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ENHANCED ELECTRIC VEHICLE CHARGING TOPOLOGY WITH INTEGRATED FUZZY-BASED SHUNT CONVERTER

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Abstract. This article presents a novel electric vehicle charging scheme that addresses power quality issues in distribution grids, caused by widespread EV charging. The system uses an interval type-II (IT-II) fuzzy-logic-based shunt converter, with a dual-direction converter enabling power flow from the grid to the EV (G2EV) and from the EV to the grid (EV2G). It incorporates iterative constant current (ICC) regulation for managing Li-ion battery charging and discharging. A fuzzy logic controller (FLC) based on an instantaneous reactive power model is used for the shunt converter, with an enhanced real-coded genetic algorithm (ERGA)-based type-I (IT-I) FLC control. The Performance is evaluated using THD analysis of the source current, and the system response is plotted. Simulations conducted in Matlab demonstrate improved power quality with harmonic distortion within acceptable limits, confirming the effectiveness of the proposed system in optimising EV charging while maintaining grid stability.

Keywords: IT-II controller, lithium-ion batteries, energy storage, RGIA IT-I FLC controller.

1. Introduction

The growing interest in electric vehicles (EVs) is driven by the depletion of oil resources, rising fuel prices, and increasing greenhouse gas emissions. In response, automakers are exploring different electric drive technologies to improve energy efficiency and reliability, including different types of renewable energy [1, 2]. From an environmental perspective, the depletion of finite oil resources and the increasing greenhouse gas (GHG) emissions from conventional vehicles are driving the push towards electrification of transport. Electric vehicles (EVs) offer a cleaner alternative, significantly reducing carbon emissions and environmental damage. From an economic perspective, the high dependency on fossil fuels not only strains national economies due to volatile oil prices but also makes countries vulnerable to energy market fluctuations. By transitioning to EVs, nations can reduce fuel import bills, stabilize their economies, and relocate resources towards sustainable infrastructure and renewable energy sources. The dependence on imported oil impacts energy security and national resilience. A nation heavily reliant on the import of oil is susceptible to geopolitical risks and supply chain disruptions. By promoting EVs adoption and investing in local renewable energy sources, countries can improve their energy independence, reduce strategic vulnerabilities, and strengthen economic sovereignty. This research aligns with these motivations by focusing on improving EV charging systems to improve their efficiency, reliability, and scalability, supporting a broader adoption of EVs. By ensuring that EV infrastructure is robust and power quality issues in the grid are addressed, the study contributes to a smoother transition towards energy independence and sustainable means of transportation [3–5]. In 2022, global passenger vehicle stock exceeded 1.4 billion, with LDVs making up a large share. By 2035, EV sales are expected to account for 80 percent of net vehicle growth. Vehicles traveled over 21 trillion kilometers annually, with EVs contributing to further growth. Road transport accounted for more than 50 percent of global oil consumption in 2023, though this is declining in regions adopting EVs. The transport sector emits over 7.3 Gt of Carbon dioxide annually, about 24 percent of global energy-related emissions, with EVs helping to reduce these emissions by up to 50 percent [6]. The environmental and economic benefits of electric vehicles (EVs) depend on the decarbonization of the electricity grid. The use of renewable energy reduces EV lifecycle emissions by lowering the carbon footprint of charging them. The use of solar and wind energy reduces the emissions of EVs, making them more sustainable than internal combustion engine vehicles. The proposed bidirectional EV charging system (G2EV and EV2G) allows EVs to serve as mobile energy storage, stabilizing

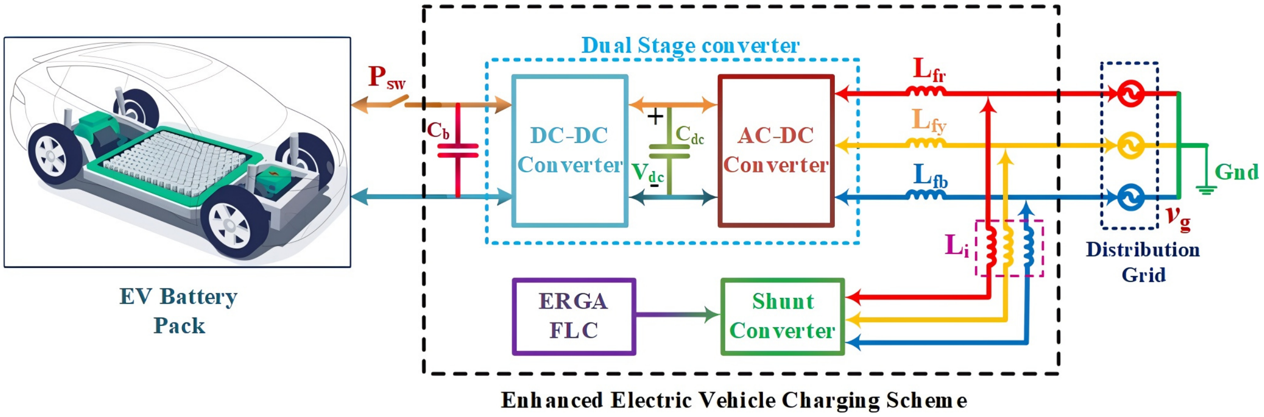


FIGURE 1. Schematic of Enhanced EVCS.

