An Improved Energy Management Strategy for a DC Microgrid with Electric Vehicle Fast Charging Stations Using Fuzzy Logic Control

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Abstract: This extension of the original study presents the incorporation of a fuzzy logic controller (FLC) into the control strategy for the DC microgrid, further enhancing the integration of the electric vehicle fast charging station (EVFCS) and distributed generation units. The fuzzy controller is employed to optimize the operation of the system by providing adaptive control for voltage regulation, improving the performance of the distribution static compensator (D-STATCOM) device, and ensuring more efficient interaction between the EV battery and the grid. The results, obtained through MATLAB Simulink/SimPower Systems simulations, demonstrate that the FLC improves the system's ability to handle voltage fluctuations, reduces charging durations, and enhances grid stability, particularly under varying load and generation conditions. The extension showcases how the fuzzy controller enhances the overall efficiency of the EVFCS, making it a more reliable and flexible solution for modern grid applications, especially in the context of vehicle-to-grid (V2G) technology.

Keywords: Electric vehicles, fast charging stations, microgrid, distributed generation,V2G, Fuzzy Logic Controller.

I. INTRODUCTION

The rapid proliferation of electric vehicles (EVs), driven by advancements in battery technology and environmental concerns, necessitates the development of efficient and high-power charging infrastructure. According to the International Energy Agency (IEA), the global EV stock is projected to reach approximately 250 million by 2030. However, conventional Level-1 and Level-2 charging systems suffer from prolonged charging durations (4–16 hours), limiting their suitability for fast and dynamic applications.

To address this limitation, Level-3 DC fast charging stations, also referred to as Electric Vehicle Fast Charging Stations (EVFCS), have been introduced, enabling significantly reduced charging times (typically <30 minutes). Nevertheless, the highpower demand of EVFCS imposes substantial stress on distribution networks, leading to voltage deviations, increased power losses, and degradation of power quality. Moreover, reliance on grid-supplied energy contributes indirectly to carbon emissions.

Recent research has focused on integrating EVFCS within **low-voltage DC (LVDC) microgrids** incorporating renewable energy sources such as photovoltaic (PV) systems and wind generation. Such architectures enhance energy utilization efficiency, reduce grid dependency, and improve system reliability. Furthermore, **Vehicle-to-Grid (V2G)** technology enables bidirectional power flow, allowing EV batteries to function as distributed energy resources for ancillary services such as voltage regulation and load balancing.

Although several studies have investigated EVFCS integration, renewable-based microgrids, and V2G-enabled energy management strategies, limited attention has been given to the utilization of EV batteries as a **DC-link energy source for Distribution Static Compensator (D-STATCOM)** applications to enhance power quality.

In this work, a **decentralized control strategy for an LVDC microgrid integrated with EVFCS** is proposed. The system incorporates renewable energy sources and utilizes the EV battery in V2G mode as a DC source for a D-STATCOM to mitigate voltage sag and swell in the distribution network. Additionally, a **Fuzzy Logic Controller (FLC)** is employed to regulate system dynamics, offering improved transient response, reduced steady-state error, and enhanced robustness compared to conventional PI controllers.

II. SYSTEM DESCRIPTION:

A low-voltage DC (LVDC) microgrid is considered in this study due to its advantages over AC microgrids for Electric Vehicle Fast Charging Stations (EVFCS), particularly in enhancing peak load performance without increasing grid capacity.

Among renewable energy sources, **photovoltaic (PV) arrays** are selected as the primary distributed generation units due to their suitability for urban deployment, ease of integration, and relatively stable output characteristics. Compared to wind energy systems, PV-based generation provides more predictable and controllable power, making it more suitable for EV charging applications.

The proposed LVDC microgrid consists of a PV array, utility grid, and EVFCS interconnected through a common DC link. The PV system operates under standard test conditions (1000 W/m² irradiance and 25°C temperature) and is interfaced with the DC bus via a DC/DC converter. The EVFCS is connected to the DC link through a bidirectional DC/DC converter, enabling both charging (Grid-to-Vehicle, G2V) and discharging (Vehicle-to-Grid, V2G) operations.

Additionally, the utility grid and local loads are interfaced with the DC link through controlled AC/DC converters. The control of these converters is achieved using a pulse-width modulation (PWM) scheme with inner current and voltage control loops regulated by conventional PI controllers. This ensures stable DC bus voltage and efficient power flow management under varying operating conditions.

The proposed configuration provides a flexible and efficient framework for integrating EV fast charging with renewable energy sources while maintaining system stability and enabling future implementation of advanced control strategies such as fuzzy logic control.

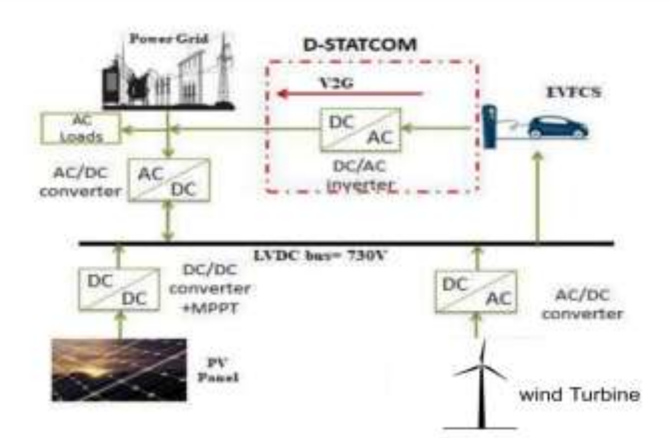


Fig. 1. Schematic diagram of the proposed system.

II.SOLAR PV GENERATION

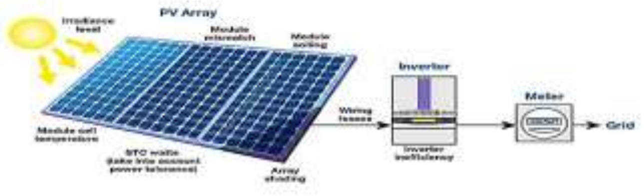


Fig.2. solar PV generation

Introduction

Solar PV generation is the process of generating electricity from sunlight through the use of solar PV technology. Solar PV systems transform solar energy into DC electricity, which can subsequently be converted into AC electricity that is suitable for powering residential and commercial buildings, as well as other electrical loads.

A solar PV system comprises fundamental components such as solar panels, an inverter, and a mounting system. Solar panels contain numerous solar cells that transform sunlight into DC electricity. The inverter converts DC into AC, which can be utilized to power electrical loads or supplied back to the grid. The mounting system is responsible for securing the solar panels in position and ensuring they are oriented towards the sun for optimal energy generation.

Solar PV generation has become an increasingly important source of renewable energy, as the cost of solar PV systems has decreased over time and their efficiency has increased. Solar PV systems can be installed on rooftops or on the ground, and can range in size from small residential systems to large-scale utility systems that generate megawatts of electricity.

One of the main advantages of solar PV generation is that it produces electricity without emitting greenhouse gases or other pollutants, making it a clean and sustainable source of energy. Additionally, solar PV systems can provide power in remote locations where access to electricity is limited or expensive, and can reduce reliance on fossil fuels and the grid.

III. Wind Power Generation

Wind power systems convert wind's kinetic energy into electricity via turbines. Key components: rotor blades, nacelle (housing generator/gearbox), tower, and control systems. Electricity feeds the grid via transformers/inverters.

