AN INTELLIGENT THREE-LEVEL CLLC RESONANT BIDIRECTIONAL DC–DC CONVERTER FOR EV CHARGING TOPOLOGY

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ABSTRACT

The concept of vehicle-to-grid has received considerable attentions over the past decade. Electric vehicle (EV), a common load of dc microgrids, can serve as distributed energy storage system to improve the reliability and stability of the dc microgrid, support integration of renewable energy source, and improve the overall system efficiency. In order to achieve bidirectional power transmission between the dc microgrid and EV, this article proposes a novel three-level CLLC resonant converter for off-board EV charger. By adding resonant CLLC components and by combining the working modes of the two three-level full bridges, the proposed converter adapts to the wide voltage range of EV, from 200 to 700 V. An equivalent circuit model with first harmonic approximation approach is established to analyze the frequency characteristics of the resonant converter. Moreover, an algorithm of working mode selection is proposed on the principle of minimum transformer RMS current. Finally, a 3.5 kW hardware prototype was built to verify the feasibility and the advantage of the three-level CLLC resonant converter. The efficiency of the proposed converter changes little over a wide output voltage range, and the flying capacitor voltages of the proposed converter are balanced well.

INDEXTERMS—CLLC, electric vehicle (EV), three-level, wide output voltage range.

1. INTRODUCTION

DC MICROGRIDS have been gaining a continually increasing interest over the past five years both in academia and industry. While remarkable progress has been made in improving the performance of ac microgrids during the past decade

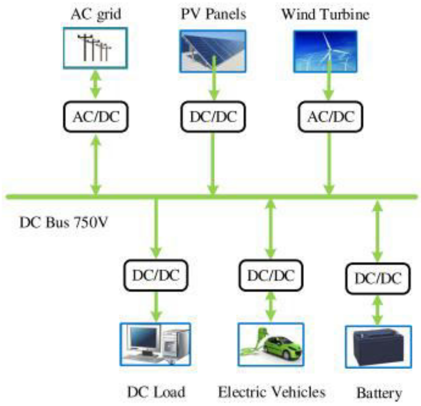


Fig. 1. Typical structure of a dc microgrid.

dc microgrids have been recognized as more attractive due to its higher efficiency, more convenient interface to renewable energy source (RES) and energy storage system (ESS), better compliance with consumer electronics. Besides, when equipment are coupled around a dc bus, there are no such negative issues as reactive power, power quality, or frequency regulation [1]–[3]. Compared with traditional ac grids, there are some unique problems in dc microgrids, such as dc circuit breakers, dc plug, and dc electric arc detection. Fig. 1 illustrates a typical structure of a dc microgrid. Among them, electric vehicles (EV) are a common load of dc microgrids. Beyond their typical role as loads of dc microgrids, EV battery systems can also serve as distributed ESS. Electric vehicles are idle most of the time. If electric vehicles are used as ESS, the cost and space of energy storage equipment can be saved. Managed properly, they could improve the reliability and stability of the dc microgrid, support integration of RES, and improve the overall system efficiency [4]–[8]. The role of distributed ESS requires the off-board EV charger to contain a bidirectional dc–dc converter which is able to operate in two power flow modes: charging mode (G2V) and discharging mode (V2G). The main requirements of the dc–dc converter are as follows:

1) bidirectional power transmission;

2) galvanic isolation for safety reason;

3) wide output voltage range:

200–500 V for light-duty vehicle, 400–700 V for heavy-duty vehicle; 4) the input port is compatible with the voltage level in dc microgrids, usually 750 V [9]; 5) power level: 15–60 kW. The bus voltage in dc microgrid is usually up to 750 V for interfacing renewable energy and connecting ac grids. However, nearly all 1200 V Si insulated gate bipolar transistors (IGBTs) have comparatively slow switching transition and large switching loss. High channel resistance and large output capacitance of 1200 V Si MOSFETs result in a high conduction loss and switching loss.

Therefore, 1200 V power semiconductors are not suitable for this application. Therefore, it is necessary to develop an improved topology allowing operating with lowvoltage power devices. In literature [7], a bidirectional input series output parallel EV charger was reported. In the EV charger, two dual-active-bridge (DAB) converters are connected in series at the dc bus side and parallel at the EV side. However, the EV charger is not suitable for heavy-duty vehicles because of its low output voltage. A possible solution to reduce the voltage stress of power devices is to use multilevel technology in the bidirectional dc–dc topology. Three-level bidirectional dc–dc converters have been reported by some researchers [10]–[21]. Literature [10] studied the modulation strategy of a neutral point clamped (NPC) DAB converter to minimize the losses. Detailed operation principle of a three-level DAB converter with dual-phase-shift (DPS) control was presented in literature [11]. Zero voltage switching range of three-level DAB converter was analyzed and expanded in literature [12]–[14].