the grid during peaks of renewable energy generation and providing backup power during lows, improving grid the reliability and optimizing renewable energy use [7–9]. Several types of motors are under consideration for EV applications, including brushless DC motors, synchronous motors, switched reluctance motors, and induction motors. Among these options, permanent magnet synchronous machines (PMSMs) stand out as strong contenders, known for their excellent performance and numerous benefits, such as rapid dynamic response, high power density, and efficiency. The multiphase PMSM, in particular, has become popular due to its advantages over standard three-phase motors. It offers improved fault tolerance, reduced torque fluctuations, better noise characteristics, and lower phase current, resulting in less strain on switches [10, 11]. However, achieving optimal PMSM performance largely depends on the control strategy implemented. Various traditional governing strategies, including scalar control and space vector modulation (SVM), have been studied for multiphase motors. This paper focuses on using the SVM control strategy to operate a five-phase PMSM in an electric vehicle.

Fuzzy logic is similar to the way humans make decisions. It covers ambiguous and imprecise data. Using this logic significantly reduces the number of practical issues, and it is based on degrees of truth rather than the standard correct or incorrect, or 1/0 in Boolean logic. Initially, the principles of FLC are discussed, focusing on its application in speed control [12]. Research indicates that fuzzy controllers are more resilient to changes in process parameters compared to traditional PI or PID controllers and demonstrate advanced noise rejection. Recent studies have highlighted the effectiveness of fuzzy control in machine driven applications due to its ability to deliver robust performance across both linear and nonlinear systems, and its advantage of not needing the mathematical model of the process [13–16]. However, designing a fuzzy logic controller relies mainly on heuristic methods, making systematic design challenging, as it often depends on personal experience and expert knowledge of the controlled process. Additionally, determining the input and output scaling gains is typically done through trial and error, which can be a lengthy process as these gains must be adjusted to achieve the desired performance. To improve the adaptability of the FLC under different operating conditions, some studies have suggested incorporating an additional FLC into the control algorithm [17–19]. This approach increases the number of rules and instructions, resulting in higher memory and execution time requirements. A fuzzy logic structure (FLS) is used to create controllers. A regular type-I (T-I) FLS is suitable for simpler systems, while an interval type-II (IT-II) FLS is more effective for composite systems. This is due to the greater flexibility it offers in determining membership degrees through the impression of insecurity in fuzzy sets (FSs). The concepts, principles, proposed methods, controls, and claims of IT-II FLS are explored in sources [20]. Additionally, [21, 22] analysed the steady-state performance of IT-II FLC and demonstrated that they provide greater robustness and a smoother control surface compared to T-I FLCs.

This article primarily focuses on designing an ERGA IT-I FLC for a shunt converter used in charging electric vehicles (EVs) in a novel method. In addition, it introduces a iterative constant current (ICC) method for charging EV batteries. Furthermore, it develops a T-I FLC optimised through the Enhanced Relative Gain Array (ERGA) to evaluate the performance in the context of the shunt converter. The rest of the article is as follows: Section 2 presents the EV advanced charging system. Section 3 provides the details about enhanced EVCS management strategy. Section 4 gives the simulation results of the proposed system. The last section (Section 5) gives the conclusion of the proposed system.

2. ADVANCED CHARGING SYSTEM FOR EV

The diagram of an Enhanced Electric Vehicle Charging System (EVCS) is shown in Figure 1. This system embraces both the AC-DC and buckboost converters. For the AC-DC conversion, either single-phase or 3-phase unrestrained or well-controlled rectifiers can be used. The buck converter is generally favoured for reducing voltage from an upper level to the lower battery voltage during DC-DC conversion and an Enhanced EVCS with the complete system is presented in Figure 1. This scheme uses dual-directional rectifier and buckboost converters to facilitate G2EV and EV2G operations. A shunt converter is coupled to reduce harmonics in the input current through these processes and IGBTs are used in the converter switches.

2.1. FACTORS AFFECTING THE SYSTEM DESIGN

Grid dependency for EV benefits: The research assumes that the electricity grid is progressively decarbonizing, leveraging renewable energy to maximise the environmental benefits of EVs. Without a clean grid, the overall emissions reduction potential is limited.

Battery performance standards: It is assumed that lithium-ion batteries, used in EVs, will continue to dominate with improvements in energy density, durability, and charging efficiency to meet the growing EV demands.

Limitations: High Initial Costs: The deployment of advanced EV charging infrastructure, including dual-direction converters and shunt controllers, incurs significant upfront costs, potentially limiting adoption in low-income regions.

Technical challenges: The complexity of designing interval type-II fuzzy logic controllers and integrating them with bidirectional power flow systems can limit scalability.

Uncertainties: Renewable Energy Integration: The extent to which renewable energy sources are adopted globally remains uncertain and heavily influenced by political and economic factors. The benefits of the proposed system diminish if renewable energy integration is slow or inconsistent.

