A versatile three-level CLLC resonant converter for off-board EV chargers with wide voltage adaptability contribution

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ABSTRACT

The vehicle-to-grid (V2G) concept has gained significant attention in the last decade due to its potential to enhance direct current (DC) microgrid stability and reliability. Electric vehicles (EVs) play a central role in distributed energy storage systems, optimizing efficiency and enabling the integration of renewable energy sources. This study offers a unique three-level CLLC resonant converter developed for off-board EV chargers to promote bidirectional power transfer between DC microgrids and EVs. The suggested converter uses resonant CLLC components and two three-level full bridges to effectively handle a broad range of EV battery voltages (200 V–700 V). To ensure effective power conversion, the first harmonic approximation (FHA) model is used to analyse the converter's resonant frequency characteristics. The proposed system achieves high efficiency (>95%), with voltage stability maintained at 750 V under various load conditions. The converter's performance was validated through MATLAB-based simulations, comparing proportional integral (PI) and proportional integral derivative (PID) control strategies. The PID-controlled system demonstrated superior dynamic response, reduced current ripples, and enhanced voltage regulation compared to the PI-controlled system. This study demonstrates the viability of implementing a three-level CLLC resonant converter for efficient, bidirectional, and wide-voltage adaptation in EV charging infrastructure, thereby contributing to grid stability and renewable energy integration.

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1. INTRODUCTION

The increasing need for sustainable energy solutions, the widespread use of non-conventional energy sources, and the fast acceptance of electric vehicles (EVs) are all drastically altering the world's energy landscape [1], [2]. To accommodate this change, the electrical infrastructure must undergo improvements, such as the creation of more efficient grid systems and the introduction of technology that facilitates the interaction of customers, storage systems, and energy sources [3], [4]. The growing use of EVs and the incorporation of distributed energy resources (DERs) into direct current (DC) microgrids have highlighted the need for efficient bidirectional power converters that enable seamless vehicle-to-grid (V2G) and grid-to-vehicle (G2V) power transfer. Existing research has explored various converter topologies, such as LLC resonant converters, which enhance efficiency through soft switching but face challenges with limited voltage adaptability and complex control. Advanced control techniques, including sliding mode control (SMC) [5], have been proposed to improve dynamic response, yet their complexity restricts practical implementation. Additionally, three-port converters (TPCs) have been investigated for integrating photovoltaic (PV) and battery energy storage systems (BES), but they suffer from increased component count and higher design complexity [6], [7].

The traditional alternating current (AC) grid has long been the standard for electricity distribution worldwide. AC grids are characterized by the periodic reversal of current flow, which allows for the efficient transmission of electricity over long distances [8]. As a result of their compatibility with a large variety of electrical equipment, the relatively straightforward nature of voltage transfer, and AC grids are quite widespread [9], [10]. Conversely, the emergence of DERs, which produce DC such solar PV systems, wind turbines, and energy storage systems (ESS), has highlighted the limitations of AC grids in modern energy systems [11]. The DC grid offers an alternative approach to electricity distribution that aligns more closely with the requirements of DERs and certain high-efficiency applications. Unlike AC grids, DC grids maintain a unidirectional flow of current, reducing energy losses associated with AC-DC conversion and enabling more efficient power management in systems with significant renewable energy penetration [12]. Additionally, DC grids are better suited for applications where stable and reliable power is critical, such as in data centers, industrial processes, and EV charging infrastructure [13]-[15]. Electric vehicles are at the forefront of the transition to sustainable transportation, with their widespread adoption posing both challenges and opportunities for grid management. One of the key innovations in this context is the bidirectional charging capability, which allows EVs to function not only as consumers of electricity but also as energy suppliers [16]-[19]. DC-DC converters enable power conversion between the vehicle's battery and the grid, allowing for V2G and G2V operations. Figure 1 illustrates the conventional architecture of a DC microgrid [20], [21].

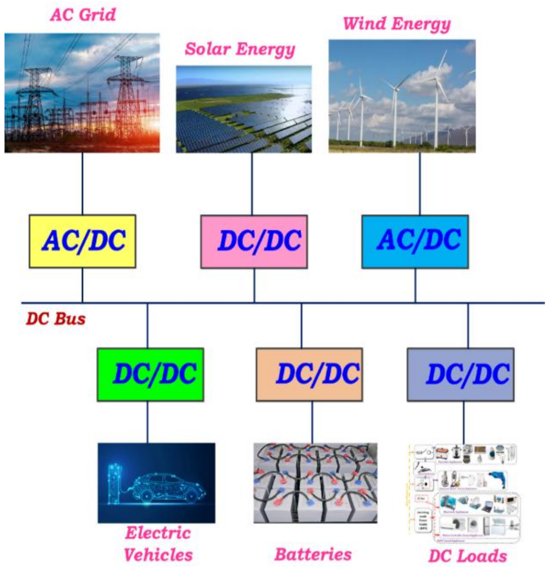

Figure 1. A conventional configuration of a microgrid working on DC

Many microgrids working on DC integrate EVs as a load. Electric vehicle battery systems can function as distributed energy storage units while also serving as loads for DC microgrids. For the most part, electric vehicles sit idling [22]. Using electric vehicles as ESS can reduce the need for expensive and bulky energy storage equipment. When handled correctly, they have the potential to boost DC microgrid stability and reliability, facilitate renewable energy sources (RES) integration, and increase system efficiency [23], [24]. The off-board electric vehicle charger must incorporate a bidirectional DC-DC converter that can alternate between two power flow modes: discharging (V2G) and charging (G2V). This is crucial for the charger to operate well as a distributed energy storage system [25]. Bidirectional power flow, high efficiency, voltage regulation, power density, thermal management, isolation, scalability, dynamic response, compatibility with standards, cost-effectiveness, reliability and longevity, and modularity are the primary requirements of a DC-DC converter, particularly in the context of bidirectional EV charging to the grid [26]-[29]. The summary of the major contributors of their work and their key findings are listed in the literature survey, and the same is explained in Table 1.