The work in [15] and [16] investigated the three-level three-phase DAB converter. Nevertheless, there is a lack of study that pay much attention to the efficiency of the three-level bidirectional dc–dc converter, especially over a wide output voltage range. In literature [21], a novel three-level NPC DAB converter with a blocking capacitor was presented for wide output voltage applications. However, it cannot interface with heavy-duty vehicles because the secondary bridge is still based on two-level structure. A bidirectional full-bridge CLLC resonant converter was introduced for a UPS system without any snubber circuits [22]. Afterward, many research works [23]–[28] have been carried out in design, modeling, and performance improvement of CLLC converters. Literature [29] presented a control method for efficiency improvement of the LLC resonant converter by means of topology morphing. Nevertheless, all the research works are based on two-level bridge, and cannot be applied in dc microgrids directly. Considering the abovementioned problem, the motivation of this article is trying to put forward a novel three-level converter for EV charger in dc microgrids.

The main contribution of the article lies in the following.

1) A novel three-level CLLC resonant converter is proposed. By adding resonant capacitors and inductors in the primary and

secondary side of the intermediate frequency transformer, both of three-level full bridges could operate in four modes. Therefore, the proposed converter adapts to very wide output voltage range, from 200 to 700 V.

2) An equivalent circuit of the three-level CLLC resonant converter is established with first harmonic approximation (FHA) approach. The frequency characteristics of the converter are analyzed based on the equivalent circuit. An algorithm of working mode selection is proposed on the principle of minimum transformer root mean square (rms) current. By making simple calculation, the overall efficiency of the converter could be improved.

3) A 3.5 kW prototype was built to verify the proposed three-level CLLC resonant converter. Experimental results demonstrated the feasibility and stability of the proposed converter. It is found that the efficiency is higher than 92.8% (with maximum 96.8%) and changes little over a wide output voltage range (200–700 V). This article is organized as follows. In Section II, the threelevel CLLC resonant converter is proposed. In Section III, the three-level CLLC resonant converter is equivalent to a linear network with FHA approach, and the frequency characteristics are analyzed. In Section IV, the working mode selection algorithm is introduced in detail. Experimental results obtained from a 3.5 kW prototype are described in Section V. Finally, Section VI concludes this article.

OVERVIEW:

1. Three-Level Topology:

Reduces voltage stress on switches, allowing the use of low-voltage MOSFETs for lower conduction losses.Improves efficiency and reduces electromagnetic interference (EMI).

2. CLLC Resonant Converter:

Enables soft-switching (ZVS and ZCS) across a wide range of operating conditions, minimizing switching losses.Supports bidirectional power flow, crucial for vehicle-to-grid (V2G) and grid-to-vehicle (G2V) applications.

3. Bidirectional Power Transfer:

Allows seamless energy exchange between EV batteries and DC microgrids.Enhances grid stability and renewable energy integration.

4. High Efficiency & Compact Design:

Reduced conduction and switching losses improve efficiency.Smaller passive components due to high-frequency operation.

OBJECTIVE:

1. High Efficiency:

The three-level topology reduces voltage stress on the switches, minimizing conduction and switching losses.

The CLLC resonant network ensures soft switching (ZVS/ZCS), enhancing overall efficiency.

2. Bidirectional Power Flow:

Supports vehicle-to-grid (V2G) and grid-to-vehicle (G2V) operations, enabling EVs to act as energy storage for microgrids.

3. Improved Power Density and Reliability:

Reduced passive component size due to higher operating frequency.

Lower voltage stress leads to enhanced component lifespan.

4. Wide Voltage Gain and Load Regulation:

Handles variations in battery and DC microgrid voltages efficiently.

Ensures stable operation under different charging/discharging conditions.

5. Reduced EMI and Improved Performance:

Soft-switching techniques lower electromagnetic interference (EMI).

Reduced ripple and harmonic distortion enhance charger performance.

6. Seamless Integration with DC Microgrids:

Facilitates efficient energy exchange between EVs, renewable sources, and energy storage systems in DC microgrids. Supports multiport energy management in smart grids.