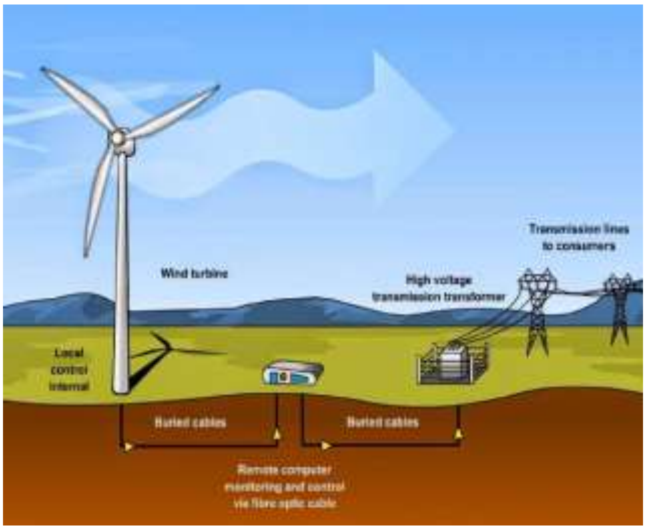


Fig.3.1. Wind power Generation

Turbines are horizontal-axis (HAWT, most common) or vertical-axis (VAWT). Installed onshore or offshore; scale from home units to utility farms. Clean (no emissions), but impacts wildlife/noise require mitigation.

Characteristics of Wind Power

Renewable and abundant worldwide.

Variable output (depends on wind speed/direction).

Scalable; low operating costs.

Environmentally friendly; land-intensive with noise/wildlife risks.

Wind Generators:

Wind generators (turbines) feature tower, rotor (2-3 blades), and generator. Sizes range from residential to utility-scale. Often paired with solar for reliability.

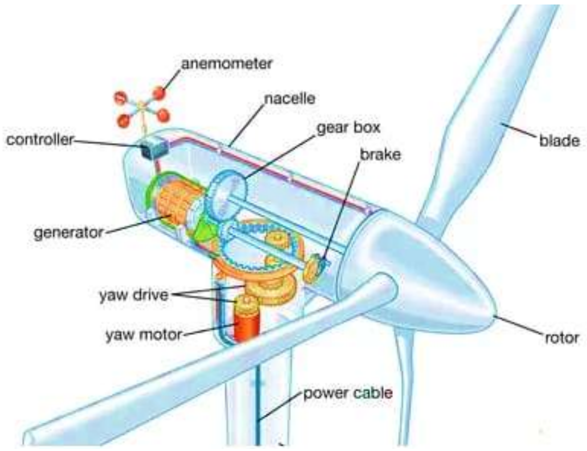


Fig.3.2. Exploded view of wind turbine components

Wind Turbine Design:

Rotor blades/hub: Capture/optimize wind (fiberglass/carbon fiber).

Nacelle: Gearbox, generator, yaw system.

Tower: Elevates for better wind (steel/concrete).

Control system: Monitors/adjusts for efficiency.

Modern turbines: Up to 200m tall, 220m rotor diameter.

Wind Power Generation Control:

Turbine control: Sensors adjust pitch/yaw.

Power output: Blade pitch limits for grid stability.

Grid integration: Power electronics stabilize variable output.

Forecasting/storage: Predicts/supplements with batteries.

IV. Decentralized Control System Based on PI Controllers

A **decentralized control system (DCS)** is implemented, where each component of the EV fast charging station (EVFCS) operates independently. This approach enables flexible integration of new elements without affecting existing system components. Independent **PI-based controllers** are designed for the power converters of the grid and diesel generator.

For the PV system, the boost converter operates under **maximum power point tracking (MPPT)** to extract maximum power by regulating the PV terminal voltage. Hence, an additional PI controller is not required for PV control.

The primary objective of the DCS is to **maintain the low-voltage DC (LVDC) bus voltage at its reference value** and ensure power balance within the system. This is achieved by coordinating the power contributions of the PV system and grid.

IV.A. Inverter Control

The voltage source AC/DC inverter is controlled to maintain a **constant DC bus voltage of 730 V**. Variations in load demand or generation are compensated by regulating the DC bus voltage, ensuring stable operation and power exchange with the grid.

The control scheme consists of:

- One **outer voltage control loop**
- Two **inner current control loops (d-axis and q-axis)**

A **phase-locked loop (PLL)** is used for synchronization with the grid and diesel generator voltages. The **d-axis current controls active power**, while the **q-axis current is set to zero**eliminate reactive power.

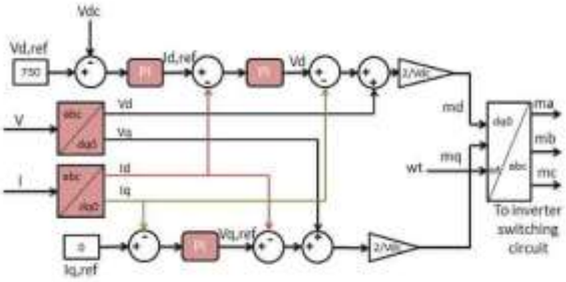


Fig.4.1. Inverter control system

IV.B. EV Charger Control

The EV charger consists of a battery, DC/DC converter, and PI-based control system. A PWM generator is used to provide switching pulses to the converter.

Two charging strategies are generally used:

- **Constant Current (CC) mode**
- **Constant Voltage (CV) mode**

In this study, **CC control** is adopted, where the battery behaves as a current source and the converter operates in boost mode. The PI controller regulates the charging current.

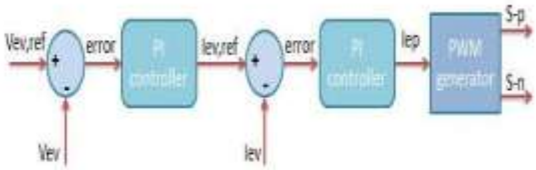


Fig.4.2. Constant Current Battery Charger Control

In this study, only the CC control methodology is implemented to operate the battery as a current source during the charging phase. The PI controller is tuned with proportional gain [kp = 5] and integral gain [ki = 0.0005].

$$V_{ev-error} = V_{ev-ref} - V_{ev} \quad (1)$$

$$I_{ev-ref} = V_{ev-error}\left(\frac{K_i}{s} + K_p\right) \quad (2)$$

$$I_{ev-error} = I_{ev-ref} - I_{ev} \quad (3)$$

$$I_{ep} = I_{ev-error}\left(\frac{K_i}{s} + K_p\right) \quad (4)$$

This CC-only formulation simplifies the control structure while ensuring stable current regulation during the main charging stage, which is critical for battery health and consistent charging performance.

V. VOLTAGE SAG/SWELL MITIGATION WITH EV BATTERY-INTEGRATED D-STATCOM

As EV battery with V2G can be used for peak shaving or valley falling and it contributes significantly to grid stability [18], EV battery in V2G mode can also be used as DC voltage source in D-STATCOM device to improve power quality. In order to have flexible charging or discharging rates as shown in Fig. 4, the charging and discharging are separated at the AC-DC converter stages [25]. The system consists of bidirectional DC-DC converter and two AC/DC converters for two-way operation.

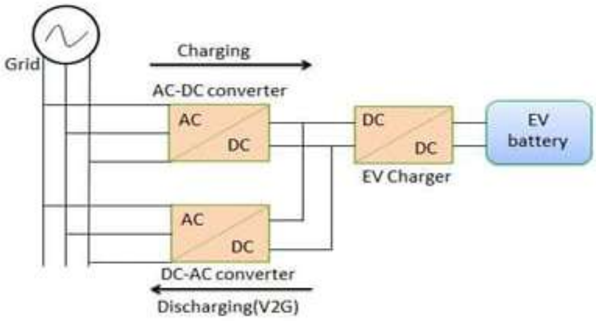


Fig.5.1. Block diagram of EV Charger and V2G Integrator

D-STATCOM is a shunt-connected power electronic based device, which is generally connected near the load at the distribution systems to mitigate power quality problems such as voltage sag, voltage swell and harmonics. In general, D-STATCOM consists of four main parts, namely, voltage source inverter (VSI), LC filter, control circuit and DC source, as shown in Fig. 5.

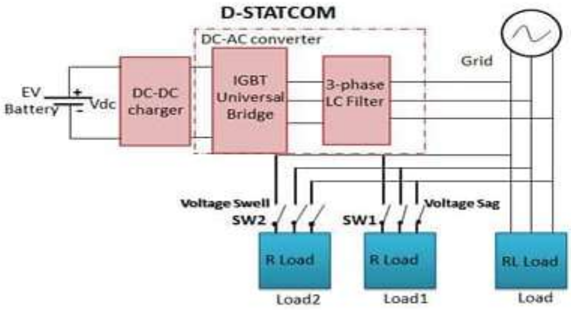


Fig.5.2. Block Diagram of D-STATCOM connected to the 3-phase distribution line.

