Three-Level Zero-Voltage Transition Interleaved Buck Converter with DC Transformer-based Isolation for EV Fast Charging Stations

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Abstract. This paper proposes a new design architecture in which a three-level zero-voltage transition interleaved buck converter (3L-ZVT-IBC) with DC transformer-based isolation is introduced for applications in EV fast charging stations. This 3L-ZVT-IBC accomplishes lossless switching thanks to ZVT ability of proposed idea, enabling a high efficiency. In addition, it also has a lower voltage stress in comparison to the conventional interleaved buck converter, still required duty-cycle lies in the vicinity of 50% for wide operating range of output voltage required for EV fast charging stations (200 V to 850 V). In addition, the proposed architecture guarantees that the multilevel input DC voltages are balanced without any specific balancing technique or extra components, while ensuring the operation with low output inductor ripple for all conditions. In order to validate the 3L-ZVT-IBC, PSIM simulations were carried out, demonstrating the feasibility of the proposed 3L-ZVT-IBC.

Keywords: EV Fast Charging Stations; Soft-Switching; Interleaved Buck Converter; LLC DC Transformer.

1 Introduction

The United Nations Environmental Program has emphasized that around 25% of worldwide manmade carbon dioxide (CO_2) emissions can be attributed to the transportation industry, with automobiles being the main contributors [1]. Several markets, such as the European Union [2], China [3], and the United States of America [4], have adopted policies with the goal of transitioning the transportation industry to electric power. The combined effect of more stringent laws and government subsidies has resulted in a substantial increase in the quantity of electric vehicles, with projections predicting a rise to 180 million by 2030 [5].

The EV market expects an increase in the number of charging stations and desires reduced charging times, with the goal of closing the gap with the time it takes to recharge combustion-engine vehicles. To accomplish the same energy in a shorter period, it is necessary to increase the charging power. However, simply increasing the

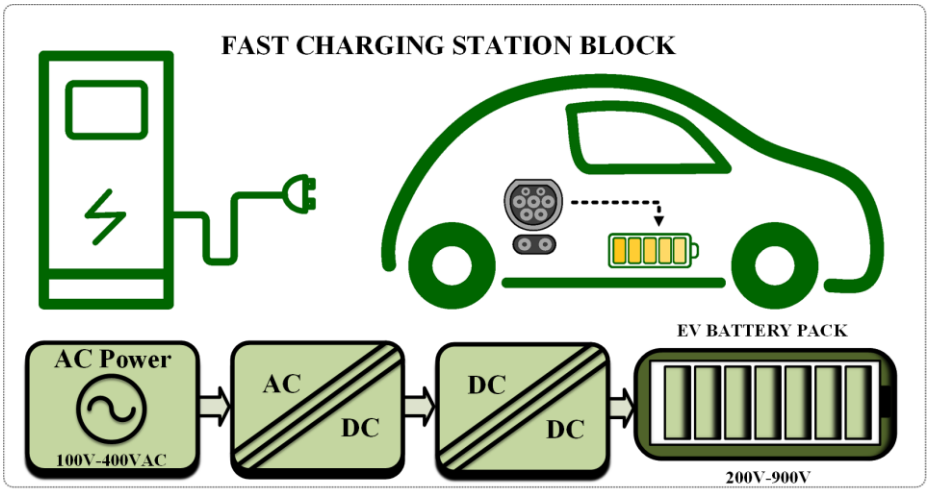


Fig. 1. Fast Charging station infrastructure.

current intensity poses challenges to system efficiency due to larger conduction losses during the charging process [6] and it can expedite the deterioration of both the charging cable and the battery [7].

In response to this, as an alternative, a growing number of EV manufacturers are implementing additional strategies by boosting the charging voltage. The electric automobiles now have battery packs with rated voltages of approximately 800 V [8], and in certain instances, even up to 900 V [9], deviating from the existing 400 V battery system. In addition, heavy-duty EVs like construction vehicles, buses and trucks are also utilizing batteries that fall within the 800 V range. The objective of this method is to satisfy the need for increased charging power, while maintaining system efficiency and preventing excessive wear on essential components. On the other hand, manufacturers of EV fast charging stations are required to produce DC fast chargers with the capability to supply an output voltage ranging from approximately 200 V to about 900 V. This flexibility is crucial for recharging EVs equipped with either of the two distinct battery systems in terms of voltage [10]- [12].

