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A Novel Control Strategy for Optimization of V2G and G2V

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Abstract: With the increasing integration of electric vehicles (EVs) into the power grid, efficient bidirectional power flow management is essential for optimizing Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations. This study investigates three different control strategies for managing bidirectional power flow and improving power quality: (1) Proportional-Integral (PI) controllers on both the converter and vehicle-side battery, (2) PI controller for converter operation and bi-directional converter, and (3) FLC on both converter and the battery sides. The proposed control strategies are implemented in MATLAB/Simulink, and their performance is evaluated based on settling time, dynamic response, and Total Harmonic Distortion (THD). Comparative analysis of the simulation results demonstrates that the FLC-based approach on both the converter and battery sides provides the best performance, offering faster settling time, improved power transfer efficiency, enhanced grid stability, and reduced THD. The study highlights the effectiveness of FLC in handling system nonlinearities and uncertainties, making it a promising solution for power quality improvement in bidirectional energy exchange between EVs and the grid.

Index Terms: Vehicle-to-Grid (V2G), Grid-to-Vehicle (G2V), Fuzzy Logic Controller (FLC), PI Controller, Bidirectional Power Flow, MATLAB Simulink, Power Quality.

I. INTRODUCTION

As electric vehicles become more prevalent, their integration poses new operational challenges while also offering opportunities to enhance power grid performance power grid operations. As global energy systems shift toward more sustainable frameworks, EVs are emerging as essential elements in the evolving energy landscape. Nevertheless, incorporating EVs into the power network introduces complications related to energy quality, system stability, and effective power distribution. Bidirectional energy technologies like V2G and G2V facilitate two-way power transfer, enabling EVs to both charge from and discharge into the electrical grid, contributing to load balancing and enhanced grid reliability Electric vehicles can also contribute to maintaining grid frequency and voltage stability[3]. Additionally, they have the potential to generate electricity when needed, particularly during peak demand periods[1].

As discussed in [2], Vehicle-to-Grid (V2G) systems allow electric vehicles (EVs) to serve as distributed energy storage units that can support power system operations. These vehicles help stabilize the grid by offering ancillary services such as load bala. Conversely, G2V technology enables EVs to charge through grid during low-demand periods, optimizing energy usage and reducing the overall cost of EV ownership[2]. However, the dynamic nature of bidirectional power flow systems introduces challenges related to power quality, harmonic distortion, and transient response during mode transitions between G2V and V2G operations. To address these challenges, advanced control strategies are required to ensure efficient and stable operation of bidirectional power flow systems. Older control systems such as PI (Proportional-Integral) controllers, have been widely used due to their simplicity and effectiveness in maintaining stability. However, PI controllers often struggle to handle the nonlinearities and uncertainties associated with bidirectional power flow systems, particularly during mode transitions. Fuzzy Logic Control (FLC) has emerged as a promising alternative, offering improved performance in terms of dynamic response, harmonic reduction, and robustness to system uncertainties.

This research explores and evaluates the application of PI and FLC-based control strategies for bidirectional power flow systems in V2G and G2V operations. Three control strategies are proposed and analyzed: (1) PI controller on both the converter and bidirectional converter, (2) PI controller on the converter and FLC on the bidirectional converter, and (3) FLC on both the converter and bidirectional converter. This study is principally focused on to compare the performance of these control strategies in terms of harmonic distortion, settling time, and output ripple, with a focus on improving power quality and dynamic response during G2V and V2G operations.

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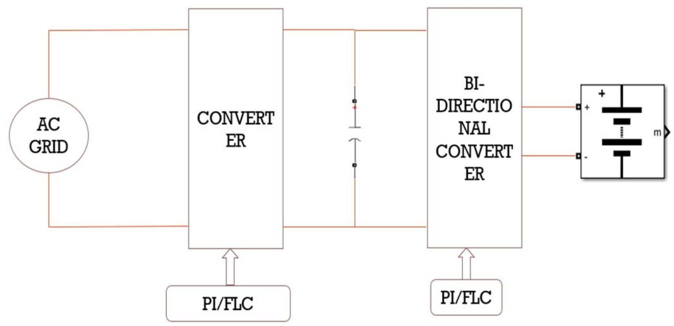

Fig.1. Overview of G2V and V2G

II. PROPOSED WORK

A. Configuration

This study aims to develop an optimized control mechanism for managing energy flow in electric vehicles (EVs). The proposed bidirectional charging system accommodates two operational states: Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G). It is composed of several integrated components that facilitate smooth power transfer between the EV and the grid infrastructure.