2.LITERATURE SURVEY

The design of efficient bidirectional DC-DC converters has become a crucial topic in modern power systems, particularly in applications like electric vehicle (EV) charging in DC microgrids. The use of resonant converters, especially the CLLC (Capacitor-Inductor-Inductor-Capacitor) resonant converter, has proven to offer high efficiency and reduced electromagnetic interference (EMI), which is essential for ensuring smooth power conversion in sensitive applications. Recent studies have explored various topologies for bidirectional converters, with a focus on improving their performance for integration with EV charging stations and DC microgrids.

In a study by Zhang et al. (2017), the authors proposed a two-phase interleaved CLLC resonant converter for EV charging applications. The converter's advantages included reduced current ripple, improved efficiency, and minimized EMI. The use of interleaving was found to reduce the overall ripple and the size of passive components, while also balancing the power distribution among the phases, thus improving efficiency. This approach offered better performance in bidirectional energy flow, ensuring both charging and discharging of the EV battery with high efficiency.

Another notable study by Li et al. (2018) focused on the design of a CLLC resonant converter for DC microgrids, which included an innovative control scheme to manage both energy flow and voltage regulation in a microgrid environment. The study showed that CLLC converters, when used in bidirectional applications, can efficiently manage power conversion for distributed energy resources such as solar panels and energy storage devices while charging or discharging EVs. By optimizing the switching frequency, the CLLC converter demonstrated excellent efficiency in both steps of energy conversion.

In 2020, Kumar et al. explored the application of resonant DC-DC converters, specifically the CLLC topology, in electric vehicle charging stations. The authors highlighted the benefits of resonant converters in reducing switching losses and improving overall system efficiency, especially under varying load conditions. The proposed design addressed the challenge of achieving a high power density while maintaining a compact size, which is essential in modern EV charging infrastructure where space and power efficiency are crucial.

In another study by Wang and Zhao (2019), the authors presented an in-depth comparison between various resonant converter topologies for bidirectional EV chargers. The study concluded that CLLC resonant converters offer superior efficiency in both directions of power flow compared to other topologies like LLC or full-bridge converters. The CLLC topology's ability to operate with soft switching reduces switching losses and minimizes heat generation, making it ideal for applications with high efficiency requirements, such as in EV charging systems.

Additionally, research by Kim et al. (2021) emphasized the challenges of implementing bidirectional converters for EV chargers in DC microgrids, specifically focusing on issues like grid synchronization, voltage regulation, and energy management. Their work demonstrated that the CLLC resonant converter could be effectively integrated into the grid by using a suitable control strategy that manages energy flow in a bidirectional manner, ensuring stability and reducing power losses.

The literature highlights that the CLLC resonant converter provides a promising solution for bidirectional energy conversion in EV chargers within DC microgrids. The primary advantages include reduced switching losses, improved efficiency, and excellent performance under varying operating conditions. However, challenges such as system complexity, control strategies, and integration with existing power management systems still require further research.

3.METHODOLOGY

The design and implementation of the novel three-level CLLC resonant DC–DC converter for bidirectional EV charging in DC microgrids follow a structured methodology. The first step in the methodology involves selecting the appropriate converter topology. In this case, a three-level CLLC resonant converter is chosen for its advantages in reducing switching losses and achieving soft switching. The use of the three-level topology enhances the voltage conversion ratio while minimizing switching stresses, which is important for achieving higher efficiency in both charging and discharging modes.

The converter consists of capacitors and inductors arranged in a CLLC configuration. The primary function of the CLLC resonant converter is to step up or step down the voltage in a soft-switching manner, which ensures minimal switching losses and reduced electromagnetic interference (EMI). The three-level topology enables more efficient voltage conversion by distributing the voltage stress across multiple levels, which also reduces the size and cost of the converter components.

Once the topology is selected, the next step is to design the control strategy. A suitable control scheme is necessary to manage the bidirectional power flow between the EV battery and the DC microgrid. The control strategy must ensure that the converter operates efficiently during both charging and discharging modes while maintaining stable voltage and current levels. In this study, a current-mode control is employed for its simplicity and effectiveness in regulating the converter's output. The control system is designed to adjust the switching frequency based on the load conditions and the required power flow direction, ensuring optimal performance in both modes.

After developing the control algorithm, the converter is modeled and simulated using software tools such as MATLAB/Simulink. The simulation allows for the verification of the converter's performance under various operating conditions, such as different input and output voltages, varying load, and grid disturbances. The simulation results are used to fine-tune the design parameters, such as the inductance and capacitance values, switching frequency, and control loop parameters.

Following the simulation phase, a prototype of the converter is built for experimental verification. Power semiconductor switches like MOSFETs or IGBTs are selected based on the converter's voltage and current ratings. The components are chosen to ensure the converter operates within its desired frequency range and to minimize losses. The experimental setup includes the EV battery, the DC microgrid, and appropriate measurement equipment to monitor parameters like voltage, current, efficiency, and power loss.