The effectiveness of single-stage EV fast charging systems is compromised by significant variations in operating conditions, the absence of soft-switching, and the need for complex control mechanisms. A recently popular alternative approach is the implementation of two-stage structures as shown in Fig. 1 [13]-[15]. These structures consist of an isolated DC-DC power stage, which is unregulated and provides galvanic isolation through a high-frequency (HF) transformer, along with at least one additional DC-DC power stage responsible for controlling the power flow. The literature frequently refers to a two-step approach [16], which usually includes a hard-switching converter in the second stage. Moreover, the DC transformer stage fails to maintain a turn ratio of unity and switching frequency below the resonant frequency, all these factors contributing to reduced overall efficiency.

This paper presents a two-stage isolated DC-DC converter topology for EV fast charging stations, which includes a wide voltage range, from 200 V to 850 V. As a key feature and aiming to guarantee high efficiency throughout the entire EV battery

charging profile, soft switching is achieved at all components the switches in both isolated and non-isolated stage. The proposed configuration, as depicted in Fig. 2, comprises of two stage power converters. The first is an isolated DC-DC converter, providing galvanic isolation for the overall EV fast charging system called DC transformer. The second is a non-isolated converter, responsible for recharging the EV batteries. The proposal in this paper employs a fixed-frequency LLC resonant converter as the DC transformer and a pulsed-width-modulated 3L-ZVT-IBC converter as the non-isolated DC-DC converter. The introduced DC-DC topology offers several advantages, which are described as:

- Easily get a wide voltage range, ranging from 200 V to 850 V, which is useful for EVs equipped with two distinct battery systems in terms of voltage.
- The LLC converter ensures ZVS features for all the primary switches and ZCS for the secondary rectifier throughout the whole EV charging process.
- Consistently achieving high efficiency throughout the whole EV battery charging profile.
- LLC provides the two-voltage output for the second stage 3L-ZVT-IBC converter.
- A 3L converter that naturally maintains a balanced DC voltage (i.e., there is no need for an extra balancing circuit or a closed-loop balancing control approach);
- Voltage stress at switches is half as compared to the conventional interleaved buck converter.
- 3L-ZVT-IBC has achieved a wide range of output voltage, from 200 V to 850 V and still the duty-cycle lies in vicinity of 0-50%.
- Single current controller is required to control the current in 3L-ZVT-IBC (conventional interleaved buck converter requires two current controllers).
- The ZVT condition is achieved in all the main switches in 3L-ZVT-IBC converter for all power conditions.
- Output inductors have lower ripples, and the ripple frequency is double the switching frequency, hence the filter size reduces.

2 EVs as Technological Innovation for Human-Centric Systems

EVs have emerged as a transformative technological innovation, revolutionizing traditional transportation systems, and aligning seamlessly with the principles of human-centric design. The transformation in the automobile sector goes beyond switching from internal combustion engines to electric motors; rather, it involves a comprehensive strategy that prioritizes human requirement and sustainability in technology advancement.

One of the key benefits of EVs is their significant environmental effect. The automobile sector shift to electric mobility reflects a dedication to decreasing carbon emissions amid the global challenges of climate change. EVs emit no tailpipe emissions, leading to enhanced air quality and a reduction in the total carbon footprint. This eco-friendly feature is in line with the increasing worldwide awareness of environmental sustainability and establishes EVs as a fundamental element in developing a more environmentally responsible transportation system.

In addition to its environmental advantages, EVs offer a user-centric approach by seamlessly incorporating edge cutting technologies to enhance the overall driving experience. Connectivity features, such as real-time updates, remote monitoring, and online software updates, not only provide convenience but also create a more personalized and efficient driving environment. Furthermore, the advancement of autonomous driving technology promises to redefine the interaction between humans and vehicles, enhancing safety and allowing individuals to use their precious time efficiently during their travels.