V. Fuzzy Logic Controller (FLC)

Introduction:

A **Fuzzy Logic Controller (FLC)** is an intelligent control technique designed to handle **uncertainty, nonlinearity, and imprecise inputs**. Unlike conventional controllers, FLC uses **linguistic rules and fuzzy sets** to model complex systems without requiring an exact mathematical model.

FLC is based on **fuzzy logic theory**, introduced by *Lotfi Zadeh*, which allows variables to have **partial membership (0 to 1)** instead of binary values. This makes FLC highly suitable for EV charging systems and microgrids where system parameters vary dynamically.

The main advantage of FLC is its **robustness and adaptability**, making it effective for systems with changing operating conditions. It has been widely applied in control applications such as power systems, robotics, and automation.

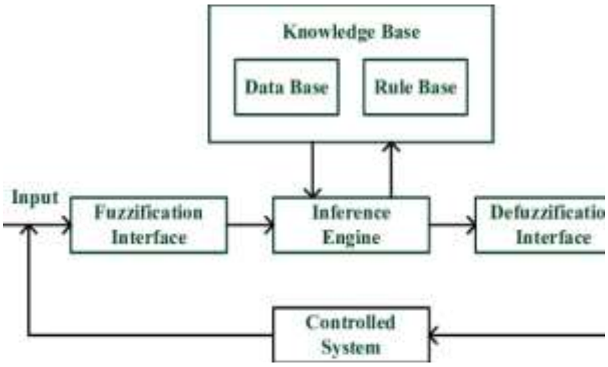


Fig.5.1. Block Diagram of Fuzzy Logic Controller

An FLC consists of four main components:

1. **Fuzzification**
   Converts crisp input variables into fuzzy sets using membership functions.
2. **Rule Base**
   A set of expert-defined **IF–THEN rules** that describe system behavior.
3. **Inference Engine**
   Processes input data and applies fuzzy logic operators (AND, OR) to determine output fuzzy sets.
4. **Defuzzification**
   Converts fuzzy outputs into crisp control signals using methods such as centroid (center of gravity).

V.B. FLC Operation

The operation of FLC involves four sequential steps:

- Fuzzification of input variables
- Rule evaluation using inference mechanism
- Aggregation of rule outputs
- Defuzzification to obtain a crisp output

In EV charging or control applications, inputs such as **error (E)** and **change in error (ΔE)** are commonly used, while the output corresponds to the control signal (e.g., duty cycle or current reference).

V.C. Rule Base (5x5 Matrix)

A **5x5 rule matrix** is typically used for better control accuracy. The input variables (E and ΔE) **are divided into five linguistic levels:**

- **NB** (Negative Big)
- **NS** (Negative Small)
- **ZE** (Zero)
- **PS** (Positive Small)
- **PB** (Positive Big)

The rule base maps these inputs to an output control action.

e *de*	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

V.D. Membership Function Plots

Membership functions (MFs) are used in a **Fuzzy Logic Controller (FLC)** to represent how each input and output variable is mapped into fuzzy sets. They define the **degree of membership (ranging from 0 to 1)** for a given input value.

Commonly used membership function shapes include:

- **Triangular** – simple and widely used due to low computational complexity
- **Trapezoidal** – suitable for representing ranges with flat regions
- **Gaussian** – smooth and effective for precise control applications

In this study, **triangular membership functions** are typically adopted for both input variables (**error (E)** and **change in error (ΔE)**) and output variables due to their simplicity and efficient implementation.

Each variable is divided into **five linguistic levels**:
NB, NS, ZE, PS, PB, which ensures finer control resolution.

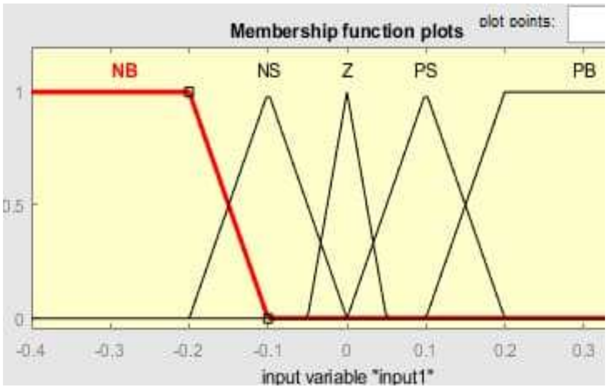


Fig. Membership function plot (input1)

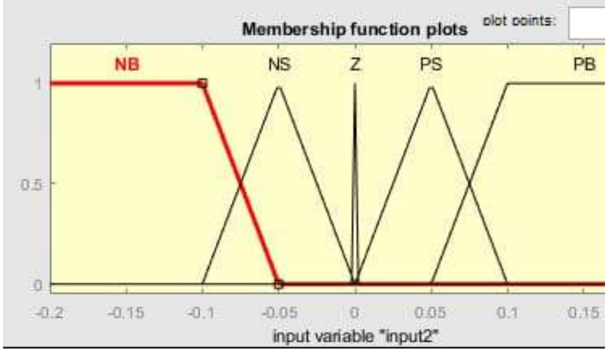


Fig. Membership function plot (input2)

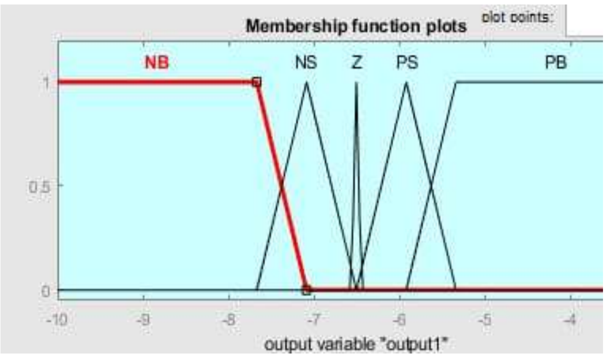


Fig. Membership function plot (output1)

The membership functions are usually **symmetrically distributed** over the input/output range to maintain system balance and stability.

V.D. Advantages of FLC

- Handles **nonlinear systems** effectively
- Works with **uncertain and imprecise data**
- Does not require an accurate mathematical model
- Provides **robust and adaptive control performance**
- Easy to implement in real-time applications .

VI. SIMULATION RESULTS

The proposed decentralized control strategy for the EVFCS integrated with a DC microgrid is simulated using MATLAB/Simulink. The system includes renewable sources and grid support. A comparison between PI and Fuzzy Logic Controller (FLC) is performed.

A. EV Battery Charging Performance

The EV battery is analyzed over 1 s. From 0–0.52 s, charging occurs from multiple sources; afterward, the grid becomes dominant. The DC bus voltage is maintained near 730 V with minor transient deviations. The FLC provides faster stabilization, reduced fluctuations, and improved efficiency compared to PI control.

B. Voltage Regulation using EV-Based D-STATCOM

The EV operates in V2G mode to regulate voltage.

- **Sag (0.2–0.4 s):** Battery supplies power to compensate voltage drop.
- **Swell (0.6–0.8 s):** System absorbs excess power to reduce overvoltage. Voltage is restored to ~300 V in both cases.

C. PI vs FLC Performance

FLC shows better performance with faster response, improved voltage regulation, reduced oscillations, and higher adaptability than PI control.

D. EV Battery Behavior in V2G

During sag, the battery discharges (↓voltage, ↑current); during swell, it absorbs energy (↑voltage, ↓current), confirming effective bidirectional operation.

