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(Research Article)

Smart micro-grid integration with bidirectional DC fast charging: Harnessing vehicle-to-grid technology

P Jeevan Kumar Reddy *, M Charan Kumar Reddy, K Uday Kiran, D Balaji, DS Sasidhar Reddy and K Santhosh Kumar

Sri Venkateswara College of Engineering, Tirupati, Andhra Pradesh, India.

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Abstract

Electric Vehicle (EV) batteries can be utilized as potential energy storage devices in micro-grids. They can help in micro-grid energy management by storing energy when there is surplus (Grid-To-Vehicle, G2V) and supplying energy back to the grid (Vehicle-To-Grid, V2G) when there is demand for it. This study focuses on the integration of a Smart Micro-Grid with Bidirectional DC Fast Charging, leveraging Vehicle-to-Grid (V2G) technology for enhanced energy management. The project employs an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller to intelligently regulate the bidirectional power flow between the micro-grid and electric vehicles. The integration of V2G facilitates energy exchange, allowing electric vehicles to serve as mobile energy storage units. The Bidirectional DC Fast Charging system is optimized through the ANFIS controller, ensuring efficient energy transfer, grid stability, and load balancing. Simulation studies are carried out to demonstrate V2G- G2V power transfer.

Keywords: DC fast charging; Electric vehicle; Grid connected inverter; Micro-grid; Off-board charger; Vehicle-to-grid; Bi- directional power flow; Grid Stability

1. Introduction

Battery monitoring is a critical aspect of electric vehicles (EVs) as the battery is the primary source of power for the vehicle. The battery pack in an EV is typically made up of several individual battery cells that work together to provide the necessary power to the vehicle. Monitoring the performance and health of these individual cells is important for ensuring the safety and reliability of the vehicle. Electric vehicles (EVs) are becoming increasingly popular due to their many benefits, such as lower emissions, lower operating costs, and quieter operation [1-5]. However, EVs also have unique safety concerns, such as the risk of battery fires, and require specific monitoring and control systems to ensure safe and efficient operation. Energy storage systems play a crucial role in micro- grids as they facilitate the integration of intermittent renewable energy sources. When electric vehicle (EV) batteries are connected for charging, they can serve as efficient storage devices within micro-grid setups [6-8].

In contrast, integrating a V2G system into a micro-grid setting is relatively straightforward. The Society of Automotive Engineers categorizes EV charging into three levels [7-11]. Level 1 charging involves using a plug to connect to the vehicle's onboard charger and a standard household outlet (120 V). This method, although the slowest, suits individuals who travel less than 60 kilometers per day and have ample time for overnight charging.

Level 2 charging utilizes dedicated Electric Vehicle Supply Equipment (EVSE) either at home or public stations to deliver power at 220 V or 240 V and up to 30 A. On the other hand, level 3 charging, known as DC fast charging, offers rapid charging capability. DC fast charging stations supply up to 90 kW at 200/450 V, significantly reducing charging time to just 20-30 minutes [12-16].

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[*] Corresponding author: P Jeevan Kumar Reddy

In recent years, the integration of renewable energy sources, electric vehicles (EVs), and smart grid technologies has emerged as a promising strategy to address the challenges of energy sustainability, grid stability, and environmental impact. One of the key components of this paradigm shift is the concept of Smart Micro-Grids, which are localized energy systems capable of generating, storing, and managing electricity efficiently. Concurrently, the widespread adoption of EVs has necessitated advancements in charging infrastructure, particularly with the development of Bidirectional DC Fast Charging capabilities [17-20].

The integration of Smart Micro-Grids with Bidirectional DC Fast Charging presents a synergistic approach that not only enables efficient energy management within micro- grid networks but also leverages the potential of EVs as distributed energy resources. This integration holds significant promise for enhancing grid resilience, optimizing energy utilization, and promoting renewable energy integration at a local level [21-23].

In this context, control and optimization play a pivotal role in ensuring the seamless operation of Smart Micro-Grids with Bidirectional DC Fast Charging. Control strategies such as Proportional-Integral (PI) Controllers and advanced techniques like Adaptive Neuro-Fuzzy Inference System (ANFIS) Controllers offer robust solutions for grid synchronization, power flow control, and intelligent charging/discharging management. Effectiveness of the proposed model is evaluated based on MATLAB/Simulink simulations for both V2G and G2V modes of operation [24-27].

2. Configuration of the V2G and G2V integration

The design of the DC fast charging station for sources. The selection of the inverter-side inductance depends on implementing V2G-G2V functionality in a micro-grid is the DC voltage, inverter modulation index, switching frequency, illustrated in Figure 1. Electric vehicle (EV) batteries are and total harmonic distortion of the current. An LCL filter is connected to the DC bus through off-board chargers. A grid- connected to the output terminals of the inverter to reduce connected inverter links the DC bus to the utility grid via an harmonics and achieve a pure sinusoidal current and voltage.

