

A Review of LLC Resonant Converters for Electric Vehicle Battery Charging Applications

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Abstract

In this paper, a review of LLC resonant converter topologies for EV/HEV battery charging applications is presented. The increasing demand for efficient and fast charging requires converters that can handle wide input voltage ranges with high efficiency. The dual-bridge LLC resonant converter with fixed-frequency PWM control is highlighted for its improved performance and soft-switching capability (ZVS/ZCS), which reduces losses. The study also discusses the integration of renewable energy sources, such as photovoltaic systems, with grid supply for hybrid charging. Overall, the reviewed methods provide better efficiency, power density, and reliability, making them suitable for modern EV charging systems.

Keywords: Dual Bridge (DB) LLC Resonant converter, fixed frequency, LLC, PI controller voltage range, PWM.

1. Introduction

The rapid growth of electric vehicles (EVs) and hybrid electric vehicles (HEVs) has created a strong demand for efficient, fast, and reliable battery charging systems. Modern EV charging applications require power converters that can operate over a wide input voltage range while maintaining high efficiency and power density. Conventional DC–DC converters often face limitations such as high switching losses, reduced efficiency at variable loads, and difficulty in handling wide voltage variations [1].

Among various power electronic topologies, the LLC resonant converter has gained significant attention due to its ability to achieve soft-switching operations, such as zero-voltage switching (ZVS) and zero-current switching (ZCS). These features help in reducing switching losses, electromagnetic interference, and improving overall system efficiency [2]. However, traditional LLC converters typically rely on variable frequency control, which complicates the design of magnetic components and limits their performance in wide input applications [3]. To overcome these challenges, advanced topologies such as the dual-bridge (DB) LLC resonant converter have been

proposed. This converter combines the advantages of half-bridge and full-bridge configurations and utilizes fixed-frequency pulse-width modulation (PWM) control to achieve a wide voltage gain range with simplified design and improved efficiency [4]. Moreover, it ensures better performance under varying load conditions and reduces the complexity associated with frequency variation techniques. In addition, the integration of renewable energy sources such as photovoltaic (PV) systems with grid supply has become an important aspect of modern EV charging infrastructure. Hybrid input configurations allow continuous and reliable charging under different environmental conditions, thereby enhancing system flexibility and sustainability [5]. This review paper focuses on the analysis of various LLC resonant converter topologies, control strategies, and their applications in EV battery charging systems. It also highlights recent advancements, key challenges, and future research directions in the development of high-performance charging solutions.

2. Literature Review

M. M. Jovanović and B. T. Irving et.al. “This paper presented a control method for efficiency improvement of the LLC resonant converter operating with a wide input-voltage and/or output-voltage range by means of topology morphing, i.e., changing of power converter's topology to that which is the most optimal for given input-voltage and/or output-voltage conditions. The proposed on-the-fly topology-morphing control maintains a tight regulation of the output during the topology transitions so that topology transitions are made without noticeable output-voltage transients” [1].

J. Deng, C. C. Mi, R. Ma, and S. Liet.al. “The efficiency-oriented design considerations are discussed based on the operation-mode analysis of the LLC converter considering the characteristics of charging profiles. The mode boundaries and distribution are obtained from the precise time-domain model. The operation modes featuring both-side soft-switching capability are identified to design the operating trace of the charging process. Then the design

constraints for achieving soft switching with the load varying from zero up to the maximum are discussed” [2].

D. Moon, J. Park, and S. Choi et.al. “This paper proposes a new interleaved current-fed resonant converter with significantly reduced high current side output filter. The proposed interleaved converter has theoretically zero output filter capacitance, low-input current ripple, ZCS turn-on and turn-off for all switches and diodes, and zero di/dt at turn-off of diodes when operated at load independent points. A two-stage power conversion technique is applied to the interleaved converter for high efficiency under wide voltage range operation”[3].

F. Musavi, M. Craciun, D. S. Gautam, and W. Eberle et.al. “In this paper, a control strategy is presented for a high-performance capacitively loaded loop (LLC) multi resonant dc-dc converter in a two-stage smart charger for neighborhood electric vehicle (NEV) applications. It addresses several aspects and limitations of LLC resonant dc-dc converters in battery charging applications, such as very wide output voltage range while keeping the efficiency maximized, implementation of the current mode control at the secondary side, and optimization of burst mode operation for current regulation at very low output voltage” [4].

C. W. Tsang, M. P. Foster, D. A. Stone, and D. T. Gladwin et.al. “This paper presents a design methodology for LLC resonant converters with capacitor-diode clamp for current limiting in overload conditions. A new fundamental harmonic approximation-based equivalent circuit model is obtained through the application of describing function techniques, by examining the fundamental behaviour of the capacitor-diode clamp. An iterative procedure to determine the conduction point of the diode clamp is also given. The behaviour of this type of converter is analysed and guidelines for designing the current limiting characteristics are discussed. The characterization of a 90 W converter design using the proposed methodology is presented”[5].