As shown in Fig. 1, the charger extracts electrical energy from the grid and converts it from alternating current (AC) to direct current (DC) for battery charging. A basic control algorithm governs this process, dynamically switching the system's mode between energy intake and energy export.

During charging, a buck converter is used to initiate the G2V process. Conversely, when energy is supplied back to the grid, a boost converter is activated to support V2G operation. These dual modes illustrate the system's flexibility in supporting Interchangeable energy interaction linking the EV and the power grid.

B. Methodology

The suggested system uses a fuzzy-based bidirectional converter to maximize the efficiency with which EV batteries may be charged with grid system. This method facilitates better EV charging integration with grid, increasing charging efficiency, flexibility, and sustainability. The following block diagram illustrates the interplay between the various parts. A different strategy is required to improve the efficiency of an EV charging system. Improved efficiency is a result of modernizing power electronics components such as the bidirectional converter and optimizing control methods like the FLC. The methodology used in the research is to examine with three different control strategies in converter and bi-directional converter approaches to which it seamlessly connect the vehicle to grid and grid to vehicle. Electric vehicle chargers integrate AC/DC and DC/DC conversion units capable of functioning in both charging and discharging modes. As described by Aishwarya and Nisha [4], bidirectional power converters in EV chargers perform AC to DC rectification for charging the vehicle and invert DC back to AC during discharging. This dual-mode functionality enables seamless switching between G2V. As discussed in [6], bidirectional energy flow allows operators to benefit from load balancing and ancillary services.

1) *Battery model:* The EV battery implemented in the simulation framework is based on lithium technology, known for its unique properties, sustainability, and efficient charging and discharging capabilities. According to the International Energy Agency [1], lithium-ion batteries are the preferred storage medium in EVs due to their high energy density and ability to sustain repeated charging cycles. These batteries operate through the reversible transfer of li. The EV battery model used in the simulation is characterized by parameters detailed in Table 1, reflecting typical performance and configuration metrics.
2) *Converter topology:* There are three different controller approaches analyzed in this work to maintain the power quality in the transition between grid to vehicle and vehicle to grid the most efficient among the three is fuzzy logic controller. Unmanaged charging or discharging of electric vehicles can negatively impact the voltage stability at distribution nodes. Irregular power flow from EVs may lead to deviations in nodal voltage levels, potentially breaching the permissible limits defined by the Central Electricity Authority (CEA). This study aims to enhance power quality during both charging and discharging cycles by implementing a Fuzzy Logic Controller (FLC) to ensure smoother voltage regulation.

3) *A. Fundamentals of Fuzzy Logic Controller:* As described by Singh et al. [2], Fuzzy Logic Control (FLC) is a powerful alternative to traditional controllers in systems with nonlinearities and uncertainties. It leverages intuitive IF-THEN rules rather than fixed models, making it ideal for the adapt. Unlike classical Boolean logic, which operates with binary values, FLC employs a straightforward IF-THEN rule structure, removing the necessity for an exact mathematical model of the system. This approach proves highly effective for complex systems where accurate modeling is challenging or impractical. However, the complexity of fuzzy logic systems tends to escalate with an increase in the number of input and output variables.

This paper implements a Mamdani-type FLC. As illustrated in Fig. 2, an FLC comprises four main components: the fuzzification module, the rule base, the inference engine, and the defuzzification module. The fuzzification process transforms crisp inputs into fuzzy variables, whereas defuzzification converts fuzzy results back into crisp outputs. These conversions utilize membership functions. The rule base holds a set of IF-THEN rules defining the control logic, and the inference engine processes these rules to determine the output fuzzy sets. The final crisp output is obtained by calculating the "fuzzy centroid" of the combined output membership functions. The adaptability and intuitive design of FLC make it especially advantageous for real-time applications where quick decision-making is essential.