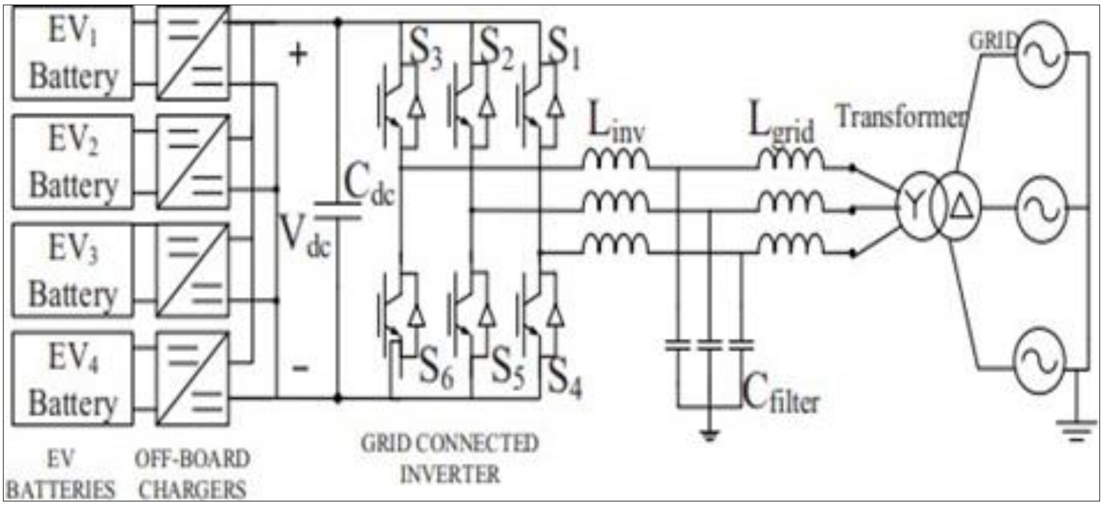

Figure 1 EV charging station for fast dc charging

2.1. Battery Charger Configuration

Off-board chargers for DC fast charging are housed within an Electric Vehicle Supply Equipment (EVSE). A bidirectional DC-DC converter serves as the fundamental building block of these chargers, enabling Vehicle-to-Grid (V2G) functionality. This converter acts as the interface between the EV battery system and the DC distribution network. The converter's design is depicted in Figure 2, consisting of two IGBT/MOSFET switches controlled independently to facilitate continuous bidirectional power flow capability.

2.1.1. Charging Mode

In charging mode, when the upper switch (S _ buck) is activated, the converter functions as a buck converter, lowering the input voltage (v _ bat). During the on state of the switch, current flows through the switch and the inductor to charge the battery. When the switch is off, the current completes its path through the inductor, the diode of the lower switch, and closes the circuit. The battery voltage during the operation of the upper switch is given by:

$$Vbat = \mathrm{Vdc} * \mathrm{D} \qquad \ldots\ldots\ldots\ldots\ldots(1)$$

2.1.2. Discharging Mode

In discharging mode, when the lower switch (S_boost) is activated, the converter acts as a boost converter, raising the battery voltage (V_batt) to the DC bus voltage (Vdc). During the on state of the switch, current continues to flow through the inductor and completes its circuit through the opposite diode of the upper switch and the capacitor. The power flow direction is from the vehicle to the grid (V2G), and the battery operates in discharge mode. If the capacitor can maintain a constant DC voltage, the output voltage during this operation mode is given by the equation:

$$\mathrm{Vdc} = \mathrm{V}batt/\ (1 - \mathrm{D}) \qquad \ldots\ldots\ldots\ldots\ (2)$$

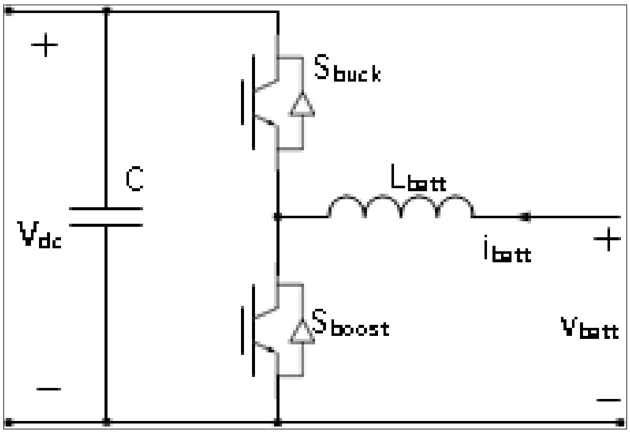

Figure 2 Battery Charger Configuration

2.1.3. Grid-Connected Inverter and LCL Filter

The grid-connected inverter (GCI) converts the DC transport voltage into a three-phase AC voltage and also enables current backflow through the anti-parallel diodes of the switches in each leg. Passive LCL filters have become state-of-the-art in reducing harmonics for grid-interfaced distributed power.