Different charging modes (0.52 to 1 solar and wind disconnected case)

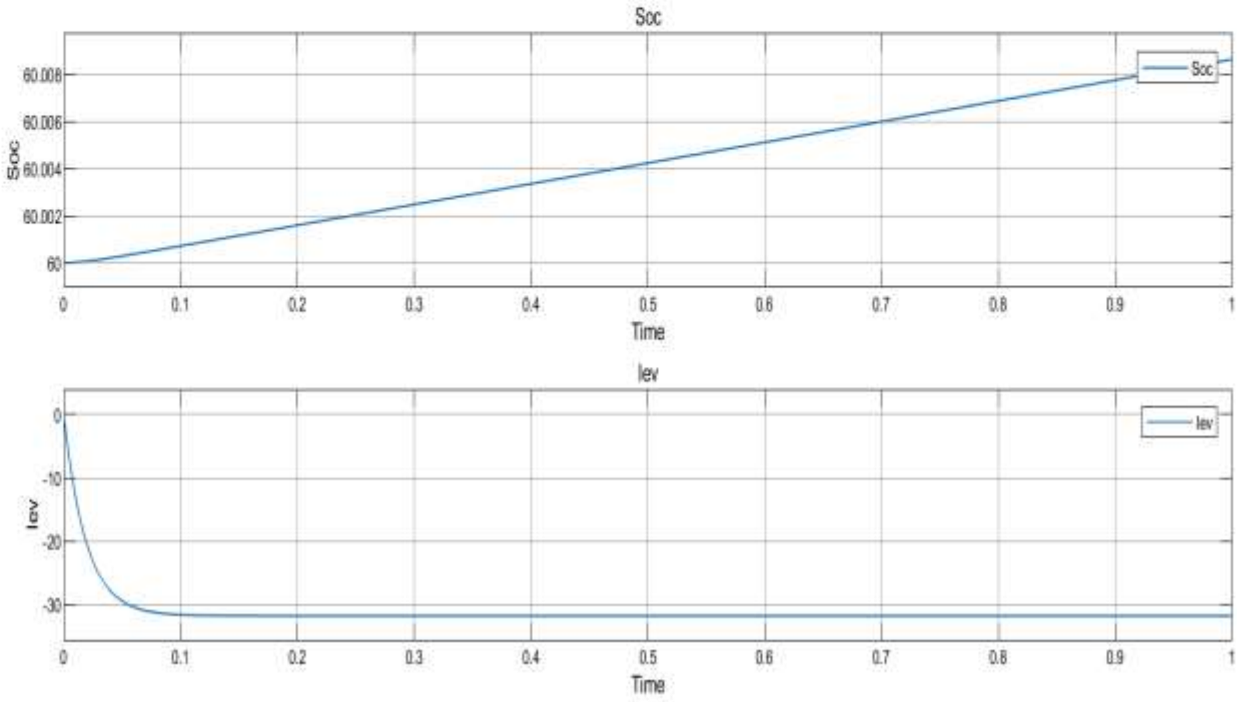


Fig. 6. Variation of EV battery variables for charging operation: (a) battery SOC, (b) battery current with PI Controller.

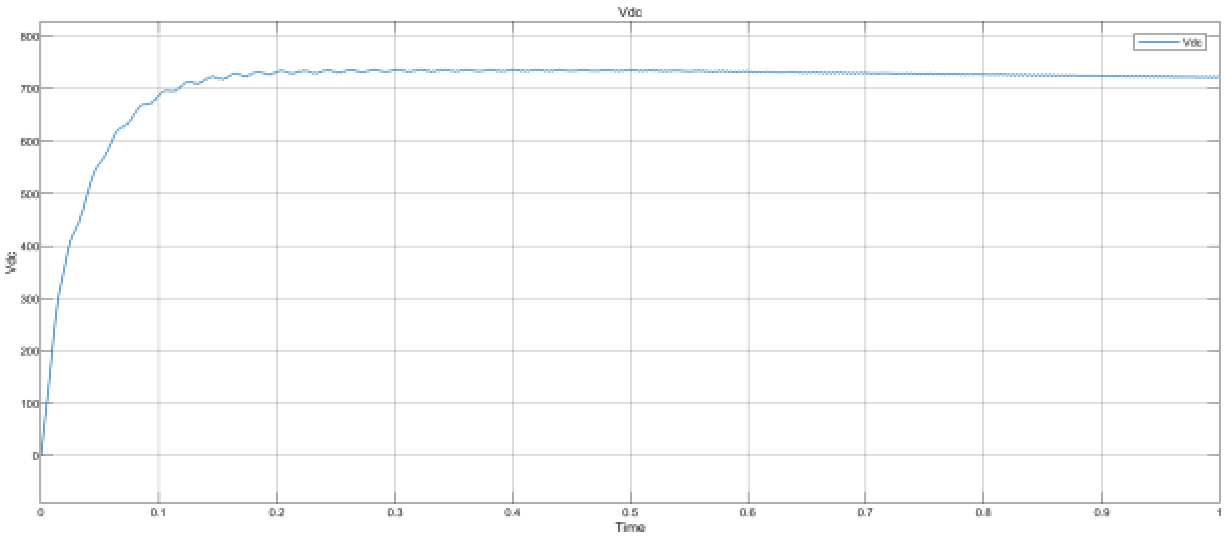


Fig. 7. DC bus voltage for different charging modes with PI Controller

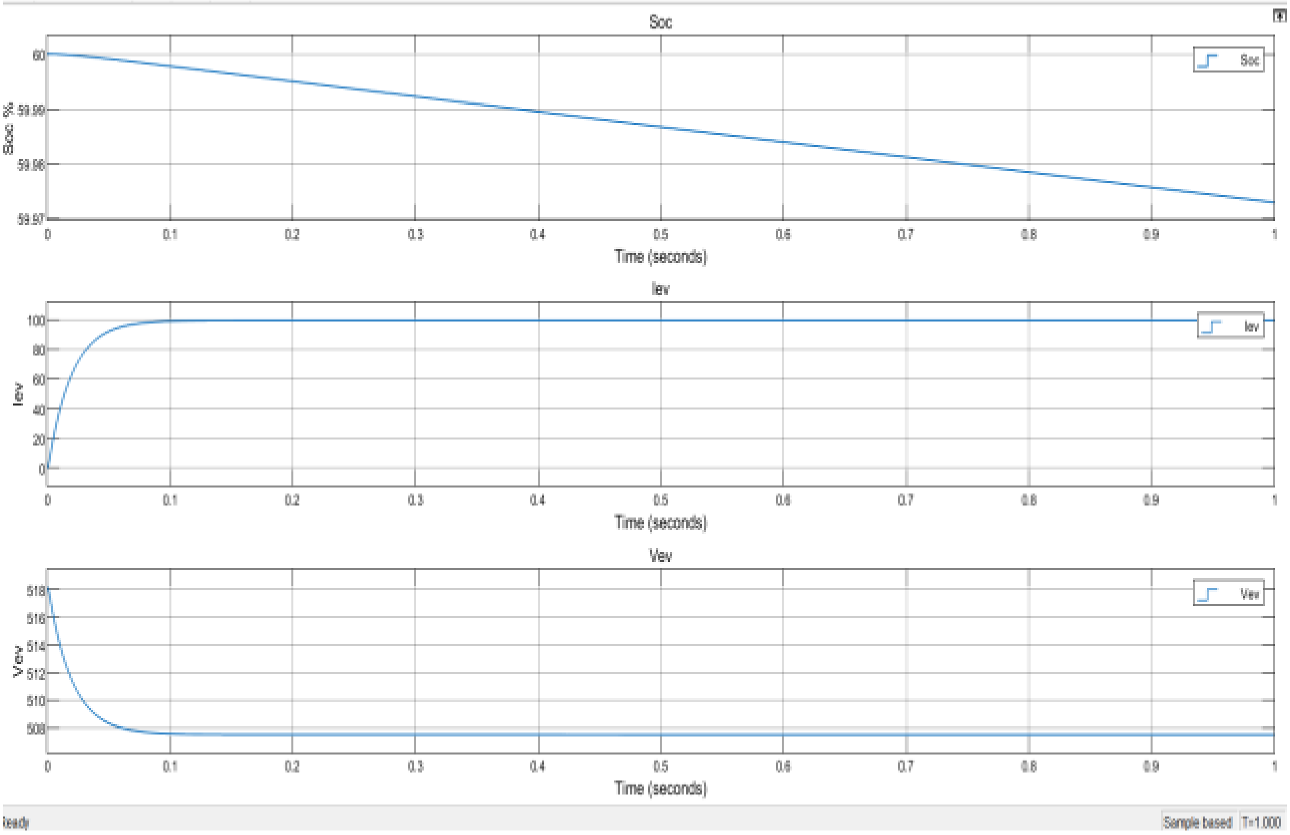


Fig.8. EV battery results for discharging operation: (a)Battery SOC, (b)Battery current, (c)Battery Voltage with PI Controller