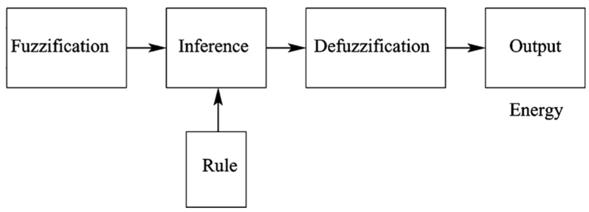

Fig.2. Fuzzy controller.

C. Fuzzy Logic Controller for Battery Current Regulation

In the MATLAB simulation, a Mamdani-type Fuzzy Logic Controller (FLC) is implemented to regulate the battery charging and discharging current efficiently. The controller takes two inputs:

1. Error (e): The difference between the reference battery current (Iref) and the actual battery current (Iactual) is calculated as:

$$e = Iref - Iactual$$

2. Change in Error (Δe): The rate of change of the error over time, determined as:

$$\Delta e = e(k) - e(k-1)$$

where e(k) is the current error, and e(k-1) is the previous error stored using a memory block in Simulink.

The controller utilizes five triangular membership functions for each input and output, ensuring smooth and computationally efficient control. It follows a rule base of 25 IF-THEN rules, where the inference mechanism is based on the min-max method handling the AND operation with the minimum function and the OR operation with the maximum function.

For defuzzification, the centroid method is employed to compute the precise control output by determining the center of gravity of the aggregated fuzzy set. This approach allows the system to effectively manage transient responses, minimize overshoot, and enhance the stability of battery current regulation in bidirectional power flow applications.

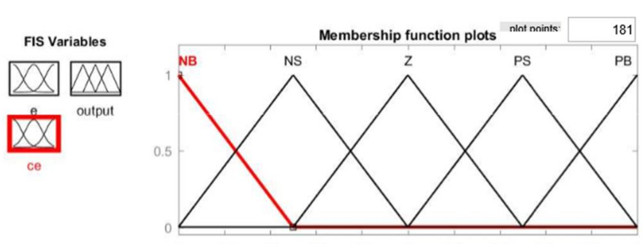

Fig. 3.

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D. Fuzzy Logic Controller for DC-Link Voltage Regulation

In the MATLAB simulation, a Mamdani-type Fuzzy Logic Controller (FLC) is implemented to regulate the DC-link voltage for stable and efficient converter operation. The controller continuously adjusts the control signal to maintain the desired voltage level.

1) Inputs to the FLC

The controller takes two input variables:
Error (E):
The deviation between the desired DC-link voltage (Vdc,ref) and the actual measured value (Vdc,ref):

$$E=Vdc,ref-Vdc,actual$$

This determines how much the actual voltage deviates from the desired setpoint.
Change in Error (ΔE):

The rate of change of the error over time:

$$\Delta E=E(k)-E(k-1)$$

Here, E(k) is the current error, and E(k-1) is the previous error stored using a memory block in Simulink.
This helps the controller predict system behavior and apply corrective action accordingly

2) Fuzzy Rule Base and Inference Mechanism

The controller is designed with 49 IF-THEN rules, ensuring an effective response to voltage fluctuations. The inference mechanism follows the min-max method:
AND operation: Handled by the minimum function.
OR operation: Handled by the maximum function.
By incorporating fuzzy logic control, the system achieves precise voltage regulation, ensuring optimal converter performance and improved stability in bidirectional power flow applications.

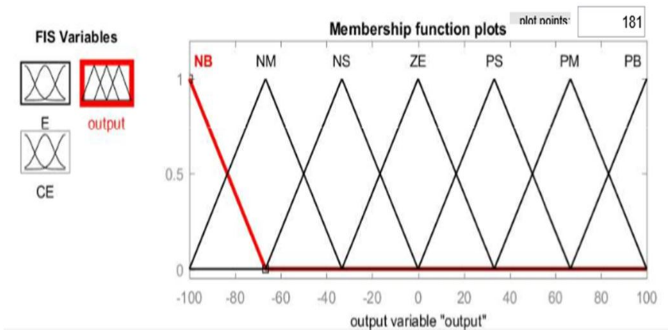

Fig. 4. Membership function plots

III. SIMULATION RESULTS

The suggested approach involves employing MATLAB/Simulink to assess the viability of a fuzzy based control strategy for a smother power conversion and battery side current control in V2G and G2V applications within an EV context. This methodology entails utilizing simulation tools to verify the effectiveness and practicality of the control technique in managing power flow bidirectional at the interface of the EV battery and the electrical grid. By leveraging MATLAB/Simulink, engineers can model and analyze various scenarios, ensuring that the proposed control method functions optimally under different conditions encountered during V2G and G2V operations. This validation process aids in refining the control algorithm, enhancing its performance, and ensuring its compatibility with real-world EV applications without directly copying existing materials. The simulation parameters are detailed in Table 1.
The converter operates bidirectional, functioning as both an inverter and a rectifier, while maintaining a unity power factor.