2.1.4. Off-Board Charger Control

This control strategy functions as if the battery were a constant current source. The output duty ratio mcc determines the converter's boost-mode operation. A stable current control system, employing PI regulators, is implemented for charge/release control of the battery charger circuit, as depicted in Figure 3. Initially, the regulator compares the reference battery current with zero to determine its polarity, thereby selecting between charging and discharging operations. Once the mode is determined, the reference current is compared with the measured current and the error is processed through a PI regulator to generate the switching signals for S_buck/S_boost. S_buck is deactivated during the charging cycle, while S_boost is deactivated during the discharging cycle.

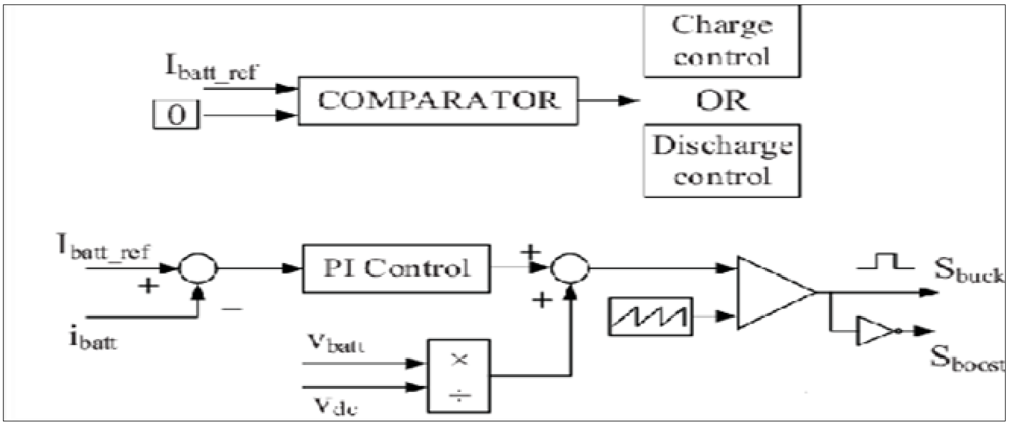

Figure 3 Constant current control strategy for battery charger

2.1.5. Inverter Control

In the cascade control system operating within the synchronous frame, there are distinct layers comprising an outer voltage loop and an inner current loop. These layers are synchronized via a phase-locked loop mechanism. The control structure includes two ANFIS controllers and two PI controllers, arranged in a nested loop configuration as illustrated in Figure 4. This arrangement further consists of two outer voltage control loops and two inner current control loops. The external d-pivot circle regulates the DC transport voltage, while the internal circle manages the dynamic AC current. Because the inverter supports bidirectional power flow, variations in the DC bus voltage can result from either negative or positive current directions and vice versa. Similarly, the external q-pivot circle modulates the size of the AC voltage by adjusting the responsive current, which is limited by the internal q-hub current circle. Additionally, dq decoupling terms such as ω Linv and feed- forward voltage signals are integrated to enhance performance, particularly during transient operational phases.

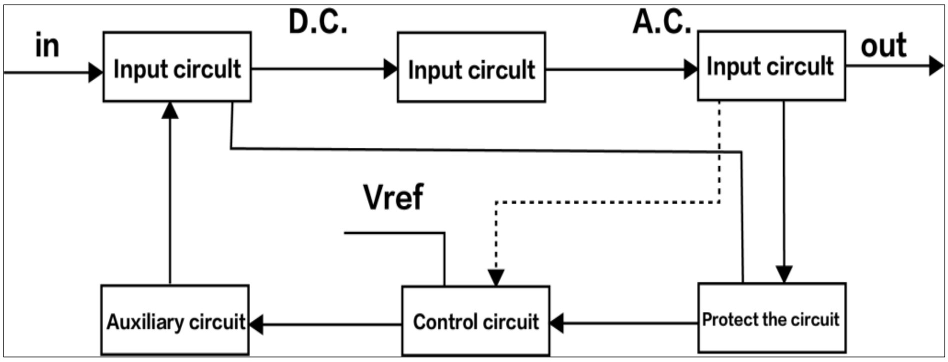

Figure 4 Inverter Control System

3. Micro-gridtest system configuration

The micro-grid test system configuration with the dc fast charging station is as shown in Figure 5. A 100kW wind turbine (WT) and a 50kW solar PV array serve as the generation sources. In this framework, the EV battery storage system involves four EV batteries linked to a 1.5 kV DC bus of the charging station via off-board chargers. Additionally, solar PV is connected to this DC bus through a boost converter equipped with a maximum power point tracking (MPPT) regulator. The utility grid comprises a 25 kV distribution feeder and a 120 kV parallel transmission system. A wind turbine-driven doubly-fed induction generator is linked to the micro-grid at the point of common coupling (PCC). Transformers play a role in stepping up voltages and connecting individual AC systems to the utility grid.