B. Yang, F. C. Lee, A. J. Zhang, and G. Huang et.al. “A new LLC resonant converter is proposed for front end DC/DC conversion in a distributed power system. Three advantages are achieved with this resonant converter. First, ZVS turn on and low turn off current of MOSFETs are achieved. The switching loss is reduced so we can operate the converter at higher switching frequency. The second advantage is that with this topology, we can optimize the converter at high input voltage. Finally, with this topology, we can eliminate the secondary filter inductor, so the voltage stress on the secondary rectifier will be limited to two times the output voltage, better rectifier diodes can be used and secondary conduction loss can be reduced. The converter utilizes leakage and magnetizing inductance of a transformer. With magnetic integration concept, all the

magnetic components can be built in one magnetic core [6]”.

H. Wang, S. Dusmez, and A. Khaligh et.al. “In this paper, a variable dc link technique is proposed to track the maximum efficiency point of the LLC converter for plug-in electric vehicle battery-charging applications over a wide battery state-of-charge (SOC) range. With the proposed variable dc link control approach, the dc link voltage follows the battery pack voltage. The operating point of the LLC converter is always constrained to the proximity of the primary resonant frequency so that the circulating current in the magnetizing inductor and the turning-off currents of MOSFETs are minimized” [7].

Z. Hu, Y. Qiu, Y. F. Liu, and P. C. Sen et.al. “LLC converters face challenges in high-current applications, where the high conduction loss limits the maximum load capacity and reduces efficiency. Interleaving technique can be used to solve this problem, but the component tolerances of the resonant tanks will cause severe load sharing problem. The SCC-LLC converter was proposed to solve the load sharing problem. However, due to its constant switching frequency operation, it has some limitations over complete line and load variation compared to conventional LLC converters. In this paper, a new control strategy is proposed for the SCC-LLC converter, which enables variable switching frequency operation; thus, it provides uncompromised performance while achieving interleaved operation”[8].

K. H. Yi and G. W. Moon et.al. “An LLC series-resonant converter has many unique characteristics and improvements over pulse width-modulation topologies. However, many output capacitors are needed in parallel to satisfy an output voltage ripple and a rated ripple current of the capacitors. This paper deals with a novel two-phase interleaved LLC resonant converter using a phase of the resonant capacitor. The proposed converter satisfies low output-voltage ripple requirement and meets the rated ripple of output capacitor's current with few output capacitors”[9].

W. Feng, F. C. Lee, and P. Mattavelli et.al. “In this paper, a simplified optimal trajectory control (SOTC) for the LLC resonant converter is proposed. During the steady state, a linear compensator such as proportional-integral or proportional-integral-derivative (PID) is used, controlling the switching frequency f_s to eliminate the steady-state error. However, during load transients, the SOTC method takes over, immediately changing the pulse widths of the gate-driving signals”[10].

3. Buck–Boost Converter

A non-isolated (transformer less) topology of the buck–boost converter is shown in Fig. 1. The converter consists

of dc input voltage source V_s , controlled switch S , inductor L , diode D , filter capacitor C , and load resistance R . With the switch on, the inductor current increases while the diode is maintained off.

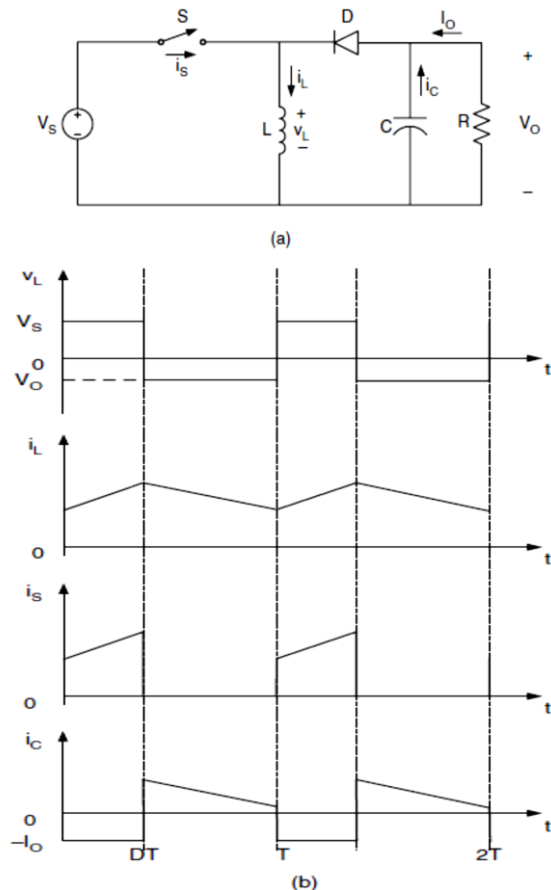


Figure 1 Buck-boost converter (a) circuit diagram (b) waveforms.

When the switch is turned off, the diode provides a path for the inductor current. Note the polarity of the diode which results in its current being drawn from the output. Applications of Buck boost converter

- It is used in the self-regulating power supplies.
- It has consumer electronics.
- It is used in the Battery power systems.
- Adaptive control applications.
- Power amplifier applications.