The increase of EVs does not involve the vehicles themselves; it extends to the advanced sophisticated charging infrastructure, further catering to human needs. The establishment of EV fast charging stations alleviates the concerns related to range anxiety issues, making EVs a feasible and practical option for both daily commuting and long-distance trips. Investments in smart charging stations and home charging solutions show a dedication to producing a smooth and user-friendly experience, eventually strengthening the human-focused aspect of this technical advancement.

The increasing popularity of EVs has encouraged innovation in several sectors, where the merging with renewable energy sources, smart grids, and energy storage technologies signifies a comprehensive strategy for developing sustainable and interconnected human-centered ecosystems. This transition has a wide-range consequences on urban planning, energy regulations, and technology breakthroughs in numerous areas.

Summarizing, EV exemplifies a paradigm shift in the automotive landscape, marking a departure from conventional practices towards a more sustainable, technologically advanced, and human-centric future. As EVs become increasingly integral to our daily lives, their impact extends beyond individual transportation to shape a more interconnected and environmentally conscious world.

3 Power Converter Description

Fig. 2 illustrates the proposed topology serving as the DC-DC converter designed for EV fast charging station application. The resonant converter is modified to produce two distinct DC voltage levels, Vo_{LLC1} and Vo_{LLC2}, from a single input DC voltage, V_{in}. The full-bridge inverter consists of switches S_1 to S_4, runs with a set duty-cycle of 50% and an 180^0 phase-shift between its two switching legs, and at a constant switching frequency F_{LLC}. The inverter is connected to two resonant blocks, referred to as upper and lower block, each including a series resonant capacitor (C_r), a high-frequency transformer (TXF) and full-bridge rectifier. The resonant blocks are linked in parallel at the input and series at the output by separated rectifiers, which leads to the total output DC voltage of the first stage being $Vo_{LLC} = Vo_{LLC1} + Vo_{LLC2}$. The TXF is divided into two parts, namely TXF1 and TXF2, to optimize the transformer size while still accommodating an output power exceeding 50 kW. To achieve this, two compact transformers are employed, arranged in parallel on the primary side and in series on the secondary side through two full-bridge diode rectifiers. The first stage designed a frequency control mechanism to guarantee that the converter functions at the resonance frequency. The purpose of this stage is to

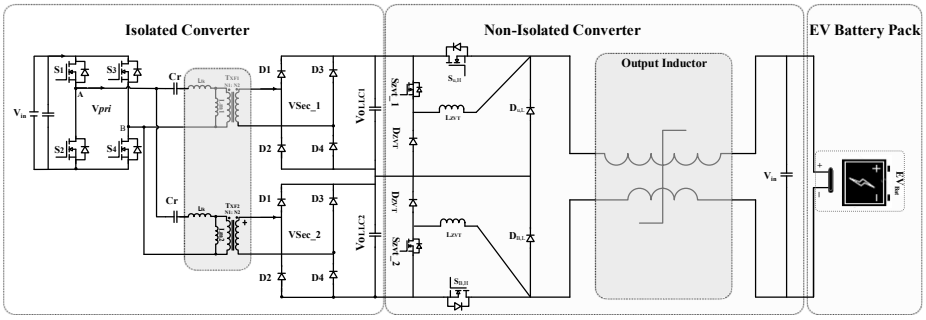


Fig. 2. Circuit diagram of proposed topology 3L-ZVT-IBC converter with DC transformer-based isolation for EV fast charging stations.

function as a voltage generation system, offering galvanic isolation and supplying two constant output dc voltages. These voltages are utilized as inputs for the second power stage, 3L-ZVT-IBC converter. The 3L-ZVT-IBC converter is regulated for operating with constant current/constant voltage (CC/CV) control loop, which is a frequently used method in EV battery charging applications [17].