Table 1. Literature survey

S. No.	Major contributions	Contributors proposed techniques	Key findings
1	LLC resonant converter for bidirectional DC-AC Conversion	Developed a modified LLC converter for bidirectional DC-DC and DC-AC conversion with high-frequency transformer galvanic isolation [30].	Enabled various power conversion functions, including grid-tied inverter and battery charging, improving efficiency and flexibility.
2	SMC for CLLC Resonant Converters	Proposed a high-order SMC to improve frequency regulation and load adaptation in automotive CLLC resonant converters [31].	Enhanced efficiency and dynamic response by reducing operational frequency range and improving load-handling capabilities.
3	TPC for energy storage	Introduced a bidirectional single-phase DC-AC converter with three power ports to manage grid and energy storage interactions [32].	Improved power transfer efficiency and minimized power loss by optimizing the direct conversion process.
4	TPC for PV and BES systems	Designed and categorized different TPC topologies for integrating PV and BES systems with grid interaction [33].	Provided insights into the advantages and limitations of various TPC designs, identifying optimal configurations for bidirectional power flow.
5	Resonant DC-DC bidirectional converter for G2V/V2G	Developed a resonant topology DC-DC bidirectional converter to enable power exchange between EVs and the grid [34].	Demonstrated improved bidirectional power conversion efficiency and potential integration with renewable energy sources.
6	Switching reluctance motor (SRM)-based EV drive system with bidirectional converter	Designed an EV SRM drive with a bidirectional boost/buck converter for efficient power management [35].	Enhanced driving performance, extended battery life, and enabled regenerative braking for energy recovery.
7	Active cell-to-cell balancing circuit with CLLC converter	Developed a cost-effective and efficient bidirectional CLLC resonant converter for EV battery balancing [36].	Reduced system cost by eliminating bidirectional switches and gate drivers while achieving zero-voltage zero-current switching (ZVZCS).
8	CLLC resonant converter for efficient energy transfer	Proposed a bidirectional CLLC converter to improve energy transfer efficiency in EV applications [37].	Achieved better voltage regulation, reduced energy losses, and enhanced system performance with resonant frequency optimization.

This paper presents a new three-level converter that can be used as an electric car charger in DC microgrids. This study is driven by the desire to investigate and optimise the technical aspects of AC and DC grid integration, with a particular emphasis on the role of DC-DC converters in enabling bidirectional energy flow between EVs and the grid. As the energy sector evolves, understanding these dynamics will be crucial for developing resilient, efficient, and sustainable power systems. Here is where the paper's key contribution is: a new resonant converter for three-level CLLCs. The three-level complete bridges can function in four modes using resonant capacitors and inductors on the intermediate frequency transformer's main and secondary sides. The three-level CLLC resonant converter's circuit is built using the first harmonic approximation (FHA) method. Output voltages ranging from 200 V to 700 V are within its capabilities. Despite the advancements, key challenges remain, including limited voltage adaptability (200 V–700 V), efficiency losses due to switching transients, and control difficulties in maintaining capacitor voltage balance. To solve these challenges, this study proposes a new three-level CLLC resonant converter for off-board EV chargers that combines two three-level full bridges with resonant components to provide high efficiency, wide voltage adaptation, and bidirectional power flow.

There is a rare chance to improve grid stability through EV inclusion, especially in systems where renewable energy is heavily used. Bidirectional charging allows EVs to perform ancillary services like frequency management, peak shaving, and load balancing, thereby transforming them into mobile energy storage units. However, achieving this potential requires advancements in DC-DC converter technology and a deeper understanding of the interplay between AC and DC grids in a bidirectional charging context. The proposed converter ensures balanced flying capacitor voltage regulation, reducing voltage stress and improving performance. Furthermore, a comparative analysis of PI and PID control techniques demonstrates enhanced dynamic response, voltage stability, and overall efficiency. MATLAB-based simulations validate the converter’s effectiveness in maintaining stable power transfer across varying voltage levels. Investigating the design and working principles of DC-DC converters used in bidirectional EV charging, evaluating the effect of bidirectional EV charging on grid stability and efficiency, especially in systems with high levels of renewable energy integration, and suggesting and assessing possible advancements in DC-DC converter technology that could improve the efficiency and dependability of bidirectional charging systems should be the main goals of this paper.

The remainder of this paper is organized as follows: Section 2 describes the suggested converter architecture and operating principles, while section 3 gives simulation results and performance evaluations. Section 4 addresses major findings, consequences, and future research prospects. Through this work, the aim to advance bidirectional EV charging systems, improve grid stability, and enhance renewable energy integration in modern DC microgrids.

2. RESONANT CONVERTER WITH THREE LEVELS: A PROPOSED DESIGN

2.1. A three-level CLLC resonant converter's topology

Figure 2 corresponds to 3-level CLLC converter with resonant feature. Two capacitors, two resonant inductors, a complete three-level bridge, and an intermediate frequency transformer make it up. When we add the transformer's leakage inductance from the secondary side to the main side, we get Lr_1, but Lr_2 is the same on both sides. The transformer winding ratio is denoted by the symbol n. We shall omit the excitation current below, as the transformer's magnetizing inductance substantially exceeds L_{r1} and L_{r2}.

