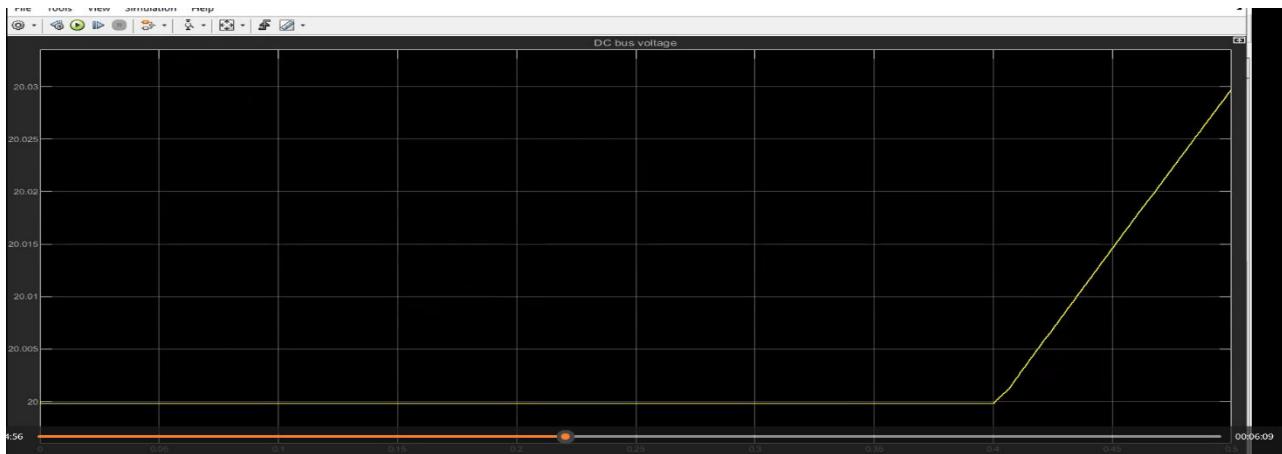


Fig .9 State of Charge of Electric Vehicle Battery 2

VI. CONCLUSION AND FUTURE SCOPE

In this work, a fuzzy logic-based energy management and control system for a hybrid DC microgrid integrating photovoltaic, wind, fuel cell sources, energy storage systems, and electric vehicle loads was successfully implemented and validated. The proposed controller effectively regulates the DC bus voltage, mitigates power fluctuations caused by renewable intermittency, and ensures coordinated power sharing among hybrid sources in real time. Experimental/simulation results confirm that the fuzzy logic controller provides faster dynamic response, improved stability, and enhanced power quality compared to conventional fixed-gain controllers under varying generation and load conditions. The implemented system demonstrates reliable operation, maximized utilization of renewable energy, and continuous power supply to EV loads, thereby validating the practicality and effectiveness of intelligent control strategies for advanced DC microgrid applications.

Future Scope:

Future research can focus on advancing the proposed DC microgrid toward real-world deployment by incorporating digital twin frameworks for real-time monitoring and predictive optimization, and AI-driven self-learning energy management systems capable of autonomous adaptation under uncertain operating conditions. The integration of wide-bandgap power electronic devices with hardware-in-the-loop validation, along with cyber-resilient and secure control architectures, represents a critical yet largely unexplored area for practical implementation. Further extensions may include peer-to-peer energy trading using blockchain, coordinated integration of hydrogen-based Power-to-X technologies for long-term energy storage, and renewable-supported ultra-fast EV charging infrastructure. Ultimately, the development of fully autonomous, self-healing DC microgrids with minimal human intervention remains an open and highly advanced research direction not yet realized in practical systems.

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