Grid infrastructure readiness: The capacity of the existing grid infrastructure to handle the bidirectional power flow (EV-to-grid and grid-to-EV) is uncertain, as it requires substantial upgrades in many regions These factors emphasize the need for robust policies, investments in renewable energy, and advancements in technology to overcome the limitations and uncertainties [23].

2.2. DUAL-DIRECTION 3-ϕ RECTIFIER MODEL

The dual-direction 3-ϕ Rectifier is interconnected with the grid via inductance. The DC output voltage as follows [24]:

$$V_{\mathrm{dc}} = \frac{2 \times \sqrt{2} \times V_{L-L}}{\sqrt{3} \times m_i}, \qquad (1)$$

where, m_i is the index of modulation and V_{LL} is Line to Line Voltage (V).

The dc-side capacitor value is determined using:

$$C = \frac{P_{\mathrm{dc-max}}}{4\pi f \times V_{dc} \times \Delta V_{\mathrm{dc-ripple}}}, \qquad (2)$$

where, $\Delta V_{\mathrm{dc-ripple}}$ is the voltage of the ripple (V) and $P_{\mathrm{dc-max}}$ is the maximum DC power.

2.3. DUAL-DIRECTION BUCK-BOOST MODEL

The dual-direction DC-DC converter is positioned between the rectifier and the electric vehicle (EV) battery container. If it functions in buck mode then the battery charges and switches to boost mode for discharging. Therefore, the filter inductor for the battery must be designed to accommodate dual ways of operation. The modelling of the inductor for the buck and boost modes is as follows [24]:

$$L_B = \frac{(V_{\mathrm{dc}} - V_B)D}{\Delta I_{L-\mathrm{ripple}} \times f_s}. \qquad (3)$$

The buckboost converter's output capacitor (C_B) is calculated using:

$$C_B = \frac{\Delta I_L}{8 \times f_s \times \Delta V_{B-\mathrm{ripple}}}, \qquad (4)$$

where, $\Delta V_{B-\mathrm{ripple}}$ is the output voltage ripple at the battery side.

2.4. BATTERY DESIGN

Because of the sophisticated specific energy and density as well as other budding advantages, Li-ion batteries are utilized by the majority of EV manufacturers for EV batteries [25, 26]. In [27], the dynamic model of the battery for charging and discharging was presented:

$$V_{\mathrm{Nl}} = V_o - R_i i - K\frac{Q}{q + 0.1Q} i^* - K\frac{Q}{Q-q} q + Ae^{-Bq}, \qquad (5)$$

where V_{Nl} represents the non-linear voltage in volts (V), V_o denotes the constant voltage also in volts (V). R_i indicates the internal resistance of the battery measured in ohms (Ω), and K is the polarization constant expressed in ampere-hours ($\mathrm{A\,h^{-1}}$). The variable i^* refers to the small frequency current dynamics in amperes (A), with i representing the battery current in amperes (A). The quantity q signifies the extracted capacity measured in ampere-hours (A h), while Q is another related variable in this context, the max. battery capacity (A h). A & B are the exponential voltage (V) and capacity ($\mathrm{A\,h^{-1}}$), respectively. The SOC of battery is calculated by:

$$\mathrm{SOC}_B = \left(1 - \frac{1}{Q}\int_o^t i(t)dt\right) \times 100. \qquad (6)$$

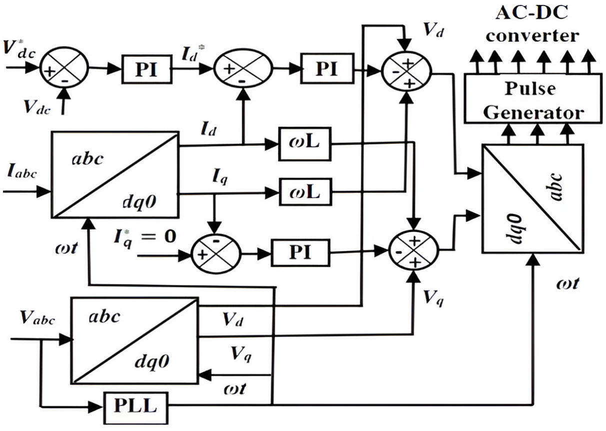


Figure 2. Three-phase rectifier control strategy.

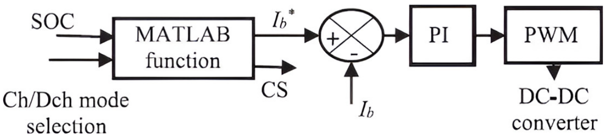


Figure 3. ICC control approach for buck-boost converter.

2.5. Shunt converter model

It is best to utilize a shunt converter with a sophisticated controller and control approach to reduce the input current distortions in the distribution system. It consists of an interacting inductor, an energy storage capacitor, and a voltage source converter. Using Equation (1), the lowest possible output voltage V_{SC} at the capacitor is determined while taking the modulation index into account as one. The interface inductor (L_i) and energy storage capacitor (C_{dc}) are constructed using the following formulas [27]:

$$\frac{1}{2}C_{dc}\left(V_{dc1}^{*2}-V_{dc1}^{2}\right)=\mathrm{k_1 3VaIt}, \tag{7}$$

$$L_i=\frac{\sqrt{3\times}m_i\times V_{dc1}}{12\times a\times f_s\times I_{cr}}, \tag{8}$$

where, the variables V, I, t, a, s, and k_1 represent the phase voltage, phase current, overcapacity factor, and energy discrepancy during dynamics, respectively.