The components of a series resonant network are C_{r1}, C_{r2}, L_{r1} and L_{r2}. At the same time, the two three-level complete bridges generate a DC component, which is balanced off by C_{r1} and C_{r2}. The voltage of an EV, ranging between 200-800 V, is typically coupled to the V_2 DC port in real-world applications. The V_1 DC port of a microgrid working on DC is connected to a DC bus, having constant voltage, 750 V.

The proposed converter, having CLCC, can naturally handle bidirectional electricity due to its fully symmetrical construction. In the G2V mode of the converter, one acts as an inverter and the second acts as a rectifier. During V2G turn-on mode, the chief bridge rectifies the current, and the secondary bridge inverts it. The working concept and characteristics in G2V mode will be mostly discussed in the following paragraphs due to the symmetry.

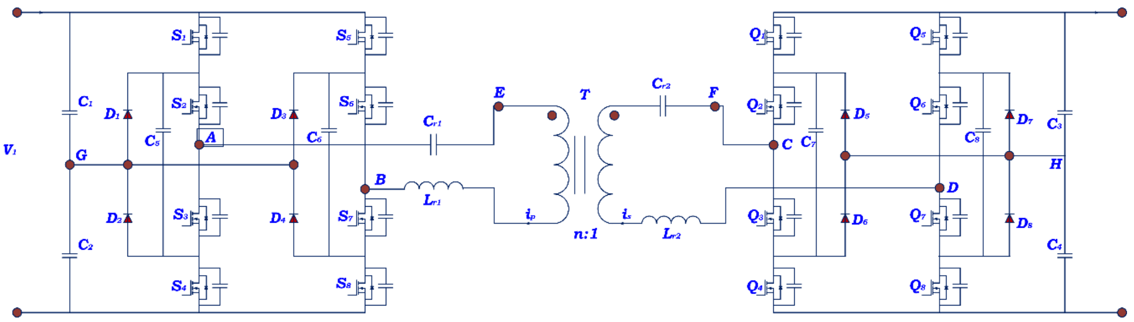

Figure 2. The three-tier CLLC resonant converter's topology

2.2. The operational modes of the primary three-level full bridge

In contrast to the standard three-level DAB converter, the proposed topology's major 3-level complete bridge has the capacity to generate a voltage waveform with a non-zero average value. To cancel out VAB's DC component, the resonant capacitor C_{r1} might be used. When everything is calm, the average voltage across the capacitor C_{r1} is obviously the same as the average value of VAB. All switches and diodes are ideal gadgets because they facilitate debate and analysis. Both the DC-link and flying capacitors exhibit a voltage of 0.5 V_1 under steady-state conditions. As indicated in Table 2, the three-level leg is capable of operating in four different switching states. To get a positive voltage level, for example, you may activate S_1 and S_2 while leaving S_3 and S_4 off.

In States P and N, the voltage of the flying capacitor C_5 is unaffected by the output current ip. In states O_1 and O_2, the current output has a varied effect on the voltage of the flying capacitor. If ip is positive, C_5 charges in O_1 and discharges in O_2. Maintaining 0.5 V_1 flying capacitor voltage necessitates clockwise cycling between zero-level states. Because of the flexible combinations of the two three-level legs, the full three-level bridge can transition between sixteen states. Figure 3 depicts the principal three-level complete bridge transitioning between four modes of operation. The resonant capacitor's average voltage, v_{Cr1}, is zero in modes A and C and 0.25 V_1 in modes C and D. v_{Cr1} minus $V_{AB} = V_{EB}$. Thus, V_{EB} is an amplitude-matched quasi-square wave with V_1, 0.75 V_1, 0.5 V_1, and 0.25 V_1. The details are seen in Figure 3. As with other three-level flying capacitor converters, the flying capacitor voltage must be regulated. Flying capacitor deviation affects converter performance. It increases voltage stress, which could irreversibly damage switches C. Successively switches O_1 and O_2 to maintain 0.5 V_1 flying capacitor voltage.

Table 2. Changing the status of the main bridge's three-story leg

State	S_1	S_2	S_3	S_4	v_{AG}
P	ON	ON	OFF	OFF	$0.5V_1$
J_1	ON	OFF	ON	OFF	0
J_2	OFF	ON	OFF	ON	0
Q	OFF	OFF	ON	ON	$-0.5V_1$

2.3. Secondary three-level full bridge operational modes

There may be new ways to operate the tributary bridge of the 3-level CLLC converter with resonant features that bring down switching loss. The steady-state voltage across the flying and DC-link capacitors is 0.5 V_2. Table 2 lists three more secondary bridge-specific switching states in addition to the four in Table 3. The leg's three switch levels are deactivated in State R_0. Leg output voltage is 0.5 V_2 when the secondary transformer current is positive. We get V_{DH} = 0.5 V_2. The three-level leg functions as a diode rectifier bridge. C_8 charges the flying capacitor when its voltage is lower than that of C_3 or C_4. Capacitors C_3 and C_4 in the DC-link are charged when the voltage of C_8 exceeds theirs. DC-link and flying capacitor voltages are automatically balanced due to this property. The output voltage can fluctuate with the current's polarity in the other two switching stages, and the capacitor voltages can be automatically balanced. Figure 4 illustrates that the tributary 3-level full bridge can function in 4 approaches based on the switching states. V_{CD}, the bridge's output voltage, fluctuates with current direction. Modes E and G have a DC capacitor voltage component of 0, while Modes F and H contain 0.25 V_2. The DC component of the V_{FD} remains 0 thanks to capacitor C_{r2}'s DC blocking feature.