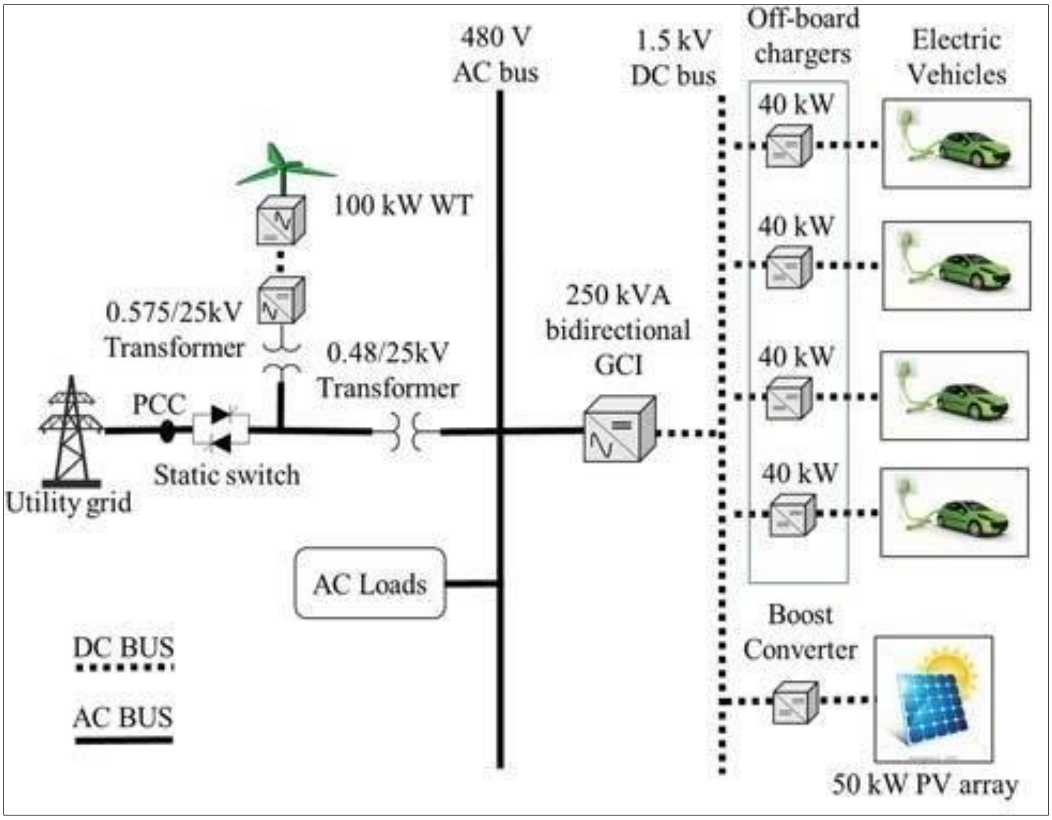

Figure 5 Proposed micro grid test system configuration

4. ANFIS controller

ANFIS, a hybrid system, combines the learning capabilities of artificial neural networks (ANN) with the strong knowledge representation and inference abilities of fuzzy logic (Jang 1993). ANFIS can self-modify its membership functions to achieve desired performance levels. It leverages an adaptive network, encompassing various neural network paradigms, to interpret fuzzy inference systems. This hybrid-learning approach makes ANFIS suitable for managing complex decision-making or diagnostic systems, proving effective in tuning the membership functions of fuzzy inference systems.

The core of ANFIS lies in its ability to transform inputs into target outputs using a fuzzy inference system model, involving membership functions, fuzzy logic operators, and if- then rules. There are two primary fuzzy system models: Mamdani and Sugeno. ANFIS operates through five main stages: input fuzzification, application of fuzzy operators, application method, output aggregation, and defuzzification.

ANFIS optimizes its performance by representing prior knowledge as network constraints (network topology) to reduce optimization search space, drawn from Fuzzy Systems, and by adapting backpropagation to structured networks to automate FC parametric tuning, sourced from Neural Networks as shown in Figure 6 and Figure 7.

In structure, ANFIS is a multilayer feedforward network where each node performs specific functions (node function) on incoming signals. For simplicity, we consider two inputs 'x' and 'y' and one output 'z '. Suppose that the rule base contains two fuzzy if-then rules of Takagi and Sugeno type (Jang 1993):