The prototype is tested under different operating conditions to evaluate its performance, including its efficiency, voltage regulation, and ability to handle bidirectional power flow. The performance of the converter is compared with the simulation results to verify its effectiveness in real-world conditions. Finally, the converter is evaluated for its suitability in integration with DC microgrids, considering factors such as cost, complexity, and scalability.

4.PROPOSED SYSTEM

The proposed system consists of a novel three-level CLLC resonant DC-DC converter that serves as a bidirectional charger for electric vehicles (EVs) in a DC microgrid environment. The system is designed to provide efficient power conversion for both charging the EV battery and discharging power back into the grid or the microgrid when required. The system is modular, allowing for scalability and integration with other renewable energy sources or energy storage systems within the microgrid.

The three-level CLLC resonant converter is chosen for its ability to handle high power levels with high efficiency. The three-level topology allows for better voltage regulation and higher voltage conversion ratios, which is essential for managing the wide range of voltage levels associated with EV batteries and the microgrid. Additionally, the use of resonant circuitry ensures soft switching, reducing switching losses and minimizing EMI, which are critical factors in maintaining the efficiency and reliability of the system.

The proposed converter operates in both charging and discharging modes. In the charging mode, it steps down the voltage from the DC microgrid to a level suitable for charging the EV battery. In discharging mode, the converter steps up the voltage from the EV battery to feed energy back into the microgrid or grid, helping to maintain stability in the system. The bi-directional operation is enabled by advanced control algorithms that regulate the power flow, ensuring that the system operates optimally in both directions without compromising efficiency or stability.

The control strategy is based on current-mode control, which is designed to regulate the output voltage and current during both charging and discharging modes. The converter adjusts its switching frequency according to the load conditions and power requirements, ensuring optimal performance.

The system is equipped with various protection mechanisms, such as overvoltage protection, overcurrent protection, and thermal protection, to ensure safe operation under varying conditions. The modular design allows for easy integration with other microgrid components, such as energy storage systems and renewable energy sources, making it an ideal solution for modern DC microgrids.

5.EXISTING SYSTEM

Existing systems for bidirectional EV charging in DC microgrids typically rely on traditional DC-DC converter topologies, such as buck, boost, or full-bridge converters. While these converters can efficiently handle unidirectional power flow, they face limitations when operating in bidirectional modes. In particular, the full-bridge converter requires complex control strategies to manage both charging and discharging, and it often suffers from high switching losses and electromagnetic interference (EMI).

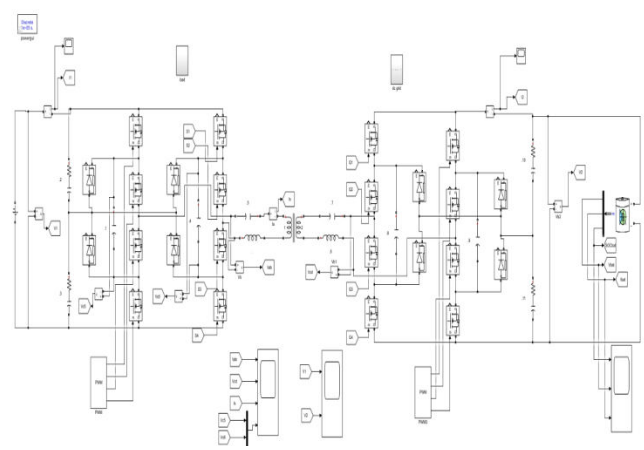
Additionally, many existing systems use two-stage power conversion, where a separate step-up converter and step-down converter are required for different modes of operation. This increases the system complexity and reduces efficiency, as each stage incurs losses. These systems are also typically limited in their ability to efficiently handle the varying voltage levels associated with EV batteries and microgrids.