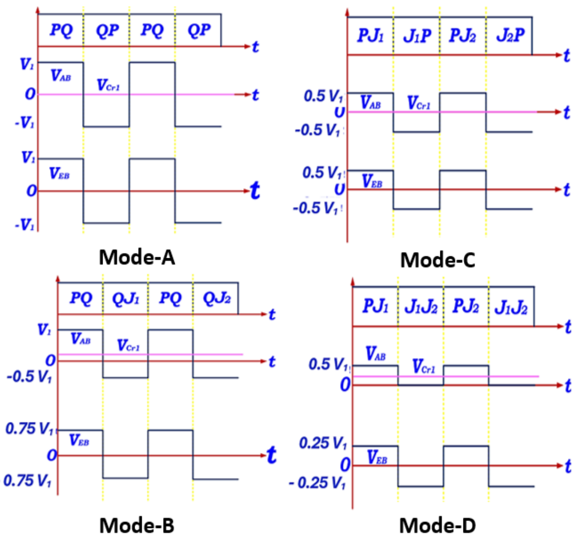

Figure 3. The main three-level complete bridge can operate in four different ways when there is no load, the quasi-square wave V_{EB} has amplitudes of V_1, 0.75 V_1, 0.5 V_1, and 0.25 V_1

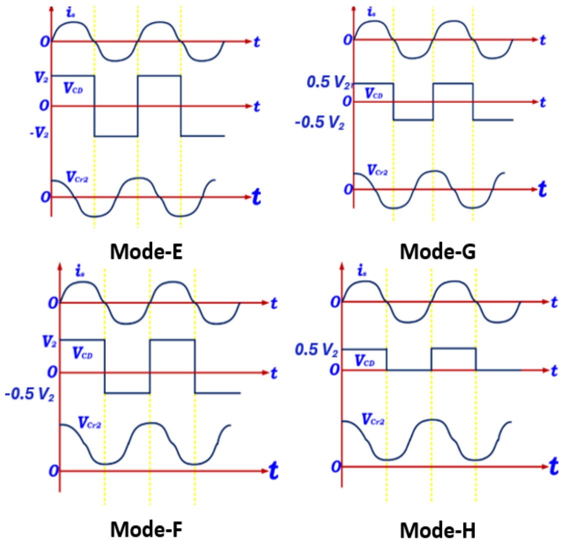

Figure 4. The CLLC residual converter's secondary three-level complete bridge operational modes

Table 3. Transitioning stages of a three-level segment of the secondary bridge

State	Q_5	Q_6	Q_7	Q_8	V_{Dh} ($i_s < 0$)	V_{Dh} ($i_s > 0$)
R_0	ON	ON	OFF	OFF	0.5 V_2	-0.5 V_2
R_1	ON	OFF	ON	OFF	0	-0.5 V_2
R_2	OFF	ON	OFF	ON	0.5 V_2	0

3. SIMULATION RESULTS

The proposed methodology of the circuit system is executed in the MATLAB simulation. The result of the simulation is described in two formats like with PI control technique and PID control technique.

3.1. With PI control technique

Figure 5 shows the supply potential of the major three-level bridge and displays the converter's constant power delivery capability in PI-controlled operation while maintaining a stable DC voltage of 750 V. Figures 6 and 7 depict the gate pulses delivered to the MOSFETs of the primary and secondary three-level bridges, demonstrating that synchronized gating assures efficient functioning of the resonant converter while accurate timing minimizes switching losses.

Figure 8 primary three-level bridge potential and Figure 9 secondary three-level bridge potential. Here both bridges deliver a stable voltage of 750 V, and it demonstrates confirms the system's capability to maintain voltage stability under resonant conditions. Figure 10 output current from the primary bridge and Figure 11 Internal three-level current of the primary bridge show the current values are consistent with the load demand, reflecting efficient energy transfer, and it signifies that the primary bridge operates within its designed current limits without overheating. Figure 12 output current from the secondary bridge and Figure 13 internal three-level current of the secondary bridge, from the figure can observe. These currents confirm proper operation, balanced power transfer between the bridges, and it highlights the symmetrical design of the converter for bidirectional operation.