Load variation:

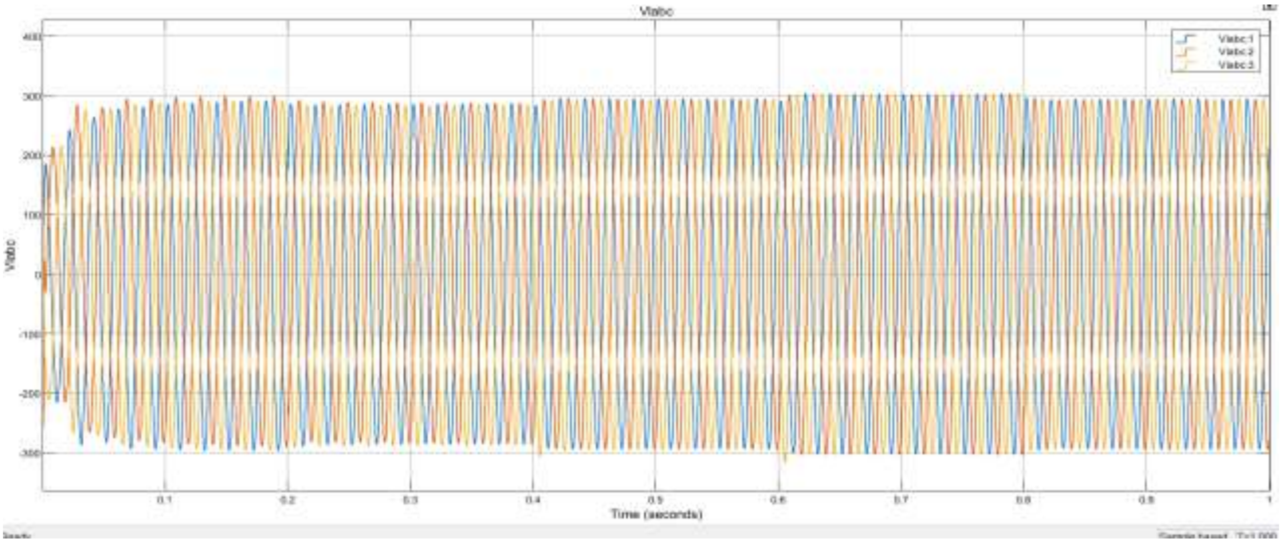


Fig. 9. Three phase voltage profile at load point with PI Controller

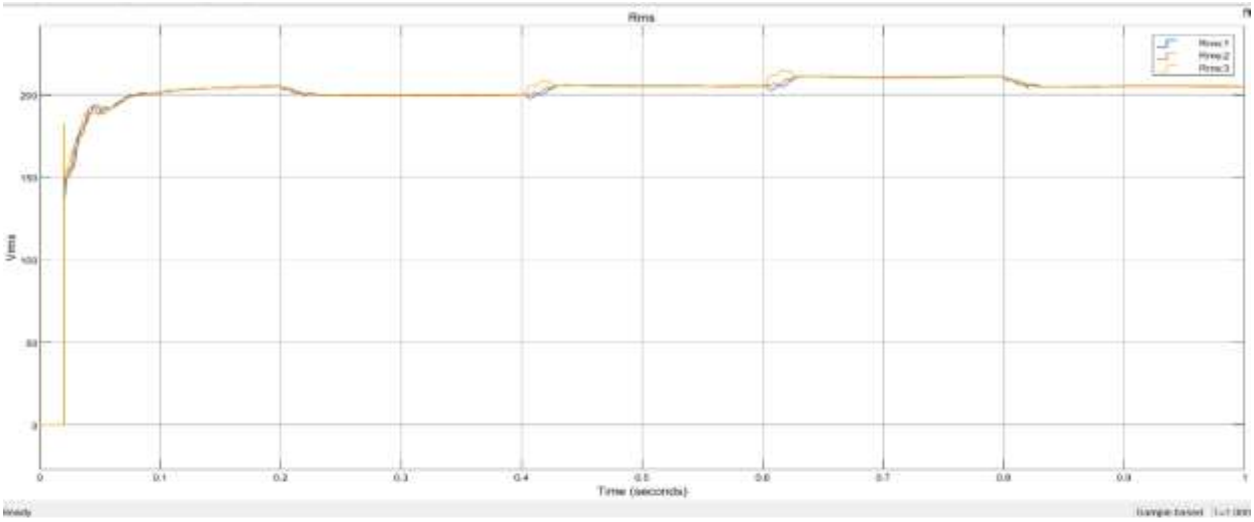


Fig.10. Voltage profile in (rms) at load point with PI Controller

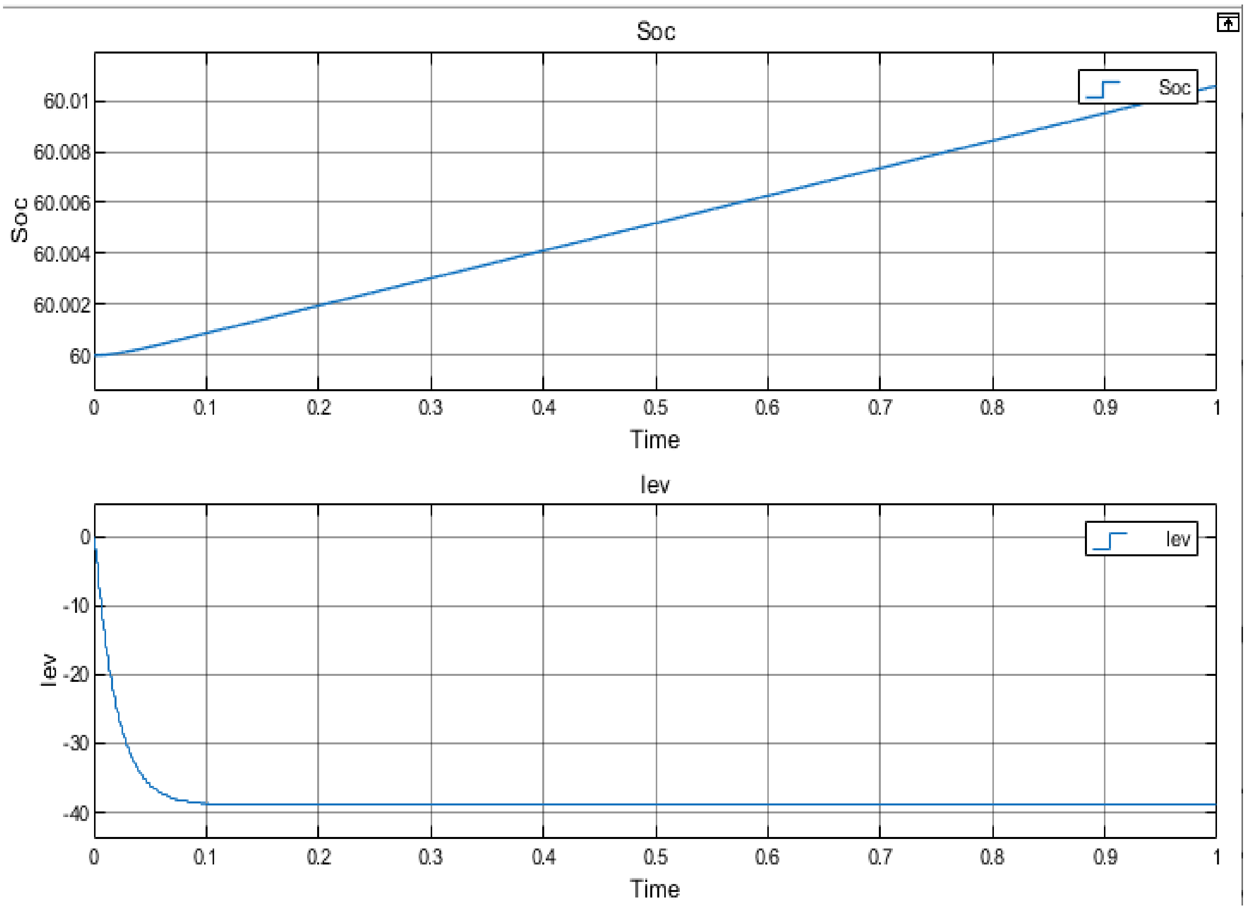


Fig. 11. Variation of EV battery variables for charging operation: (a) battery SOC, (b) battery current with Fuzzy Logic Controller.