3. Enhanced EVCS management strategy

3.1. EV charging controller

This EV charger consists of a dual-direction rectifier and buck-boost converters with a DC-link voltage and a current control mechanism which is shown in Figure 2. This technique offers good static performance and a quick transient reaction by using an inner current loop in conjunction with an outside voltage [27, 28].

The dual-direction BUCK-BOOST control approach of the converter is then developed using battery charging techniques like trickle current charging, pulsed charging, constant voltage (CV), constant current (CC), Constant power (CP), and constant current constant voltage (CCCV) in the literature. Among these techniques, EV Li-ion battery charging is frequently done using CCCV. In this approach, the accumulator is first charged by CC and then switches to CV mode to charge the remaining 20 % of SOC after it has reached 80 %. When compared to the CC approach, the CV method takes approximately three times as long. When switching from CC to CV mode, the CCCV approach produces more transients. The CC payment process quickly raises the battery voltage; this can even surpass the maximum voltage of the battery. This article uses an ICC control process to maintain the set current for the buck-boost converter. Figure 3 shows the ICC control technique, which generates reference current for charging/discharging (Ch/Dch) mode signal and the SOC (battery voltage).

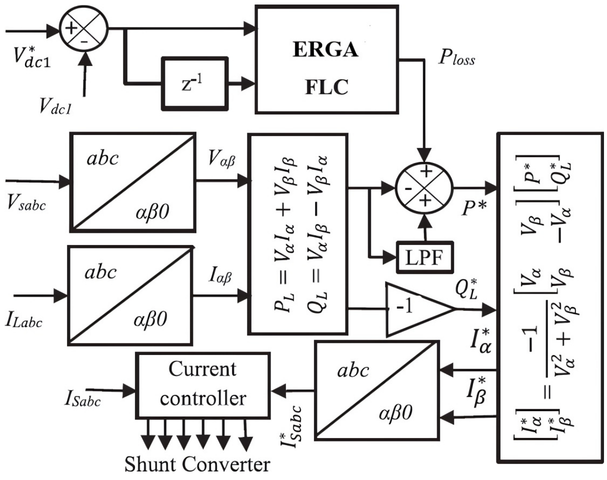


Figure 4. Shunt converter control approach.

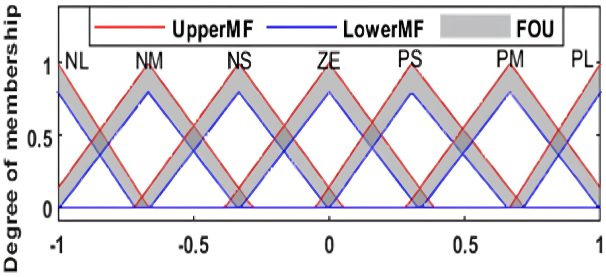
3.2. Shunt converter controller

The present study proposes the use of IRPT-based shunt converters in advanced enhanced EVCS, namely for the IT-II and ERGA FLC Takagi Sugeno type FLCs as shown in Figure 4. Figures 5 and 6 shows the organizational framework of the suggested control approach and Table 1 gives the FLC rules for the controller.

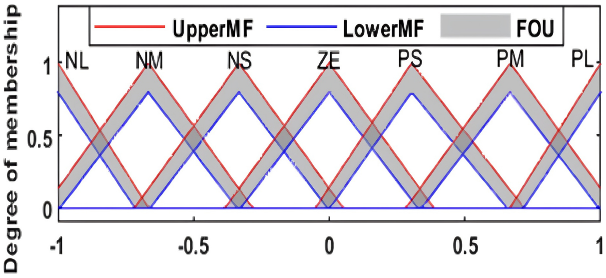
The ERGA Flowchart is shown in Figure 7 , where a clear the operational structure of the algorithm is presented. Furthermore, only IT-II FLC involves a type reducer. The T-I FLC in ERGA is created by remapping the T-I FLC MFs with optimal values taken from literature.

4. Simulation results

The MATLAB/Simulink platform is utilized to model the entire system. Table 2 lists the parameters used in the simulation. For IT-II and ERGA FLCs, the effectiveness of the shunt converter-linked charging strategy is investigated. Each controller's performance in G2EV and EV2G operation has been examined.

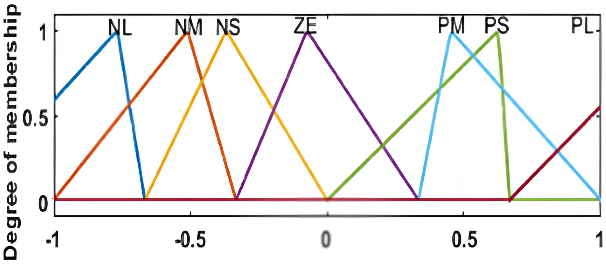


(a). Deviation.