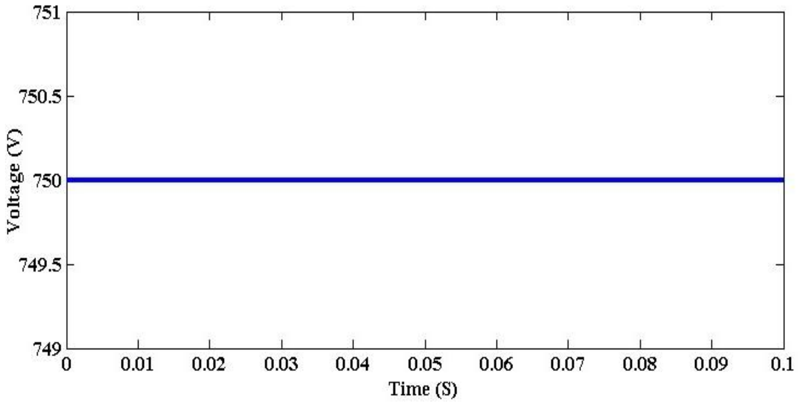

Figure 5. Supply voltage

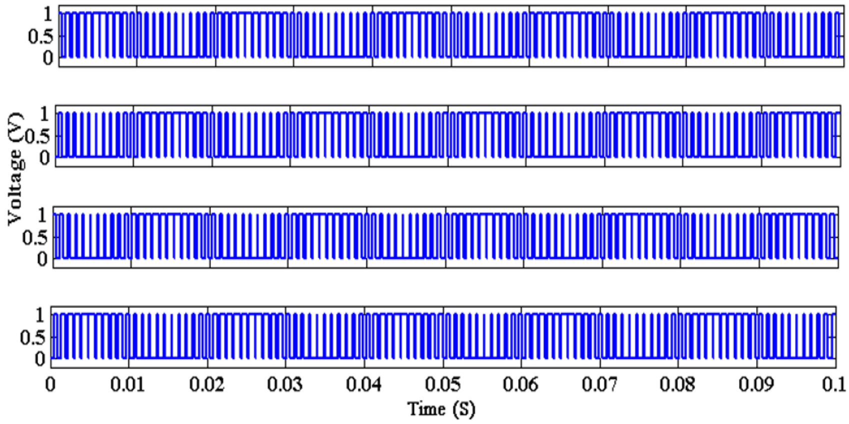

Figure 6. Gate pulses-1

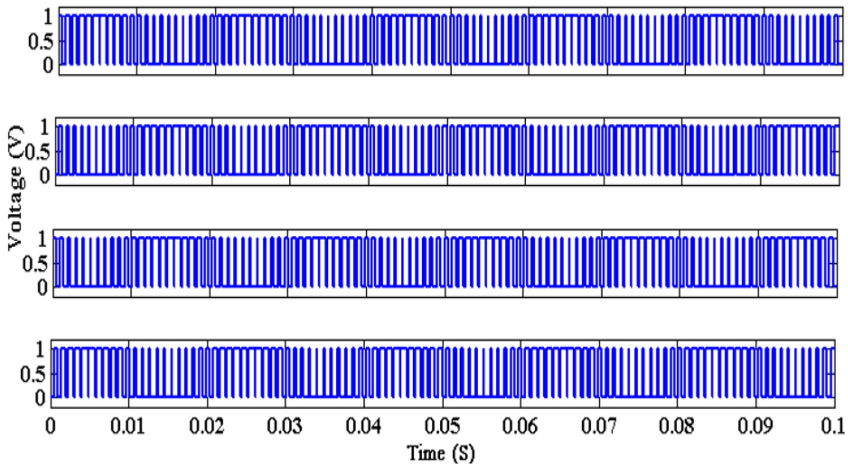

Figure 7. Gate pulses-2

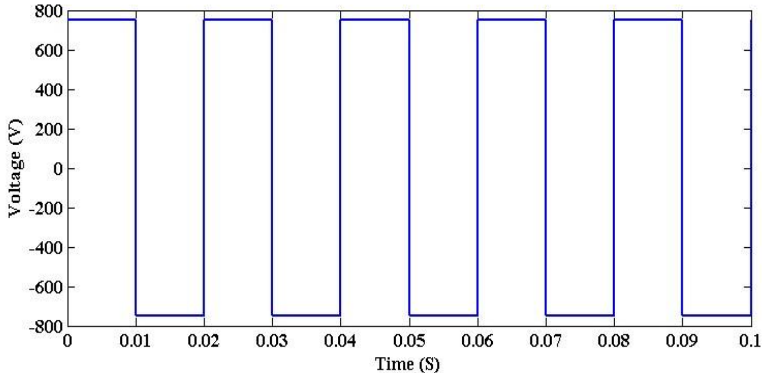

Figure 8. Primary three-level voltage

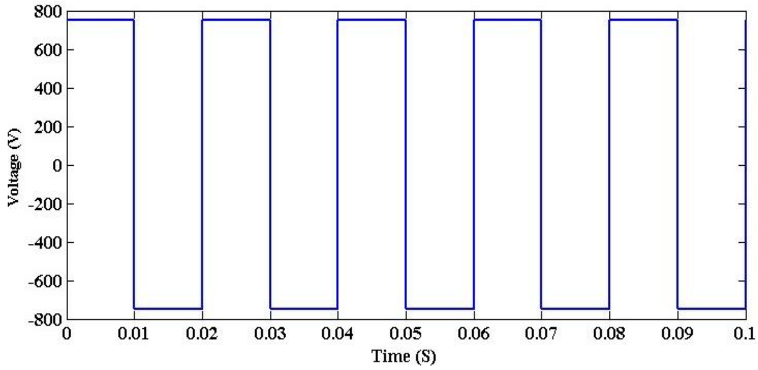

Figure 9. Secondary three-level voltage

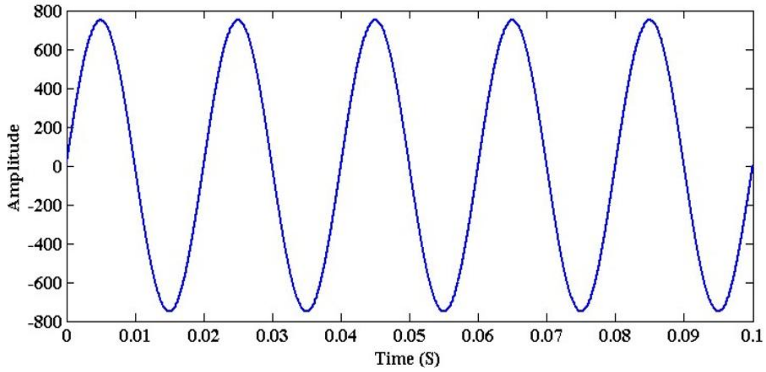

Figure 10. Output current primary

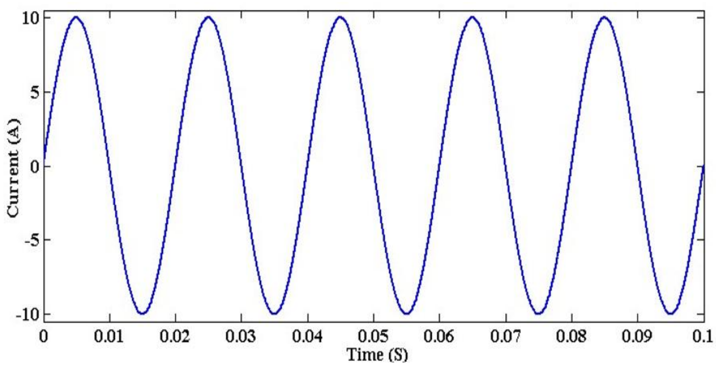

Figure 11. Primary three-level current

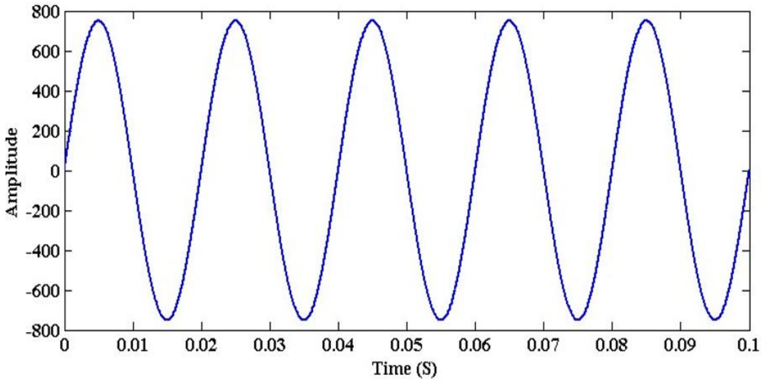

Figure 12. Secondary output current

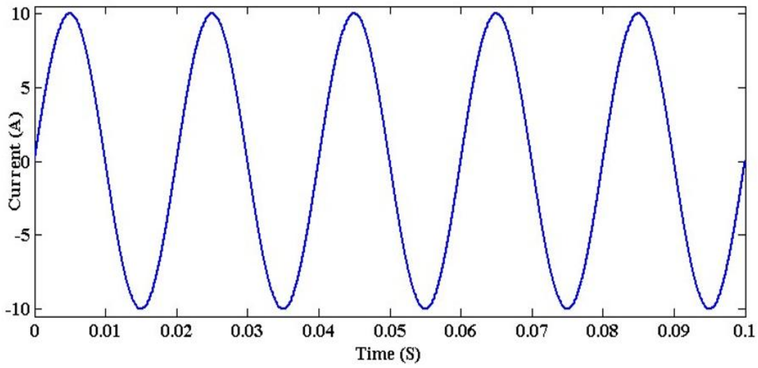

Figure 13. Secondary three-level current

3.2. With proportional integral derivative (PID) control circuit

Figure 14 DC supply voltage from the primary three-level bridge, it demonstrates the improved dynamic performance under PID control compared to PI. Figures 15 and 16 gate pulses, MOSFET gate pulses for primary and secondary bridges and it highlights the benefits of PID control in improving system responsiveness and these waveforms describe the MOSFET gating pulses of primary and Secondary three level bridge circuits. Figures 17 and 18 three-level voltages, both bridges achieve the target voltage of 750 V efficiently and it verifying the robust performance of the system under PID control.

Figure 19 output current from the primary bridge, and Figure 20 internal current of the primary bridge, here the current waveforms indicate minimal fluctuation, showing effective PID regulation which signifies the primary bridge handles varying loads without performance degradation. Figure 21 Output current from the secondary bridge, Figure 22 internal current of the secondary bridge figures can observe the stable currents reflect the efficiency of power transfer to the load which confirms the symmetrical operation of the converter in PID-controlled mode.