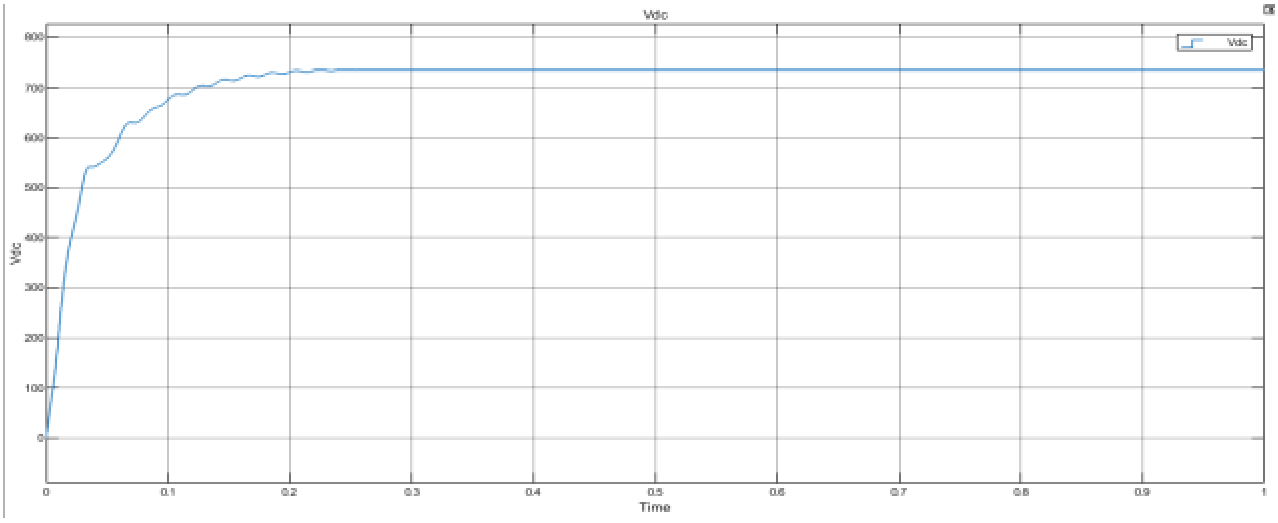


Fig.12. DC bus voltage for different charging modes with Fuzzy.

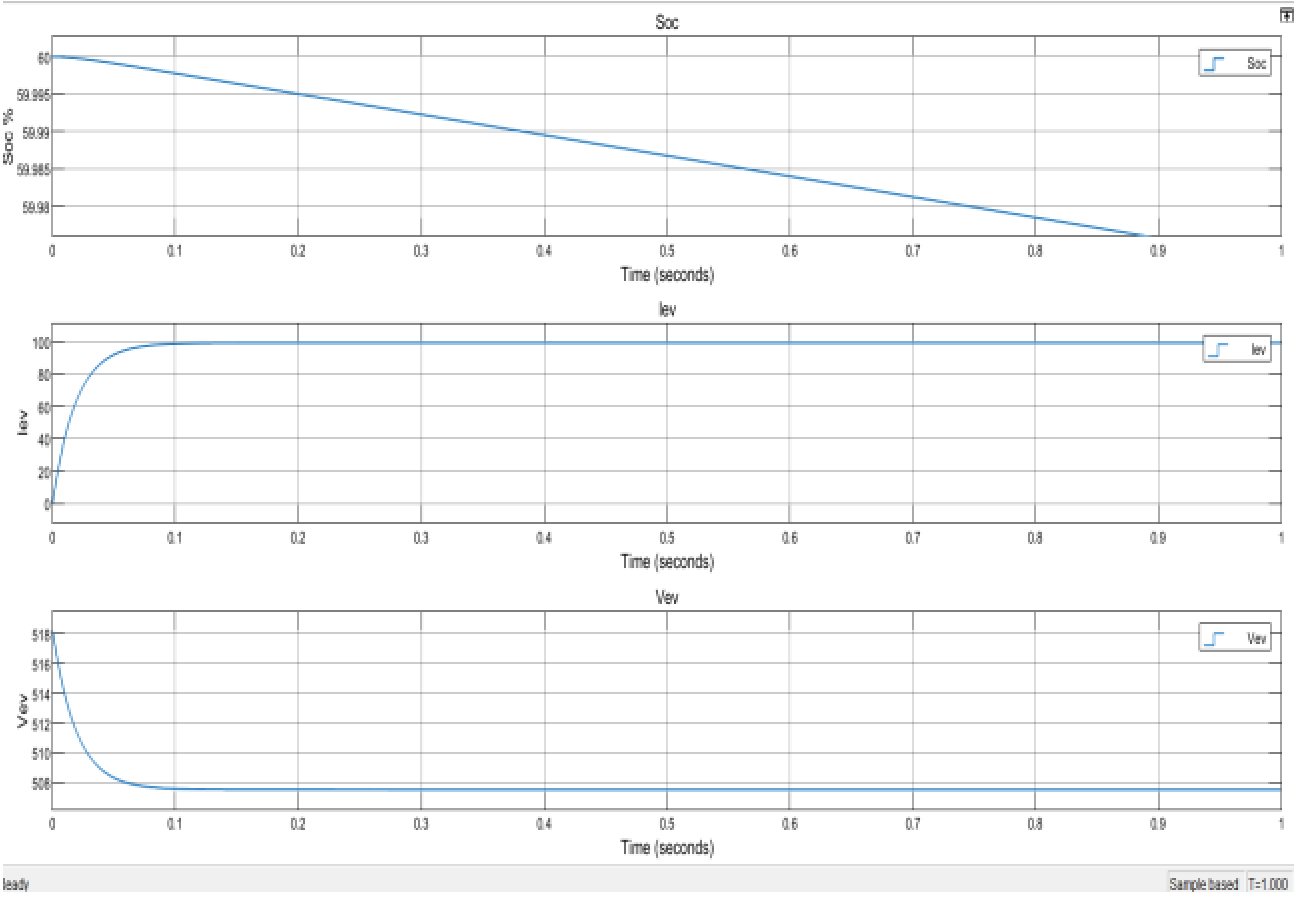


Fig.13. EV battery results for discharging operation: (a)Battery SOC, (b)Battery current, (c)Battery Voltage with Fuzzy logic Controller