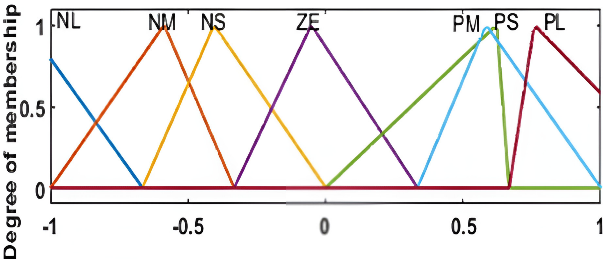


(b). Change in deviation.

Figure 5. MFs of IT-II FLC.



(a). Deviation.



(b). Change in deviation.

Figure 6. MFs of ERGA T-I FLC.

CE/E	NS	NM	NL	ZE	PL	PM	PS
NS	NM	NL	NL	NS	PM	PS	ZE
NM	NL	NL	NL	NM	PS	ZE	NS
NL	NL	NL	NL	NL	ZE	NS	NM
ZE	NS	NM	NL	ZE	PL	PM	PS
PL	PM	PS	ZE	PL	PL	PL	PL
PM	PS	ZE	NS	PM	PL	PL	PL
PS	ZE	NS	NM	PS	PL	PL	PM

Table 1. FLC Rules.

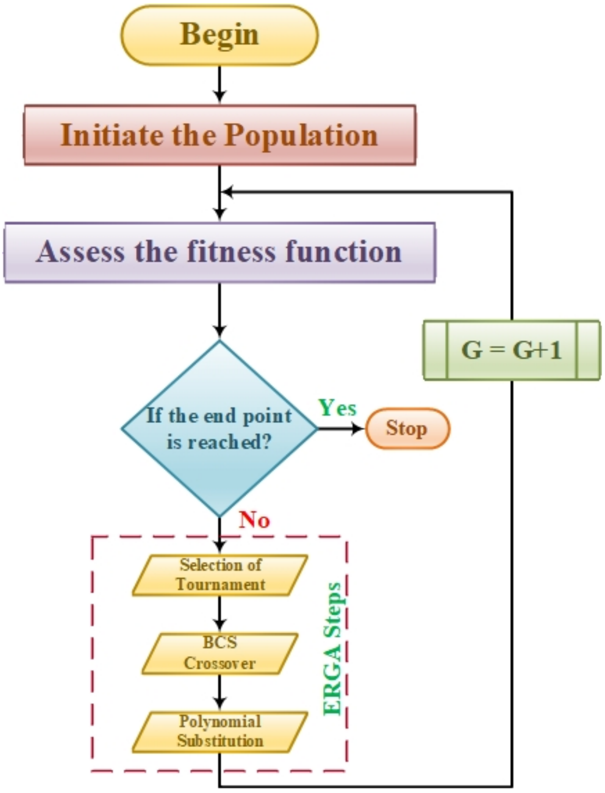


Figure 7. ERGA FLC Flowchart.

Parameters	Values
DC side Capacitor (C)	3 200 µF
System Frequency (f)	50 Hz
3-∅ source voltage (v_g)	415 V (L-L)
Inductance ($L_{fr} = L_{fy} = L_{fb}$)	4.8 mH
Inductance (L_b)	3.5 mH
Capacitance (C_b)	60 µF
Switching Frequency (F_s)	12 kHz
Battery Voltage (V_b)	355 V
Battery Capacity	65 A h
Inductance (L_i)	0.6 mH

Table 2. Simulation Values.

A 4-second simulation is run on the modelled system. It operates in G2EV mode for the first two seconds and EV2G mode for the remaining two seconds. The system's overall response time is observed to be 5 µs. With IT-II, and ERGA optimized FLCs, different parameters are observed, as presented in the results. The Harmonic spectrum analysis is shown for all scenarios in G2EV and EV2C modes.

4.1. SHUNT CONVERTER CONTROL VIA IT-II FLC

Figure 8 shows the output results of the presented shunt converter linked charging strategy with IT-II FLC in G2EV set-up. Further, rectifier and buckboost converters allow the battery to absorb grid power. As a result, the power factor has remained over 0.97 and the battery voltage and state of charge are rising.