The second power stage consists of a multilevel buck converter that incorporates an extra ZVT cell to provide soft switching. This ZVT cell facilitates the discharge of main switches output capacitance (Coss). During the switching transition, ZVT cell create path for discharge of drain to source voltage, allowing the voltage across the switching device to reach zero before it turns ON. By achieving the ZVT reduces the voltage stress on the switching device, resulting in lower switching losses, hence improve the efficiency. The 3L-ZVT-IBC converter has LC filter arrange in such a manner that the inductance is divided into two identical inductors positioned at the positive and negative terminals. The construction has two switching blocks: the upper block, which is equipped with high side switch $S_{u,H}$ and low side diode $D_{u,L}$; and the bottom block, which includes high side switches $S_{B,H}$ and low switches $S_{L,L}$. 3L-ZVT-IBC converter regulated the output voltage from 200 V to 850 V with maximum power of 50 kW and also have capability of achieving the soft-switching throughout the EV battery charging profile. The symmetry in the proposed converter is defined by the following:

- In the first stage, both resonant blocks have a rated power of P/2, where P denotes the overall rated power of the system.
- The DC-link voltages, Vo_{LLC1}, and Vo_{LLC2}, between both power stages are the same.
- In the second stage may use three different output voltage levels: the entire DC-link voltage (Vo_{LLC}), half of the DC-link voltage ($Vo_{LLC}/2$), and zero.

It is important to understand that the power in the second stage operates as a multi-level converter (i.e., depending on the EV battery voltage), hence it is essential to guarantee that its input DC-link voltages are balanced. To do this, additional balancing circuits and/or a specific closed-loop balancing control are often used. Nevertheless, in the proposed structure, the input voltage levels to the second stage, Vo_{LLC1} and Vo_{LLC2}, are produced by the first stage, which has a specific configuration that ensures an inherent equilibrium of dc voltage. Therefore, the power in the second stage is simply responsible for regulating the power supplied to the EV battery,

without the requirement to manage the voltage levels Vo_{LLC1} and Vo_{LLC2}. A single control variable, the duty-cycle is required.

Table 1. Parameter and specification of proposed converter.

Parameter	Symbol	values
Input Dc Voltage	V_{in}	850 V - 900 V
Stage I Output Voltage 1	V_{OLLC1}	900 V
Stage I Output Voltage 2	V_{OLLC2}	900 V
Output Voltage	V_O	200 V - 850 V
Rated Power	P_{LOAD}	50 kW
STAGE I		
Switching Frequency	F_{LLC}	103 kHz
TXR 1 Leakage Inductance	L_{lk_1}	5 µH
TXR 1 Magnetizing inductance	L_{lk_2}	400 µH
TXR 2 Leakage Inductance	L_{m1}	5 µH
TXR 2 Magnetizing inductance	L_{m2}	400 µH
Resonant Capacitor	C_{r1} /C_{r2}	480 nF
STAGE II		
Switching Frequency	$F_{3L\text{-}ZVT\text{-}IBC}$	100 kHz
Output Inductor Top	L_1	50 µH
Output Inductor Bottom	L_2	50 µH