Advantages of Buck Boost Converter

- It gives higher output voltage.
- Low operating duct cycle.
- Low voltage on MOSFETs

4. Proposed Methodology

This thesis proposed fixed frequency a fixed frequency DBLLC converter with pi controller are used for hybrid electric vehicles and it is used for wide input voltage range application. The proposed system can be seen as combination of AC grid, DBR HB LLC converter FBLLC converter battery DC motor drive, PI controller and PWM Generator. The output voltage is regulated by controlling the percentage of operating time of FB and HB during a switching circle. This converter employs the fixed frequency PWM control, and the switching frequency equals to the resonant frequency, which facilitates the design of magnetic elements Unlike traditional PFM-controlled LLC resonant converters, the voltage gain range is independent of the quality factor Q . Moreover, the magnetizing inductor has little influence on the voltage gain, which means that the parameter design process can be simplified, and the magnetizing inductor can be designed as large as possible to reduce the conduction loss. In addition, all main switches and rectifier diodes are softly switched over the full load range, which significantly decreases the switching loss and the reverse recovery loss

The proposed circuit topology is updated with input as PVA source which is switched to utility grid during low voltage level. The low voltage level in PVA is generated because of low solar irradiation. Two switches are connected to grid and PVA individually which operate complimentarily. The charging of battery is done through either grid or PVA depending on the switching of the switches. The updated circuit is shown in fig. 4.1

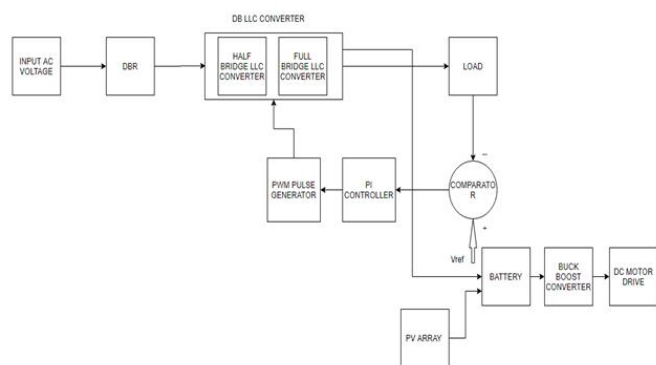


Fig. 4.1 proposed system of Single-phase AC input Dual LLC bridge resonant converter

4.1 DBLLC CONVERTER

Fig.4.1 shows the circuit diagram of the proposed converter. The divided capacitors C_{in1} , C_{in2} and output filter C_o are assumed to be large enough, and thus, they are regarded as three constant-voltage sources. $C1-C6$ are the junction capacitors of power switches.

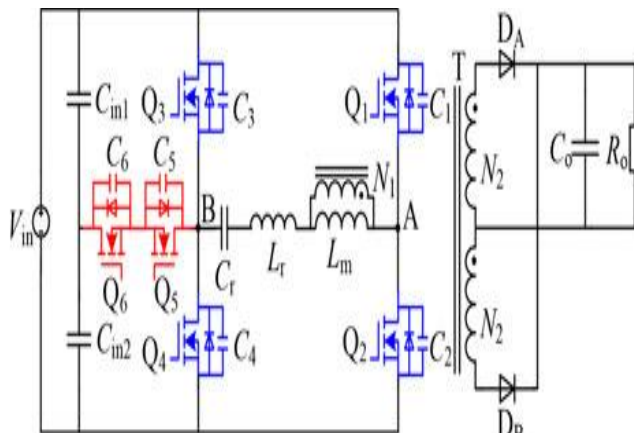


Fig. 4.1 DBLLC resonant converter

Advantages:

- The voltage gain range is independent of the quality factor.
- Over the full load range, zero-voltage switching (ZVS)
- and zero current switching (ZCS) can be achieved for primary switches and secondary rectifier diodes

Applications:

- PWM and phase-shift control strategies.
- Wide input applications.

5. Conclusion

This review paper presents a comprehensive study of LLC resonant converter topologies for EV and HEV battery charging applications. With the increasing demand for efficient and fast charging systems, conventional converters are found to be less suitable due to higher losses and limited capability to handle wide input voltage variations. In contrast, LLC resonant converters offer significant advantages such as soft-switching operation (ZVS/ZCS), high efficiency, and improved power density. Among the various topologies discussed, the dual-bridge (DB) LLC resonant converter with fixed-frequency PWM control demonstrates superior performance in terms of wide voltage gain range, reduced switching losses, and simplified control strategy. Additionally, the integration of renewable energy sources like photovoltaic (PV) systems with grid supply enhances the flexibility and reliability of EV charging infrastructure. Overall, the study concludes that advanced LLC-based converter designs are highly suitable for next-generation EV charging systems. However, further research is required to optimize control techniques, improve dynamic response, and reduce system complexity for practical large-scale implementation.

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