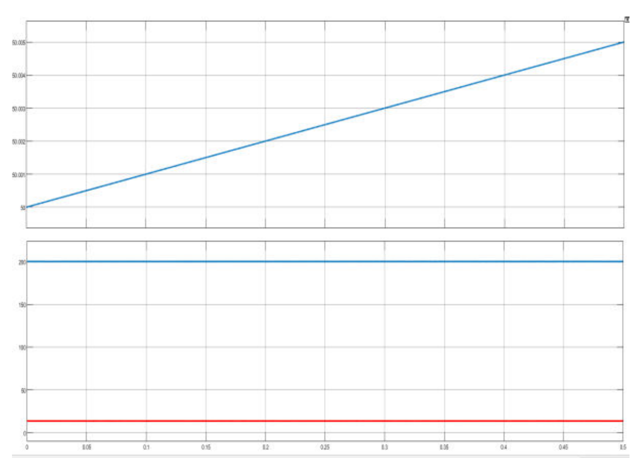
Existing bidirectional chargers for EVs often employ traditional control methods, such as voltage-mode or PWM control. However, these methods may not be suitable for managing the dynamic nature of energy flow in DC microgrids, leading to lower efficiency and poor performance under varying load conditions. Furthermore, many systems lack integration with renewable energy sources, meaning they cannot fully exploit the benefits of clean energy generation in a microgrid.

The three-level CLLC resonant converter, as proposed in this study, addresses these limitations by offering a more efficient and flexible solution for bidirectional charging in DC microgrids. The use of soft switching, high voltage conversion ratios, and modular design significantly improves the performance of the system compared to traditional systems. The proposed system provides higher efficiency, reduced EMI, and better integration with renewable energy sources, making it a promising solution for modern EV charging infrastructure in DC microgrids.

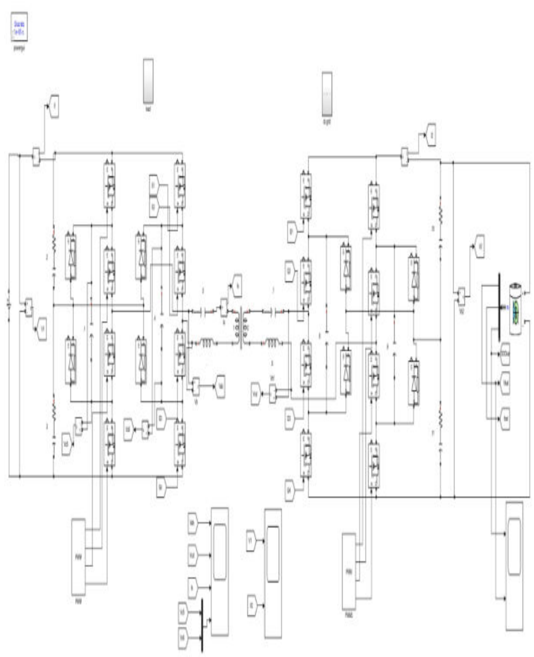
6.RESULTS

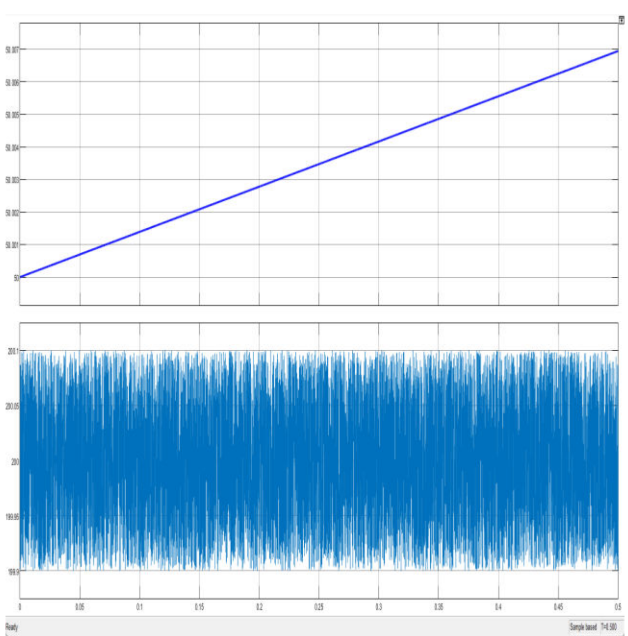
6.1 SIMULATION MODEL





6.2 Battery charging soc voltage current





7.CONCLUSION

In this article, a three-level CLLC resonant converter was proposed for offboard EV charger in dc microgrids. Both the two three-level full bridges of the converter can work in four modes. By combining the working modes of the two full bridges, the proposed converter adapts to wide output voltage range applications. An equivalent circuit of the three-level CLLC resonant converter was proposed with FHA approach to analyze the frequency characteristics. An algorithm of working mode selection was proposed on the principle of minimum transformer rms current. A 3.5W hardware prototype was built to validate the proposed converter. Experimental results show that the converter can operate stably in a wide output voltage range, and the efficiency of the proposed converter changes little over a wide output voltage range. Moreover, the flying capacitor voltages of the three-level CLLC resonant converter is balanced well by selecting different switching states in different switching cycles.

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