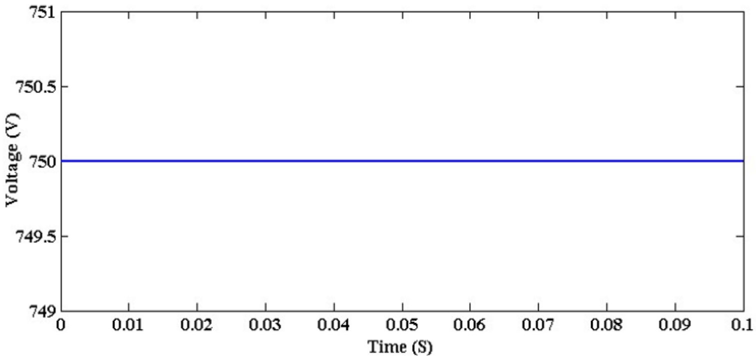

Figure 14. Supply voltage

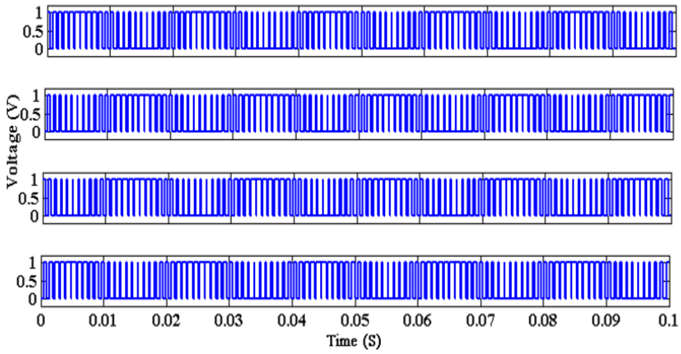

Figure 15. Gate pulses primary

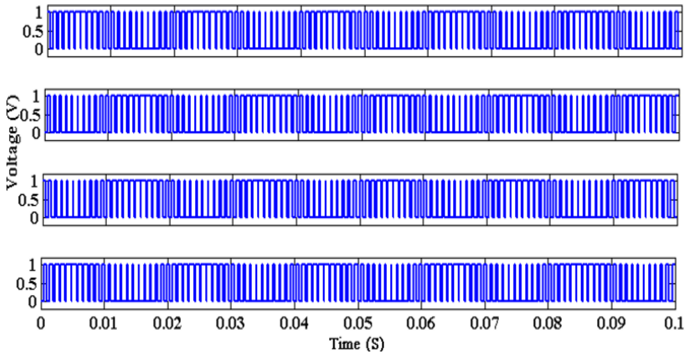

Figure 16. Gate pulses secondary

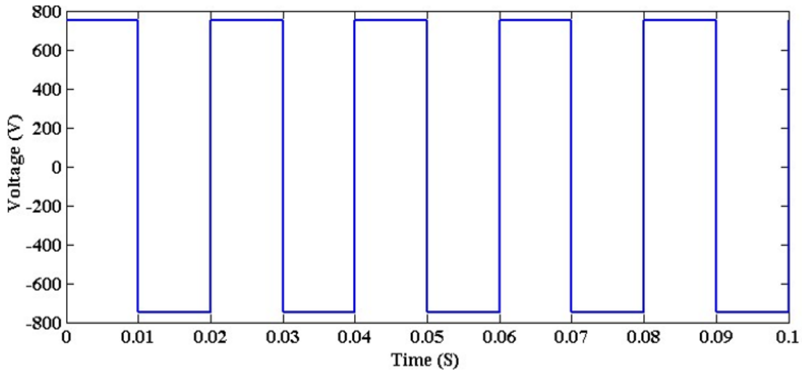

Figure 17. Primary three-level voltage

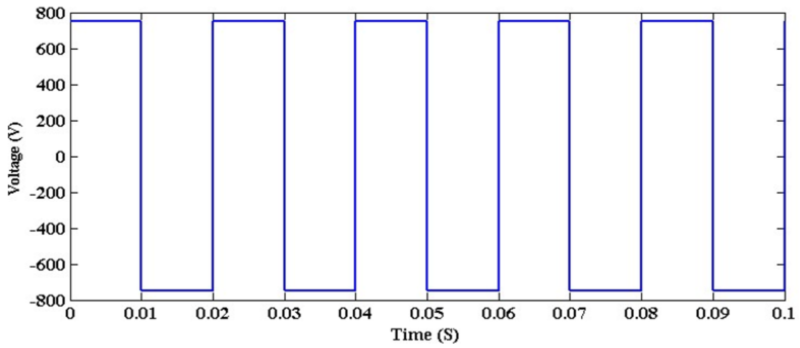

Figure 18. Secondary three level voltage

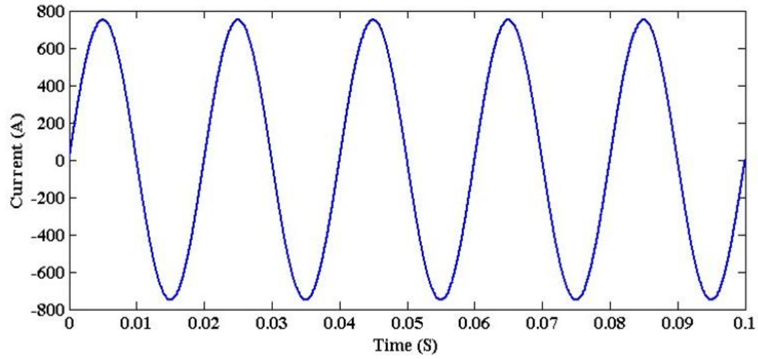

Figure 19. Output current primary

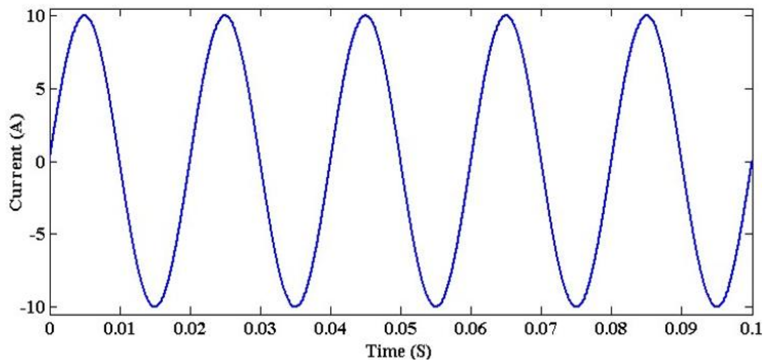

Figure 20. Three level primary current

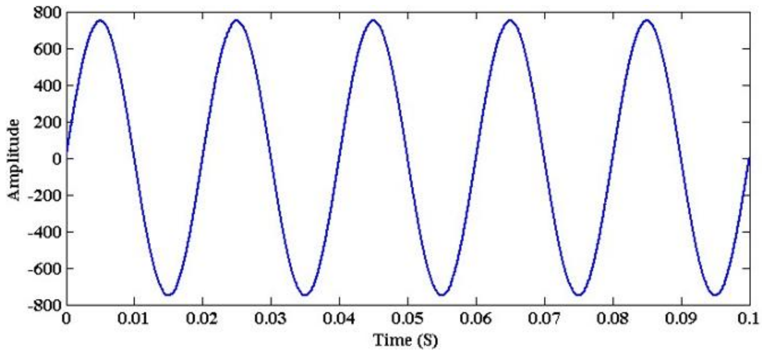

Figure 21. Secondary output current

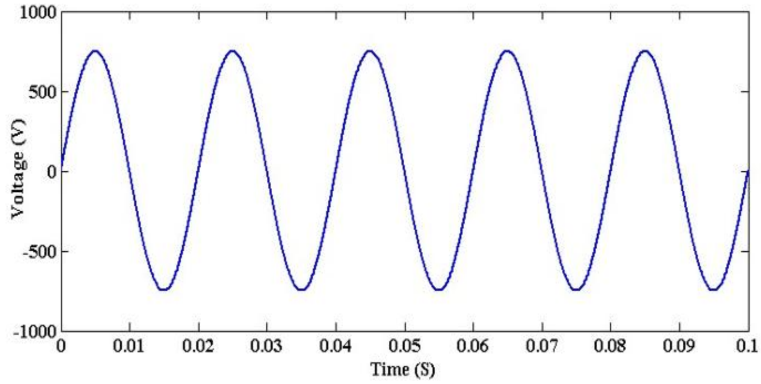

Figure 22. Secondary three level current

The article describes a novel three-level CLLC resonant converter for off-board EV chargers that achieves efficient bidirectional power flow and a wide voltage range (200 V - 700 V). Simulation results confirm its ability to maintain voltage stability while minimizing switching losses. The balanced flying capacitor voltage regulation reduces voltage stress on semiconductor switches, enhancing reliability over conventional two-level converters. The integration of two three-level full bridges ensures seamless V2G and G2V operations, contributing to improved grid stability and renewable energy integration. Furthermore, the use of FHA modelling optimizes resonant frequency, resulting in great efficiency via zero-voltage zero-current switching. However, the system's complexity demands precise control, with PID outperforming PI in dynamic response and voltage regulation. Future research should focus on hardware validation, AI-driven control techniques, grid interaction studies, and scalability for high-power applications. These advancements will further enhance EV charging infrastructure, supporting sustainable energy transitions.

From Table 4, it can observe that the PI control: suitable for steady-state operations and simpler systems, and the PID Control: more effective for dynamic systems requiring precise and quick responses. This article introduces a novel three-level CLLC resonant converter developed for off-board EV chargers, with wide voltage adaptability (200 V to 700 V) and bidirectional power flow for G2V and V2G operations. The converter combines two three-level complete bridges with resonant components to ensure efficient and reliable power transfer. The research uses FHA modelling to optimise the converter's resonant frequency. It supports multiple operational modes with balanced flying capacitor voltages, ensuring high efficiency and minimal losses. A comparison of PI and PID control methods highlights the system's ability to maintain stable voltage and handle dynamic load conditions effectively. Through detailed simulations, the article validates the converter's design, offering a practical solution to enhance grid stability, integrate non-conventional energy, and advance EV charging infrastructure.

Table 4. Comparative table summarizing the key aspects of the article