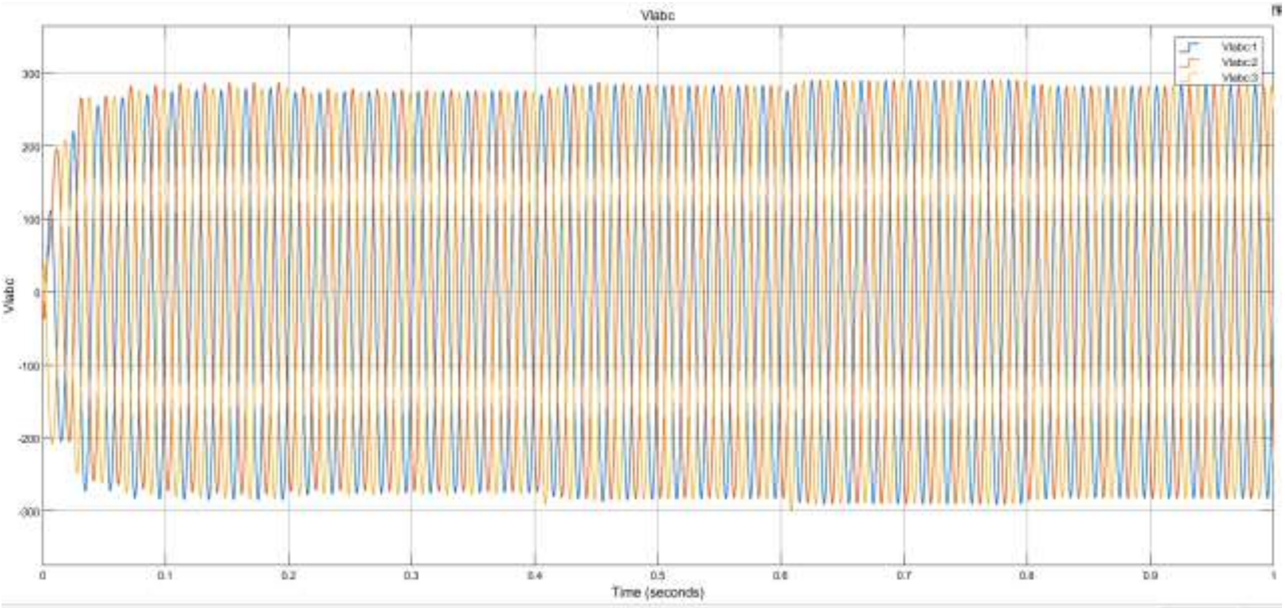


Fig. 14. Three phase voltage profile at load point with Fuzzy

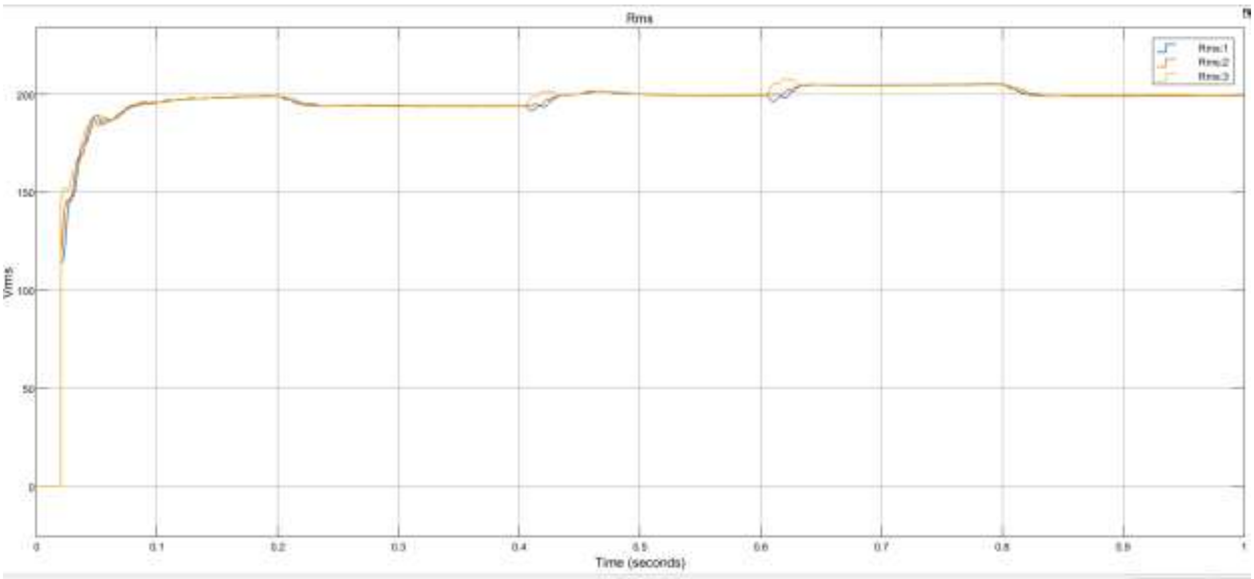
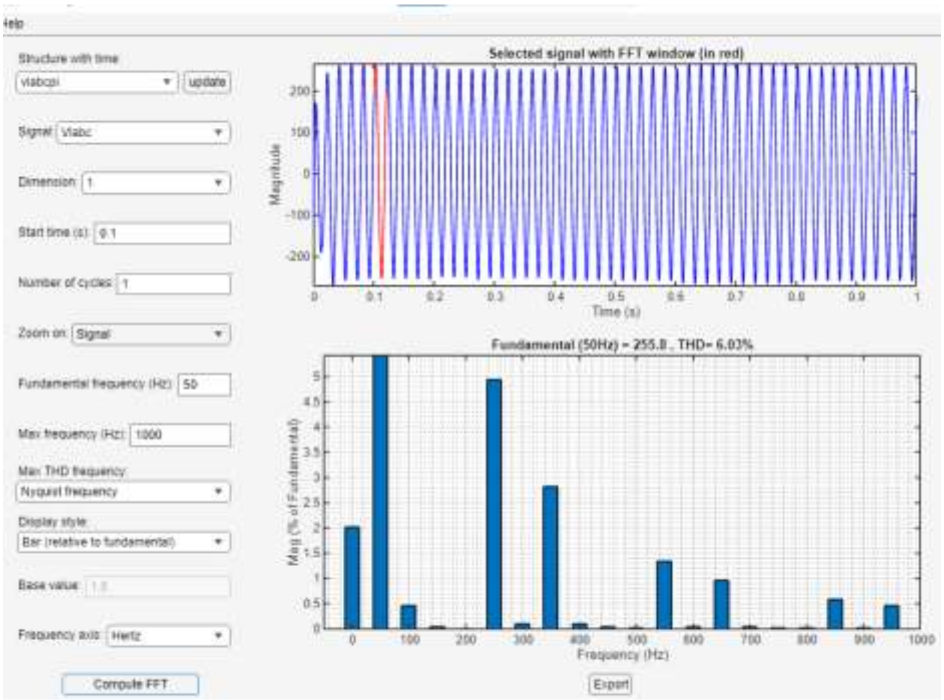
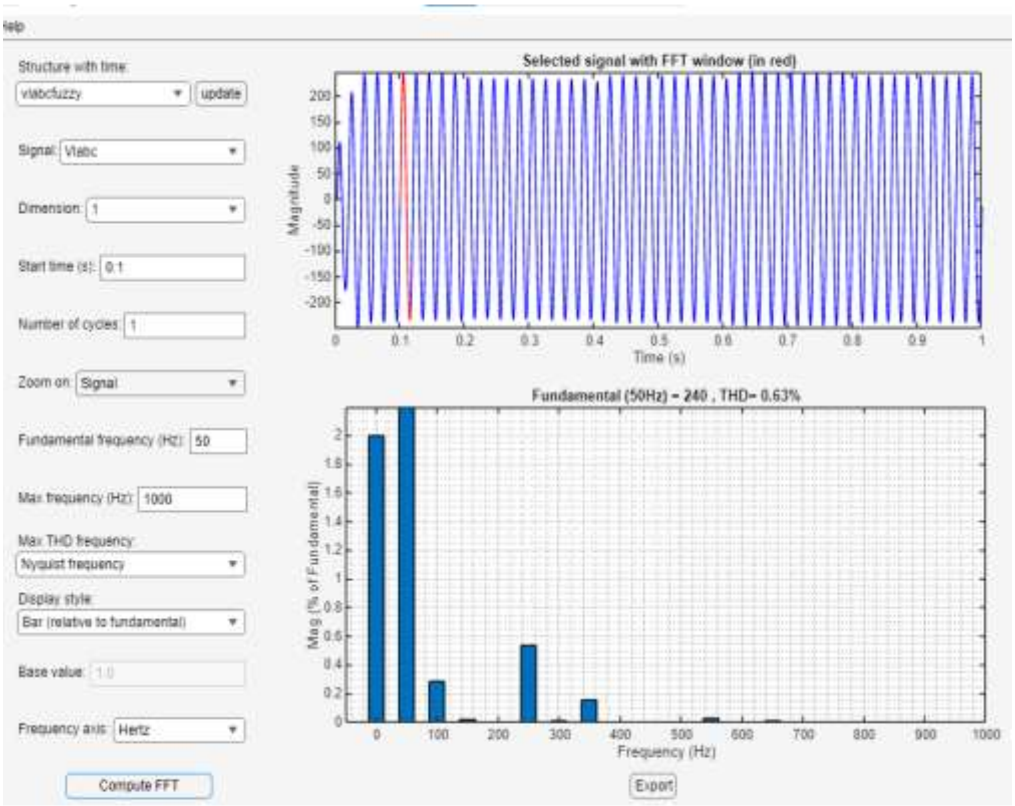