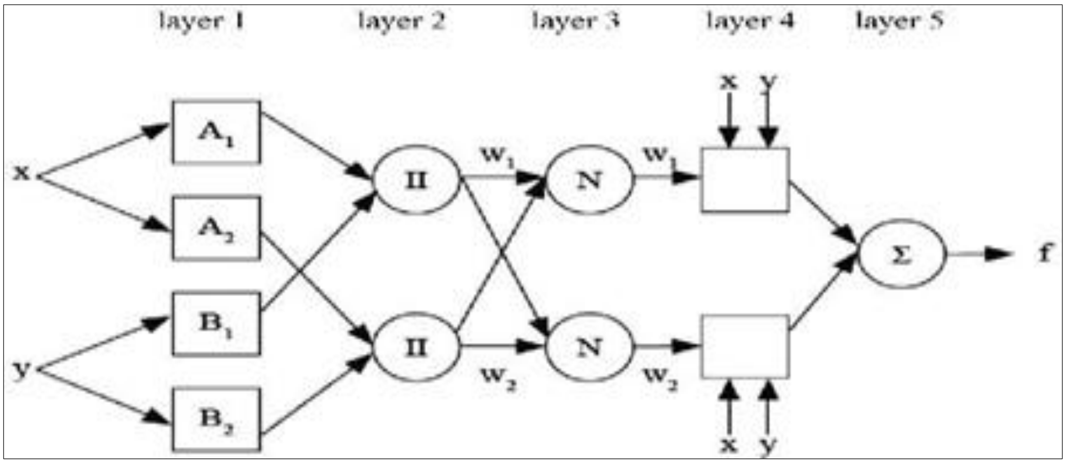

Figure 6 ANFIS Architecture

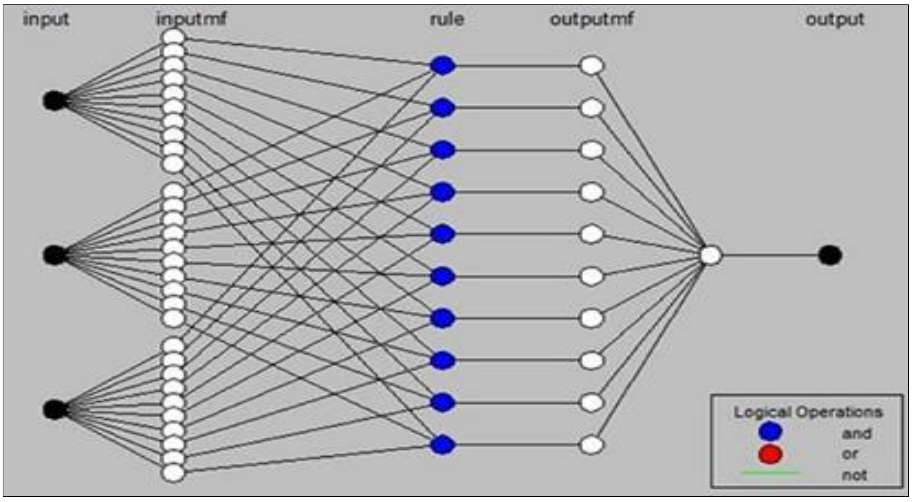

Figure 7 ANFIS Architecture

4.1.1. Simulation Results

The wind turbine operates at its rated speed, producing a maximum power output of 100 kW. Similarly, the solar photovoltaic (PV) system operates under standard test conditions, with an irradiance of 1000W/m2 and a temperature of 25°C, providing a maximum power output of 50 kW. A resistive load of 150 kW is connected to the 480 V AC bus. The grid-connected inverter (GCI) is set with a reactive current reference of zero for unity power factor (pf) operation. Initially, the state of charge (SOC) of the electric vehicle (EV) batteries, specifically EV1 and EV2 as depicted in Figure 8, is set at 50%. Once the system reaches steady-state conditions, the EV1 and EV2 batteries are utilized for Vehicle-to-Grid (V2G) and Grid- to-Vehicle (G2V) power transfers. The overall performance of the system presented from the Figure 8 to Figure 16.

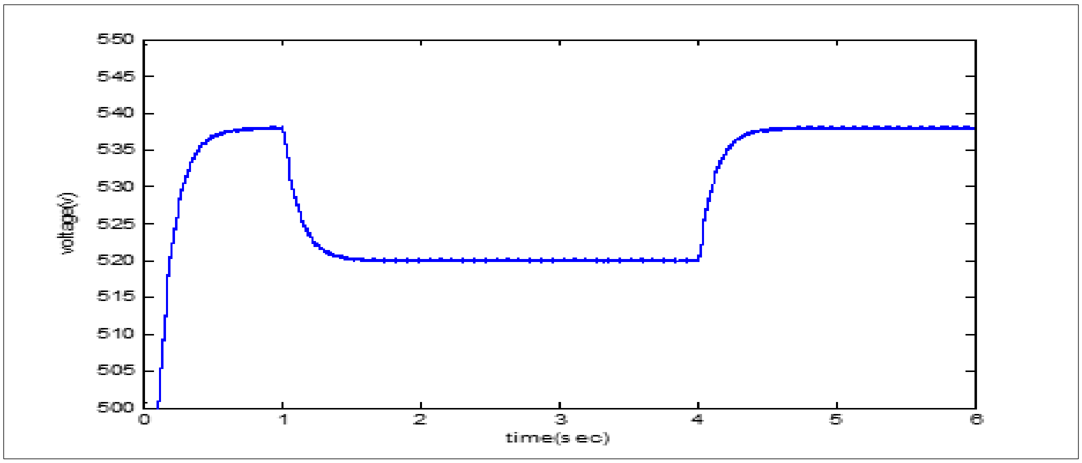

Figure 8 Voltage of EV1 battery during G2V operation

- Rule 1: IF x is A1 and y is B1 THEN f1=P1x+Q1y+R1
- Rule 2: IF x is A2 and y is B2 THEN f2=P2x+Q2y+R2