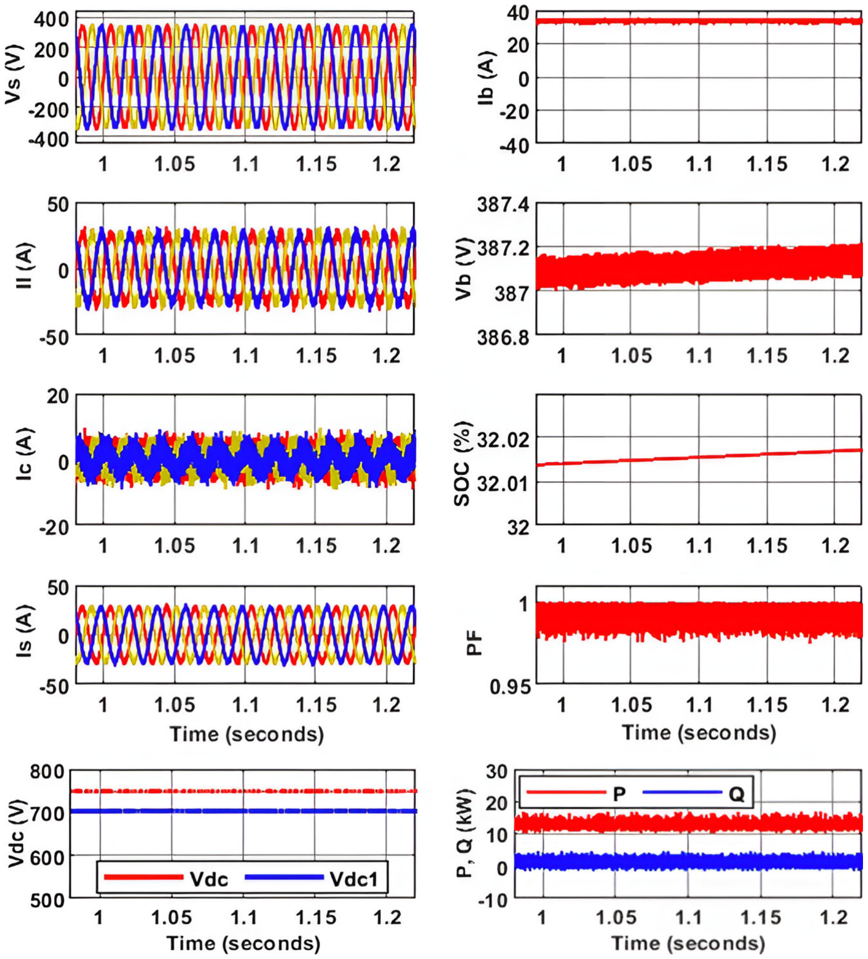


Figure 8. Characteristics of IT-II FLC performance during G2EV operation.

The output results for the suggested charging strategy with IT-II FLC in EV2G set-up are shown in Figure 9. The DC-link voltage of the rectifiers and shunt converter are kept at a predetermined value while its voltage and SOC are falling.

4.2. Shunt converter control via ERGA T-I FLC

Figure 10 shows the output responses of the ERGA T-I FLC during G2EV when using a shunt converter coupled charging method. The battery is charging in this mode, which is why the voltage and SOC are rising.

The output responses of the suggested charging system with ERGA T-I FLC during EV2G set-up is shown in Figure 11. As a result of the battery being depleted in this mode, its voltage and SOC are falling. The performance of the current charging method and the proposed shunt converter-linked charging scheme are compared and initial response in G2EV to EV2G conversion is shown in Figure 12.

According to the IEEE-519 standard, Figure 13 clearly shows that the ERGA-tuned T-I FLC operated effectively in G2EV mode based on the source current THD. The IT-II FLC operated effectively in the EV2G mode. In both the G2EV and EV2G modes, ERGA IT-I FLC has a shorter settling time, peak time, and overshoot than IT-II FLC. In both G2EV and EV2G modes, ERGA T-I FLC has a shorter rise time than IT2 FLC. It is evident from all of the research findings and analysis that the ERGA IT-I FLC performs robustly when compared to the other controller. Future work of the concept will be carried out using experiments to further validate and improve the system performance.

5. Conclusion

This paper describes the creation of a revolutionary advanced charging strategy for electric vehicle (EV) applications using a shunt converter. Using the Matlab/Simulink platform, the proposed system was built and verified. In this article, an integrated shunt converter with efficient and effective control strategy is discussed and the proposed system charging scheme is presented. The Harmonic Spectrum Analysis of the proposed system is within the limits of IEEE-519 standards. By efficiently controlling the shunt converter DC-link voltage, an ERGA T-I FLC will improves the system performance. Ultimately, the proposed ERGA IT-I FLC approach outperforms the competing controller in terms of response time and performance.