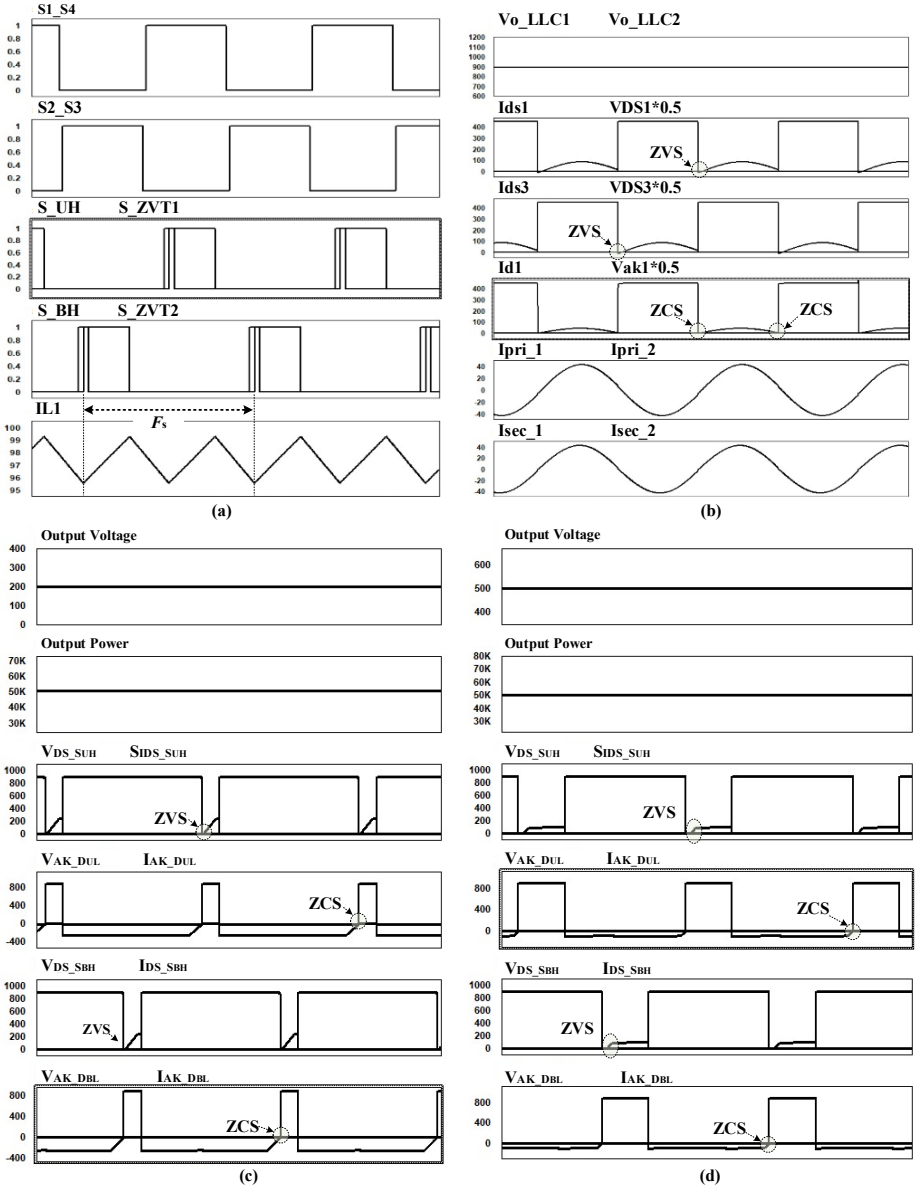
4 Simulation Validation and Discussion of Results

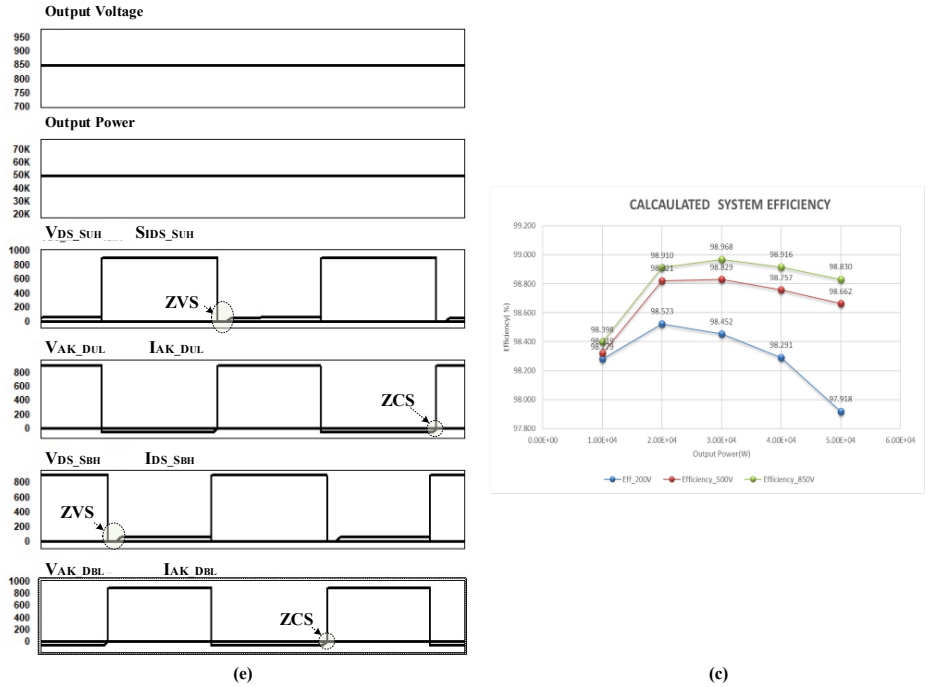
The simulation of the proposed system, utilizing the PSIM model of silicon carbide switch UF3SC120016K4S and silicon carbide schottky diode GD30MPS12J, this approach is essential for accurately predicting the behavior of the proposed system under various operational conditions.