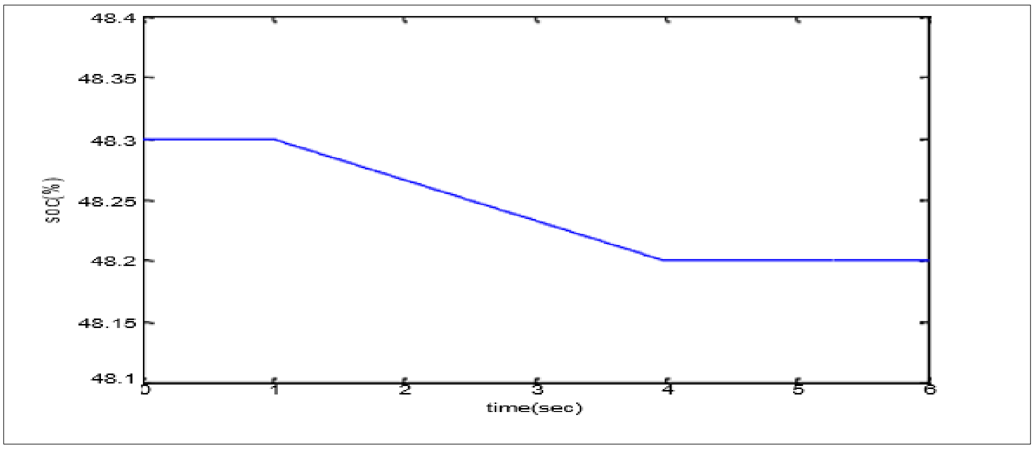

Figure 9 State of Charge (SOC) of EV1 battery during V2G operation

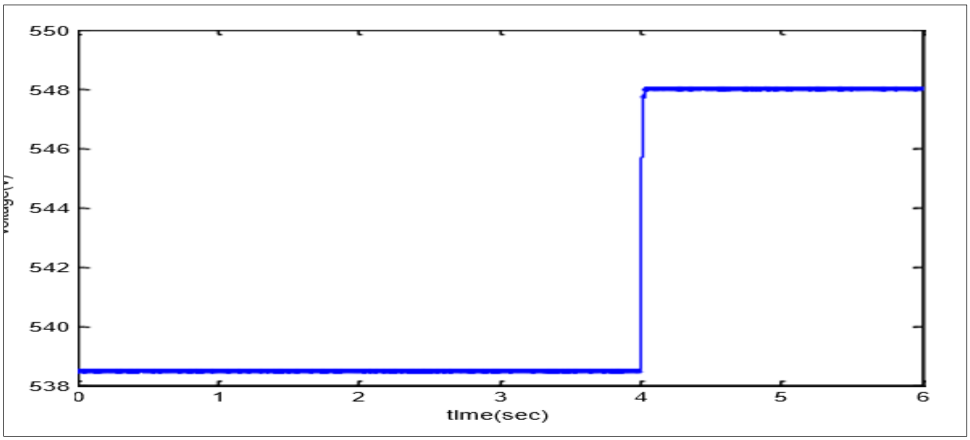

Figure 10 Voltage of EV2 battery during G2V operation

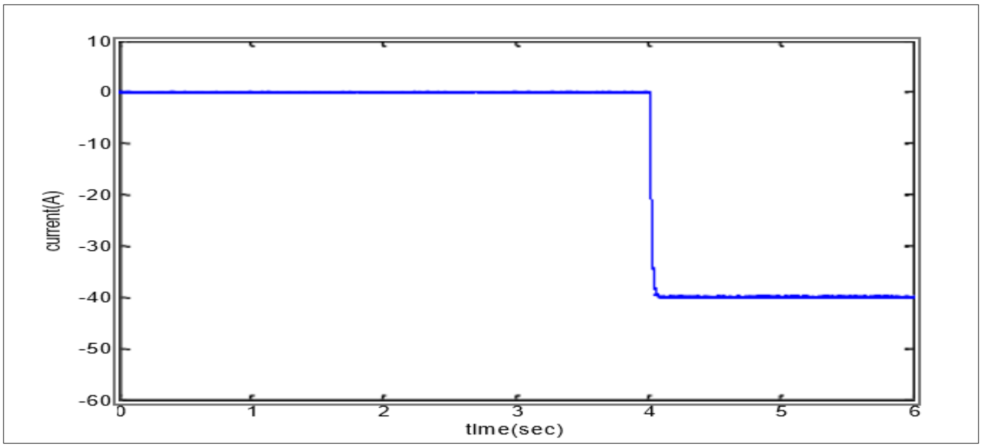

Figure 11 Current of EV2 battery during G2V operation

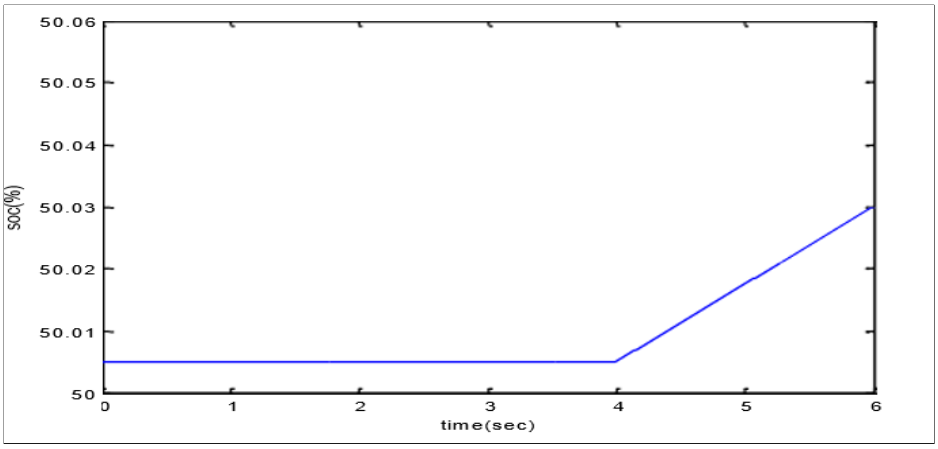

Figure 12 SOC of EV2 battery during G2V operation

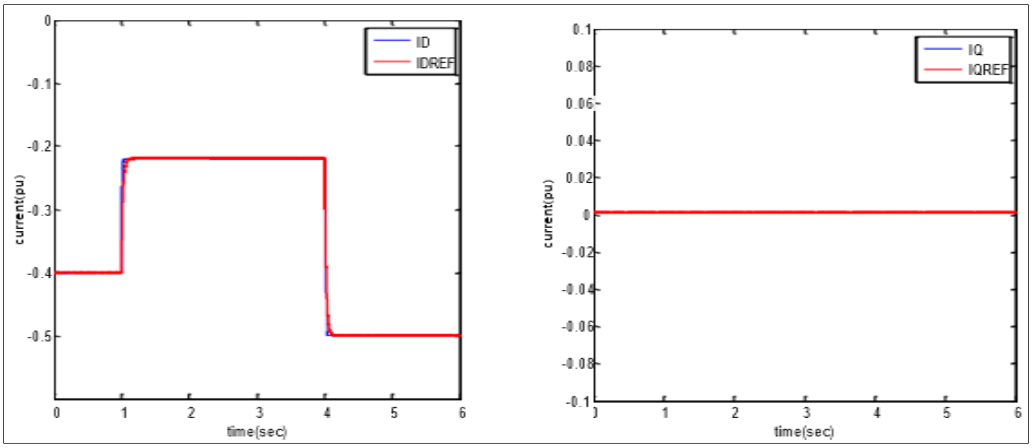

Figure 13 Reference current tracking by the inverter controller

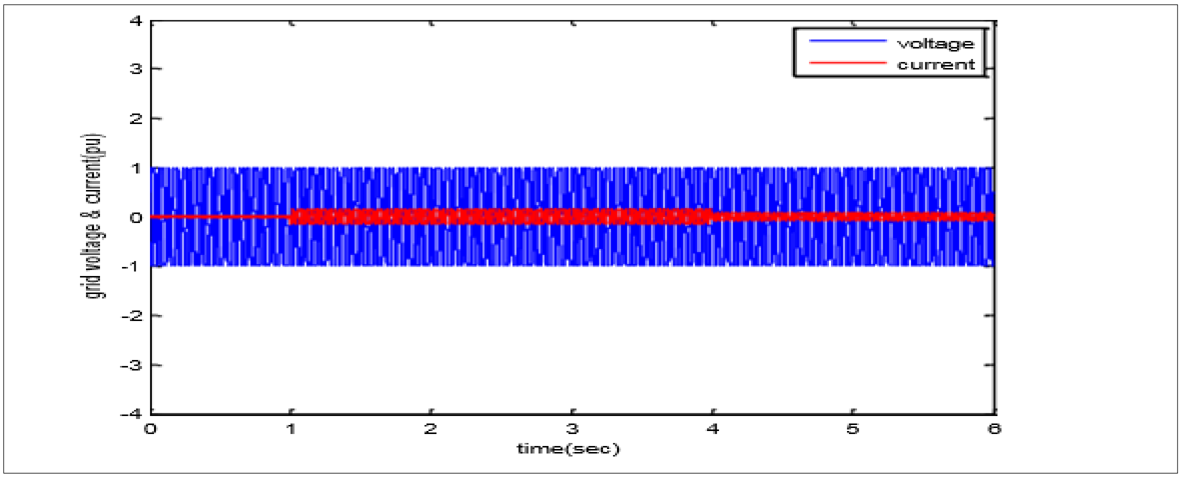

Figure 14 Grid voltage and grid injected current during V2G-G2V operation

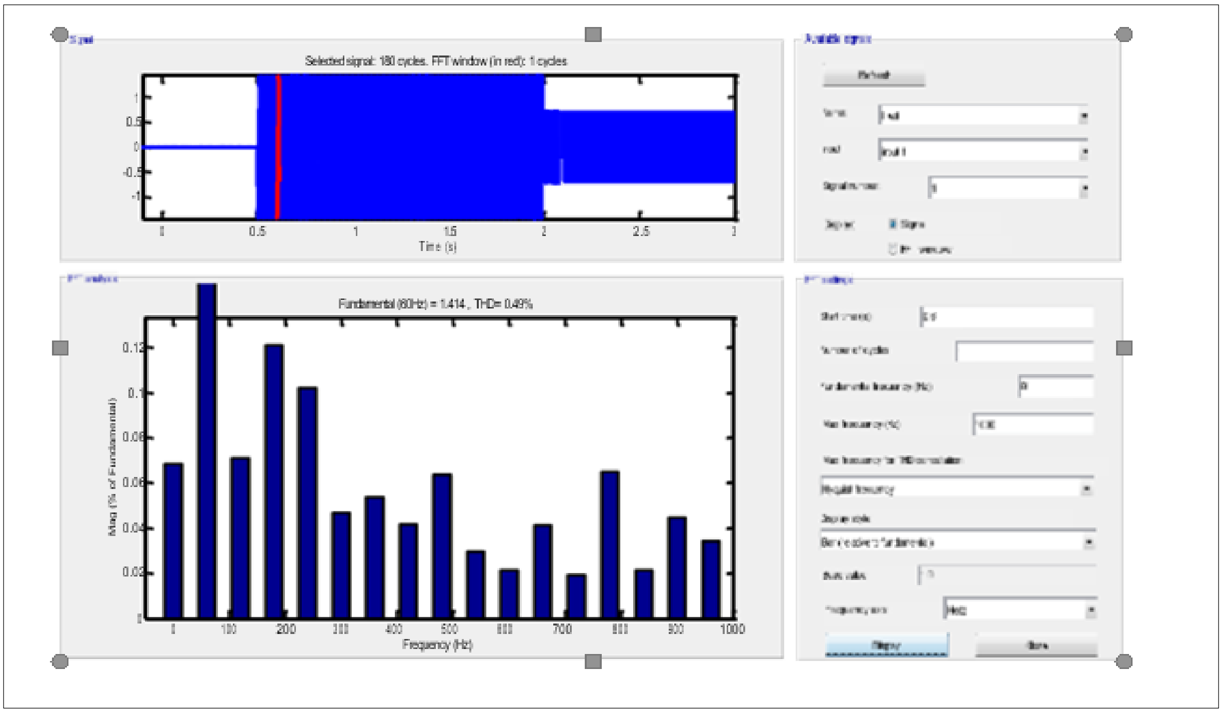