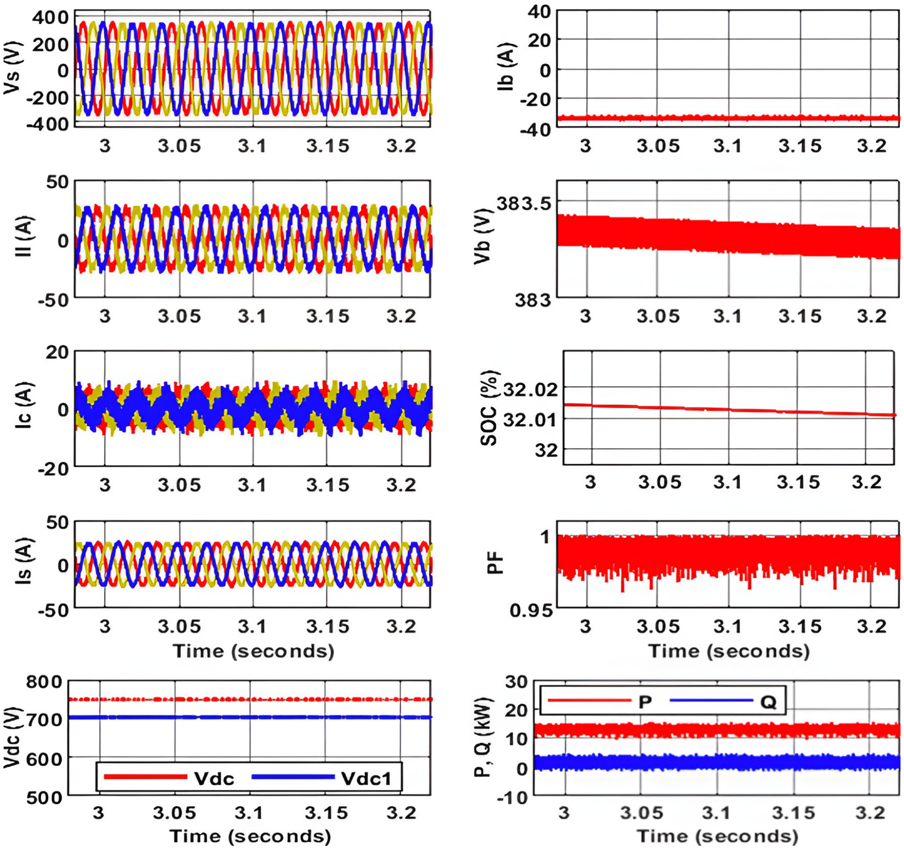


Figure 9. Characteristics of IT-II FLC performance during EV2G operation.

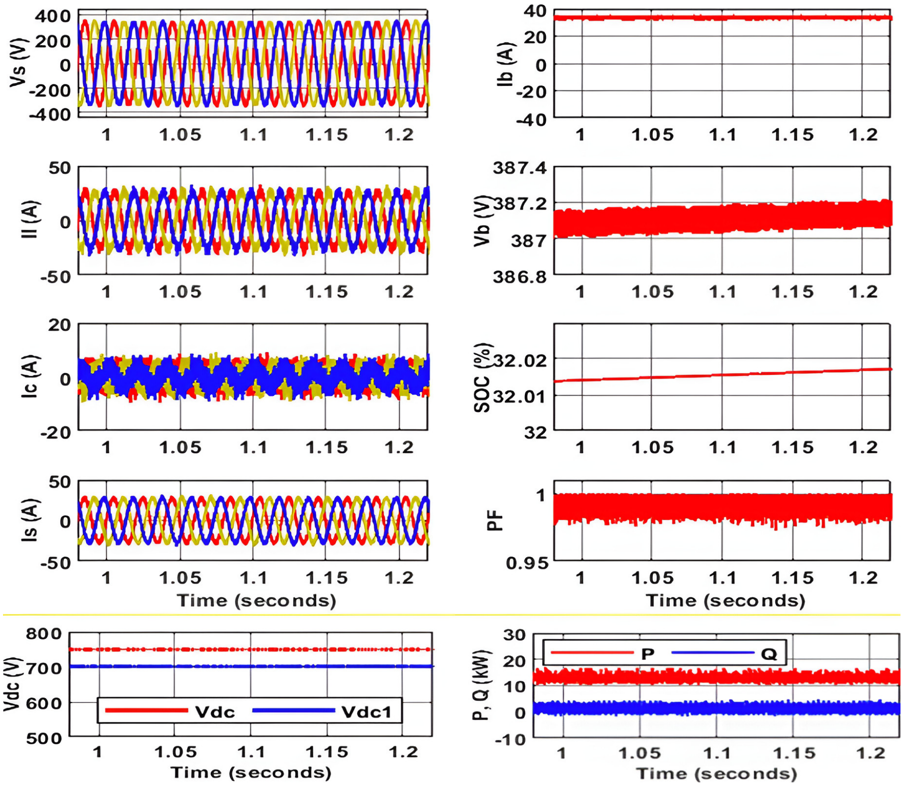


Figure 10. Characteristics of ERGA T-I FLC performance during G2EV operation.