Fig. 3(a) depicts the gate signal for Stage I and Stage II. Signals S_1-S_4 are for LLC Converter, and S_{UH} and S_{BH} are the gate signals of 3L-ZVT-IBC. The other small duty gate pulse signals, S_{ZVT1} and S_{ZVT2}, are gate signals for the ZVT leg switches. Fig. 3(a) also demonstrates that the inductor ripple frequency is twice the switching frequency. On the other hand, Fig. 3(b) demonstrates an equal output Vo_{LLC1} and Vo_{LLC2}, which has been generated by the Stage 1 LLC converter for 3L-ZVT-IBC. This also illustrates a significant feature of the proposed DC-DC conversion system that equivalence in output voltages highlights the system intrinsic ability to maintain voltage balance across its outputs without requiring additional circuits or complex control mechanisms. As depicted in Fig 3(b), the LLC Primary side switches achieve ZVS at the turn on time, and with very low turn off current. On the other hand, secondary side rectifier diodes are turned on and off with ZCS conditions. Achieving soft switching at both the primary and secondary sides throughout the load condition made this fixed frequency LLC converter an efficient DC transformer that provided galvanic isolation for the input output of a fast-charging station.

The simulation results in Fig. 3(d), (e), and (f) of the proposed DC-DC converter for fast EV charger demonstrate its capability to effectively manage a wide output

voltage range, from 200 V to 850 V. This range is particularly significant as it covers the requirements for both the standard 400 V charging systems and the newer, more advanced 800 V systems used in EVs. These figures also reveal that for the Stage II non-isolated converter 3L-ZVT-IBC, soft switching at the main switches and diodes is successfully achieved throughout the wide operating range of EV battery voltages (i.e., from 200 V to 850 V). This achievement is significant for several reasons, primarily because it indicates a decrease in switching losses, leading to higher efficiency, decrease switch voltage rating and reduced thermal stress on the





(e) (c)

Fig. 3. Simulation results showing the: (a) switching signal for Stage I, II and also output inductor current waveform; (b) the drain-to-source voltage, switch current of primary side of Stage I and transformer primary and secondary current waveform; (c) efficiency analysis at 200 V, 500 V and 850 V with different load power; (d)(e)(f) results of soft switching of Stage II at load voltage 200 V, 500 V, and 850 V.

components.

Fig. 3(c) shows the achieved efficiency of the proposed converter, where calculation and thermal model simulation of PSIM are both used for efficiency analysis. The efficiency graph displays that the proposed converter has an efficiency greater than 98% throughout the load power and wide operating voltage conditions of 200 V to 850 V.

5 Conclusions and Further Work

This paper proposes a three-level zero-voltage transition interleaved buck converter (3L-ZVT-IBC) with DC transformer-based isolation for EV DC charging station. The proposed converter is characterized by lossless switching in both power stage and inherently balanced voltage in the second stage. The 3L-ZVT-IBC with DC transformer for EV DC chargers is described in detail, including the power losses calculation analysis of both power stages and the nature of the inherent DC voltage balance. The 3L-ZVT-IBC is validated by means of a 50 kW PSIM simulation, which can apply an output voltage from 200 V to 850 V. In addition, the efficiency expected more 98% throughout the voltage and power conditions. It is concluded that the

proposed 3L-ZVT-IBC with DC transformer-based isolation offers attractive properties, namely the inherently balanced DC voltage, not requiring any balancing circuit nor balancing closed-loop control, as well as the high efficiency and wide output voltage range. In future work, the proposed study will be analyzed with more detailed analysis and validated by the experimental results.

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