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TABLE 1 MODELPARAMETERS

Parameter	Values
Grid Voltage (Vs)	320 V
Grid frequency (f)	50 Hz
Nominal Battery Voltage (V_{bat})	120V
Initial State of Charge (SOC) %	50%
Rated capacity (Ah)	48Ah
Inductance (L1) and (L2)	2.3mH 1.9mH
Capacitance	1mF
Battery type	Li-ion
Simulation Time	2Sec
DC link voltage	380V

The response of the DC-link voltage during bidirectional energy flow—covering both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes—is examined across multiple control techniques. As illustrated in Fig. 3, the simulation outcomes reflect the system's behavior under both transient and steady-state conditions.

Initially, at t = 0s, all control strategies exhibit an overshoot due to system startup. The conventional PI-based approach shows significant voltage overshoot and prolonged settling time, leading to higher oscillations during mode transitions. The introduction of a bidirectional converter-based approach significantly reduces these fluctuations, providing faster stabilization and improved voltage regulation.

A key observation occurs around t = 1s, where the system transitions between G2V and V2G modes. The PI controller-based approach results in noticeable oscillations and slower recovery. In contrast, the bidirectional converter-based control exhibits minimal overshoot, faster convergence, and better dynamic response, ensuring smooth voltage transitions and improved power quality.

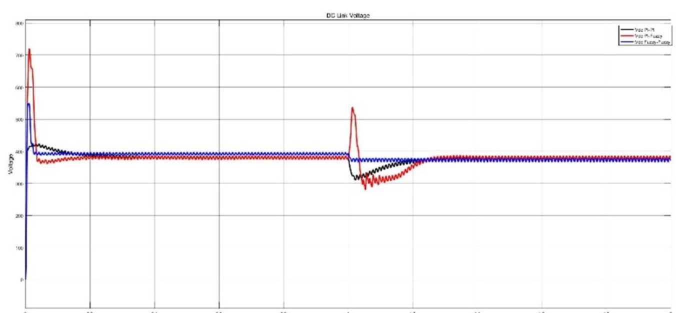

Fig.3. DC link voltage waveform of V2G and G2V

A. Total Harmonic Distortion (THD) Analysis

A FFT analysis was performed to assess the power quality of the system under various control schemes by calculating the THD present in the output signal. The resulting THD values corresponding to each strategy are presented in Table 1.

The simulation results indicate that the PI-PI control strategy exhibits the highest THD of 8.31%, demonstrating significant harmonic distortions in the system.

When the PI controller is used for the converter operation and a fuzzy logic controller (FLC) is applied for battery-side current regulation (PI-FLC approach), the THD is reduced to 6.10%, showcasing an improvement in waveform quality. The FLC-FLC control strategy, where fuzzy logic control is implemented on both the converter and battery side, achieves the lowest THD of 4.06%, signifying the best harmonic performance.

These results suggest that fuzzy logic control plays a crucial role in reducing harmonic distortions, with the FLC-FLC configuration providing the most effective suppression of unwanted harmonics. The enhanced effectiveness of the
FLC-FLC approach can be credited to its nonlinear control capability, which Seamlessly mitigates switching harmonics and improves power quality.