Parameter	PI control	PID control	Remarks
Supply voltage stability	Stable at 750 V	Stable at 750 V	Both control methods successfully maintain the required voltage.
Dynamic response	Slower adjustment to changes	Faster and more precise response	PID control outperforms PI in dynamic scenarios.
Gate pulses	Synchronized but slower switching	Synchronized with faster switching	PID ensures improved switching speeds, enhancing efficiency.
Primary potential	Consistently 750 V	Consistently 750 V	Both methods ensure voltage stability.
Secondary potential	Consistently 750 V	Consistently 750 V	Secondary bridge also shows no deviation in voltage across both methods.
Primary current	Stable with slight fluctuations	Stable with minimal fluctuations	PID control reduces current ripples better than PI.
Secondary current	Balanced and consistent	Balanced and consistent	Current regulations are effective in both control schemes.
Waveform accuracy	Moderate accuracy	High accuracy	PID control provides better tracking of the reference waveform.
Efficiency	High efficiency with slight energy losses	Improved efficiency with reduced losses	PID control minimizes losses more effectively.
System complexity	Simpler implementation	Slightly more complex implementation	PID control requires more computational resources due to derivative calculation.
Control advantages	Easier to implement, reliable for steady-state systems	Superior for systems with rapid transients	A suitable method depends on application requirements.

4. CONCLUSION

The three-level CLLC resonant converter represents a significant leap in the design of off-board electric vehicle chargers for DC microgrid systems. The converter can accommodate a broad spectrum of output voltage needs with exceptional flexibility because to its novel twin full-bridge construction, which in turn enables it to offer four distinct modes of operation. A robust framework for understanding the behavior of the converter is provided by the utilization of an FHA-based equivalent circuit for frequency analysis. Additionally, the mode selection technique based on minimizing root mean square (RMS) current improves the converter's working efficiency. furthermore, the reliability of the system is enhanced by the fact that the voltages of the flying capacitors are efficiently balanced together by selective switching. The proposed converter has been demonstrated to work in real-world conditions, and this study opens the door to further developments in the area, which should make DC microgrids more stable and trustworthy.

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Chandra Babu Guttikonda	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Pinni Srinivasa Varma		✓				✓		✓	✓	✓	✓	✓		
Malligunta Kiran Kumar	✓		✓	✓			✓			✓	✓		✓	
Kambhampati Venkata Govardhan Rao		✓				✓		✓	✓	✓	✓	✓		
Rakesh Teerdala					✓		✓			✓		✓		
Santoshi Kanagala	✓		✓	✓			✓			✓	✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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