Fig.15. Voltage profile in (rms) at load point with Fuzzy



Structure with time: vlabcpi
Signal: Vlabc
Dimension: 1
Start time (s): 0.1
Number of cycles: 1
Zoom on: Signal
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max THD frequency: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Voltage THD Profile at Load point PI Controller



Structure with time: vlabcfuzzy
Signal: Vlabc
Dimension: 1
Start time (s): 0.1
Number of cycles: 1
Zoom on: Signal
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max THD frequency: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Voltage THD Profile at Load point Fuzzy Logic Controller

VI.CONCLUSION

This study introduced a simplified decentralized control strategy for a renewable-energy-supported fast-charging system designed to reduce grid dependency and environmental impact. Solar and wind sources were incorporated into the simulation, and subsystem converters were initially controlled using conventional PI regulators to ensure coordinated operation. The concept of utilizing an EV battery as a DC source for a D-STATCOM to mitigate voltage sag and swell was also examined, with the complete system modeled in MATLAB/Simulink and SimPower Systems. To improve upon the baseline PI controller, a Fuzzy Logic Controller (FLC) was proposed. Simulation results show that the FLC provides enhanced voltage regulation, improved dynamic response, and significantly lower Total Harmonic Distortion (THD) compared to the PI-controlled system. These improvements demonstrate the suitability of FLC for power-electronic interfaces operating under the variability of renewable energy sources. Overall, the proposed V2G-enabled system effectively addresses key power-quality issues and strengthens grid support. Future work will focus on validating the approach in larger grid environments with higher renewable penetration and additional system components to further assess scalability and practical implementation.

VII. REFERENCES

[1] G. E. Outlook, "to Electric Mobility." IEA: Paris, France (2019).

[2] M. Nour, H. Ramadan, A. Ali, and C. Farkas, "Impacts of plug-in electric vehicles charging on low voltage distribution network," in 2018 International Conference on Innovative Trends in Computer Engineering (ITCE), 2018, pp. 357–362.

[3] X. Gong and J. Rangaraju, "Taking charge of electric vehicles both in the vehicle and on the grid," Texas Instruments, Dallas, TX, USA, pp. 1–13, 2018.

[4] K. Karmaker, S. Roy, and M. R. Ahmed, "Analysis of the impact of electric vehicle charging station on power quality issues," in 2019 International Conference on Electrical, Computer and Communication Engineering (ECCE), 2019, pp. 1–6.

[5] P. García-Triviño, J. P. Torreglosa, L. M. Fernández-Ramírez, and F. Jurado, "Decentralized fuzzy logic control of microgrid for electric vehicle charging station," IEEE J. Emerg. Sel. Top. Power Electron., vol. 6, no. 2, pp. 726–737, 2018.

[6] D. Wang, F. Locment, and M. Sechilariu, "Modelling, Simulation, and Management Strategy of an Electric Vehicle Charging Station Based on a DC Microgrid," Appl. Sci., vol. 10, no. 6, p. 2053, 2020.

[7] L. Yang and H. Ribberink, "Investigation of the potential to improve DC fast charging station economics by integrating photovoltaic power generation and/or local battery energy storage system," Energy, vol. 167, pp. 246–259, 2019.

[8] S. Wang, L. Lu, X. Han, M. Ouyang, and X. Feng, "Virtual-battery based droop control and energy storage system size optimization of a DC microgrid for electric vehicle fast charging station," Appl. Energy, vol. 259, p. 114146, 2020.

[9] S. Wang, K. Kuang, X. Han, Z. Chu, L. Lu, and M. Ouyang, "A model-based continuous differentiable current charging approach for electric vehicles in direct current microgrids," J. Power Sources, vol. 482, p. 229019, 2021.

[10] M. Dicorato, G. Forte, M. Trovato, C. B. Muñoz, and G. Coppola, "An integrated DC microgrid solution for electric vehicle fleet management," IEEE Trans. Ind. Appl., vol. 55, no. 6, pp. 7347–7355, 2019.

[11] F. Ahmad, M. S. Alam, S. M. Shariff, and M. Krishnamurthy, "A cost-efficient approach to EV charging station integrated community microgrid: A case study of Indian power market," IEEE Trans. Transp. Electrif., vol. 5, no. 1, pp. 200–214, 2019.

[12] B. Singh, A. Verma, A. Chandra, and K. Al Haddad, "Implementation of solar PV-battery and diesel generator based electric vehicle charging station," IEEE Trans. Ind. Appl., 2020.

[13] Y. R. Rodrigues, A. C. Z. de Souza, and P. F. Ribeiro, “An inclusive methodology for Plug-in electrical vehicle operation with G2V and V2G in smart microgrid environments,” Int. J. Electr. Power Energy Syst., vol. 102, pp. 312–323, 2018.

[14] G. A. Salvatti, E. G. Carati, R. Cardoso, J. P. da Costa, and C. M. de O. Stein, “Electric vehicles energy management with V2G/G2V multifactor optimization of smart grids,” Energies, vol. 13, no. 5, p. 1191, 2020.

[15] O. Egbue and C. Uko, “Multi-agent approach to modeling and simulation of microgrid operation with vehicle-to-grid system,” Electr. J., vol. 33, no. 3, p. 106714, 2020.

[16] Q. Yang et al., “An improved vehicle to the grid method with battery longevity management in a microgrid application,” Energy, vol. 198, p. 117374, 2020.

[17] M. C. Falvo, L. Martirano, and D. Sbordone, “D-STATCOM with energy storage system for application in Smart Micro-Grids,” in 2013 International Conference on Clean Electrical Power (ICCEP), 2013.

[18] D. Leskarac, M. Moghimi, J. Liu, W. Water, J. Lu, and S. Stegen, “Hybrid AC/DC Microgrid testing facility for energy management in commercial buildings,” Energy Build., vol. 174, pp. 563–578, 2018.

[19] M. Humada, M. Hojabri, S. Mekhilef, and H. M. Hamada, “Solar cell parameters extraction based on single and double-diode models: A review,” Renew. Sustain. Energy Rev., vol. 56, pp. 494–509, 2016.

[20] M. K. Siddiqui, M. A. Mallick, and A. Iqbal, “Performance analysis of closed loop control of diesel generator power supply for base transceiver (BTS) load,” 2019.

[21] F. M. Shakeel and O. P. Malik, “Vehicle-To-Grid Technology in a Micro-grid Using DC Fast Charging Architecture,” in 2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE), 2019, pp. 1–4.

[22] P. García-Triviño, J. P. Torreglosa, L. M. Fernández-Ramírez, and F. Jurado, “Control and operation of power sources in a medium-voltage direct-current microgrid for an electric vehicle fast charging station with a photovoltaic and a battery energy storage system,” Energy, vol. 115, pp. 38–48, 2016.

[23] Y. Shan, J. Hu, K. W. Chan, Q. Fu, and J. M. Guerrero, “Model predictive control of bidirectional DC–DC converters and AC/DC interlinking converters—A new control method for PV-wind-battery microgrids,” IEEE Trans. Sustain. Energy, vol. 10, no. 4, pp. 1823–1833, 2018.

[24] Arancibia and K. Strunz, “Modeling of an electric vehicle charging station for fast DC charging,” in 2012 IEEE International Electric Vehicle Conference, 2012, pp. 1–6.