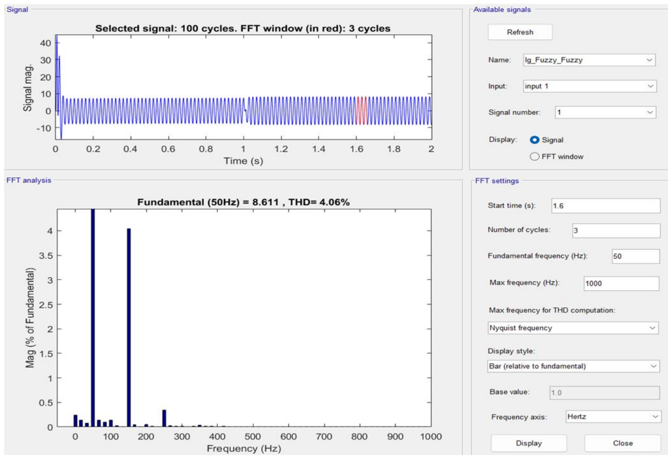

Fig.4. FFT using FLC

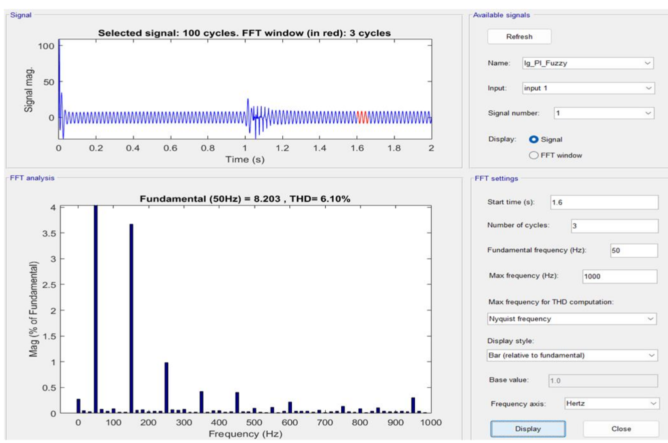

Fig.5. FFT using PI&FLC

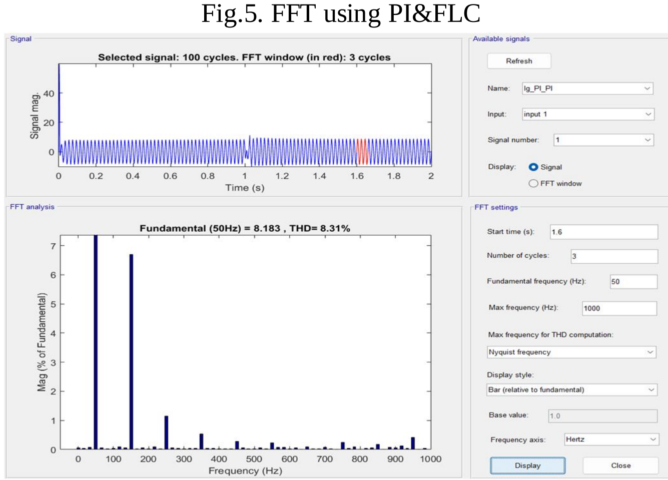

Fig.6. FFT using PI

IV. CONCLUSION

This work explores different methods To manage the flow of power across electric vehicles and the grid in both V2G and G2V modes. The system performance was evaluated under three different control approaches: (i) conventional PI control for both converter and battery-side current regulation, (ii) PI control for converter operation and Fuzzy Logic Controller (FLC) for battery-side current regulation, and (iii) FLC for both converter and battery-side current regulation.

The DC-link voltage analysis revealed that PI-based controllers exhibit higher voltage overshoot and prolonged settling times, leading to increased oscillations during mode transitions. In contrast, the incorporation of fuzzy logic control significantly enhanced system stability by reducing transient fluctuations and improving dynamic response.

Furthermore, Total Harmonic Distortion (THD) analysis demonstrated that the PI-PI control strategy resulted in the highest THD of 8.31%, indicating poor power quality. The PI-FLC approach reduced the THD to 6.10%, showcasing an improvement in harmonic performance. The FLC-FLC strategy achieved the lowest THD of 4.06%, highlighting its effectiveness in minimizing harmonic distortions and ensuring superior power quality.

From the comparative analysis, it is evident that Fuzzy Logic Control (FLC) outperforms conventional PI controllers in terms of transient response, power quality, and harmonic mitigation. The FLC-FLC approach provides the most stable voltage regulation and the best harmonic suppression, making it the most suitable choice for bidirectional power flow applications in electric vehicle-grid integration. Future work can focus on optimizing fuzzy logic rule sets and exploring hybrid control techniques to further enhance system efficiency and robustness.

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