Figure 15 Harmonic spectrum and THD of grid-injected current

The THD of grid injected current is obtained as 0.44% and is achieved by the ANFIS Controller in Figure15.

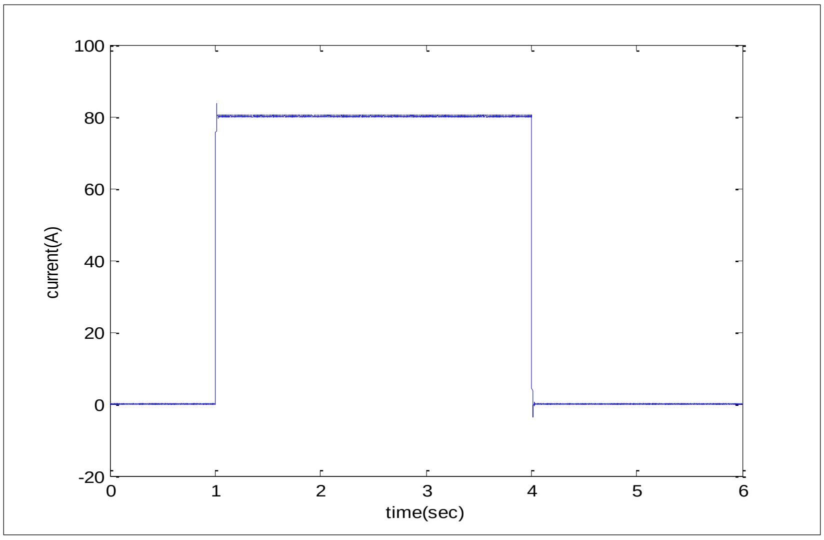

Figure 16 Current of EV1 battery during V2G operation

5. Conclusion

The paper presents an ANFIS Control Strategy designed for the DC fast charging of electric vehicles (EVs) connected to a microgrid. The setup includes a DC quick charging station with off-board chargers and a grid-connected inverter to link EVs to the microgrid. This power electronic interface's control system enables bidirectional power transfer between EVs and the grid. Simulation results demonstrate smooth power transfer between EVs and the grid, with the quality of grid-injected current meeting relevant standards. The ANFIS controller exhibits good dynamic performance in maintaining DC bus voltage stability and tracking dynamic power reference changes. Additionally, the proposed Vehicle-to-Grid (V2G) system can offer various services such as reactive power control to reduce harmonic distortion, minimise steady-state errors, and regulate frequency, enhancing overall grid stability and performance.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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