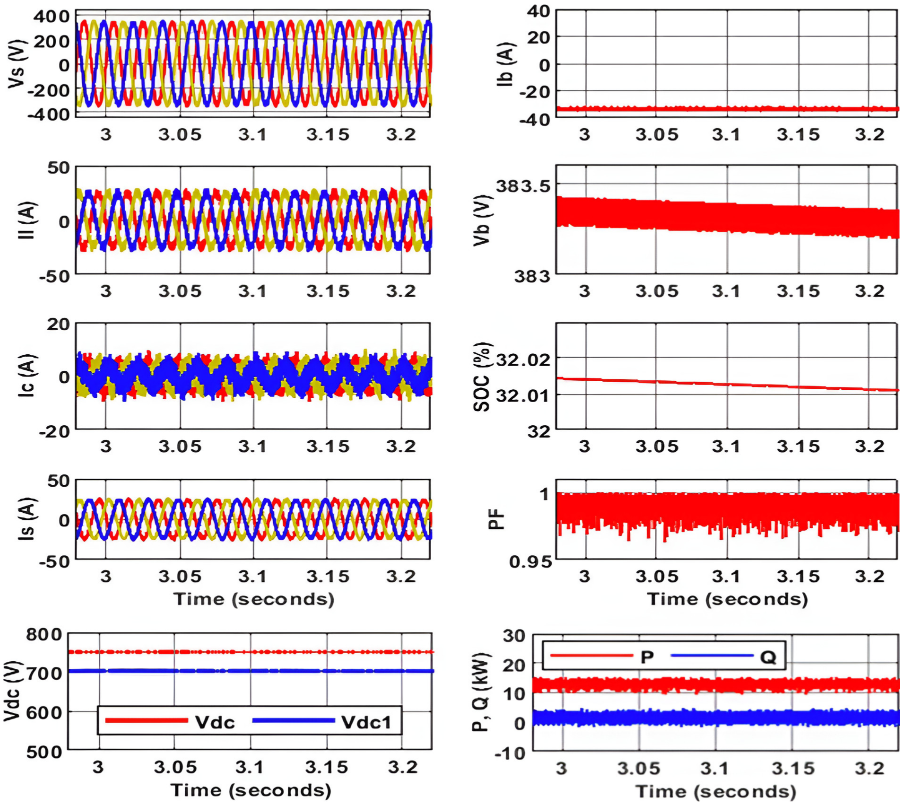


Figure 11. Characteristics of ERGA T-I FLC performance during EV2G operation.

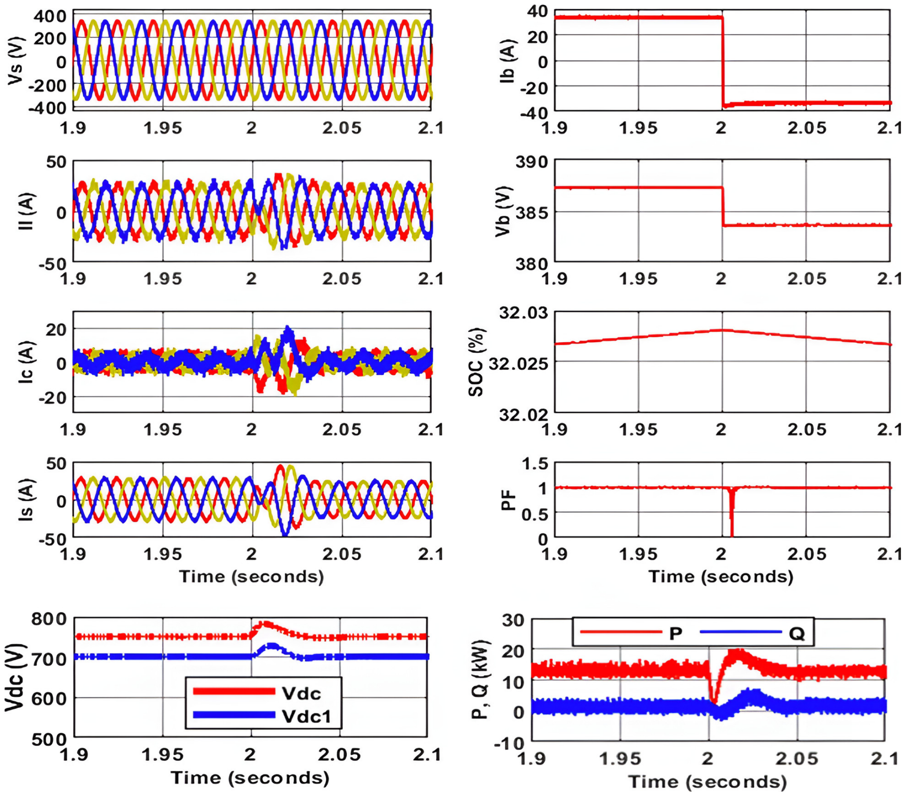


Figure 12. Initial response in G2EV to EV2G conversion.

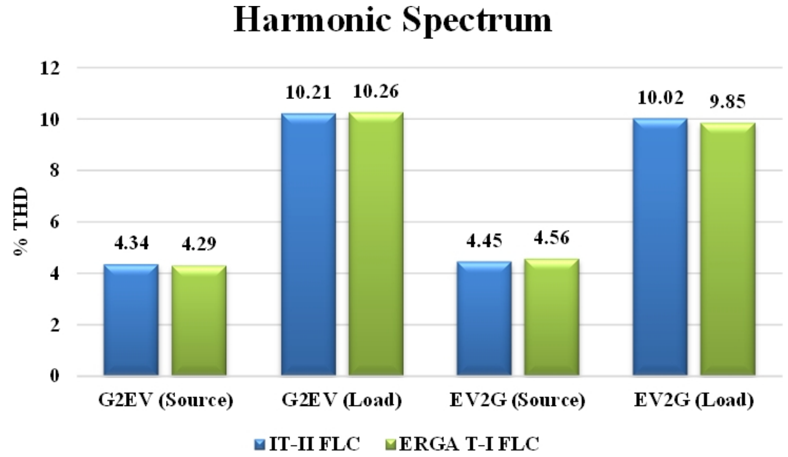


FIGURE 13. Harmonic Spectrum Analysis.

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