Maximizing Switch Utilization for Fast Battery Charging in Light Electric Vehicles

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Abstract. The primary focus of this initiative is the onboard fast charger of the Electric Vehicles (EVs), on single phase. One of the limiting characteristics of on-board rapid charging density is the power capacity of the converter. The current stress on the current flowing between the inverting segments restricts the rate at which most of the current converter setups in operation in the discontinuous conduction mode can be charged. Also, irrespective of the conduction modes, filter inductivity coupled with circuit inductivity restrict the rate of charge of these converters of EVs and significantly strains the voltage over the semiconductors. This paper suggests a new idea that would use the capability of the converter switch to enable fast charging to address these problems. At the switch it is demonstrated that it can be operated at its Maximum rating to maximize the power taken out of the input. To achieve the aforementioned objective of fast charging of EV a two phase system with a Bridgeless Switched Inductor (BLSI). Proposed is (BLSI) Cuk converter. The proposed method illustrates the ability of charging EV. When it is added to the Super Twisting Sliding. Mode Controller (STSMC) of BLSI Cuk converters.

Keywords: Power factor correction (PFC), electric vehicle (EV), quick chargers, discontinuous conduction mode (DCM), bridgeless switching inductor (BLSI), Super Twisting Sliding Mode Controller (STSMC), Cuk converter.

1. Introduction

The usage of the electric vehicles (EVs) and light electric vehicles (LEVs) has been on the rise in recent years due to the growing need to curb the emission of greenhouse gases and the impact on the environment to a minimum [1].They are electric vehicles, whereby the propulsion power is supplied by onboard battery systems [2], lithium-ion batteries have been widely adapted due to their low capacity to self-discharge, compact structure and large energy density. To extend battery lifespan, reduce overcharging problems, and enable the use of multimode charging strategies under low-current operating conditions, several studies have been carried out [3].At the same time, the fast advancing technologies are essential to ensure the quick energy replenishment and eliminate the range anxiety in drivers [4].Based on their power capacity, electric vehicle chargers are categorized into three distinct levels by the U.S. Department of Energy [5].Level-one chargers operate below 5 kW, Level-two chargers operate between 5-50 kW and Level-three chargers run above 50 kW as fast DC chargers. The diameter and mass of Level-one and Level-two chargers limit the velocity of the charging as they are in-built into the vehicle. Although off-board Level-three chargers can provide direct DC power to the battery [6], they are costly, and their operation takes much time to install. Therefore, Level-two on-board chargers of high-power are considered a more viable choice in the faster charging process. The detailed analysis of these onboard chargers with high power is provided in [7]. Early Level-1 charging systems typically employed a front-end line rectifier, a dc-link capacitor, and either isolated or non-isolated DC–DC converters. To enhance power quality and meet present regulatory requirements, modern standards mandate the use of single-stage or two-stage power factor correction (PFC) rectifiers ahead of the DC conversion stage [8]. However, DCM generates more current stress and this can be lessened by the interleaving techniques. The interleaved PFC converters find a strong application to minimize the current ripple and minimize the charging time [9]. But the charging rate which can be attained, regardless of the conduction mode, is restrict able by the interaction between circuit inductances and input filters. This interaction causes voltage stress on semiconductor switches at higher power levels, causing partial use of the nominal voltage capability of these switches. This weakness offers an avenue to come up with converter topologies that utilize the available switch voltage more effectively to charge fast, and this is the main subject of this work. LEVS are battery systems that are usually powered in a current of 24-72 V range, and this necessitates converters with high step-down properties. To satisfy this requirement, conventional buck-boost chargers have to operate at very low duty cycles to achieve low inductance values at the expense of lower inductive values and higher amplitude current and voltage stresses. This leads to the need to use more highly rated semiconductor devices and hence a larger converter and higher cost. Conversely, higher duty cycles of converters can use larger inductance and lower electrical stress and charge much faster with the same switch ratings. Even though high step-down converters with coupled-inductors or transformer have been developed, they add new components and design complexity. The bridge-free (BL) bridge-free system helps in reducing the conduction losses and hardware. The high rates of battery current are needed to charge faster and to utilize the full ratings of semiconductors. In a traditional buck -boost converter, the voltage on the switch is the voltage on the DC-link plus the voltage on the input. The switches may be used more efficiently by operating with higher DC-link voltage, with the input voltage kept the same. This paper aims at increasing the energy transfer by increasing the intermediate DC-link voltage, with the same components as a traditional charging system. In order to do this, a high step-down cuk converter using a bridgeless switched inductor (BLSI) is used. A DC-to-DC buck converter cascaded deals with the regulation of the low battery voltage. The BLSI converter has higher duty cycles hence faster dynamic response and higher efficiency in charge. Time charging is minimized by utilization of the full switch voltage rating at the high DC-link levels. Moreover, much faster charging is obtained by using a high step-down gain BLPFC-based AC -DC converter than is possible by using slow chargers with the same switch components.

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2. Proposed On-Board EV Fast Charging

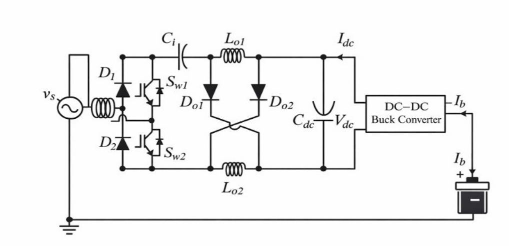

Fig.1. BLSI Cuk Converter

A high step-down gain converter with stage-II high converter setup is proposed to be used in charging LEVs, as illustrated in Fig. 1. The design proposed will have a Cuk converter, whose output-side switching inductor and input-side totem pole BL boost structure. These Cuk converters of BLSI are dual semiconductor switches. This circuit consists of two switches $(SW_1 and SW_2)$ and two line diodes $(D_1 and D_2)$.The capacitor C_i is a device that connects the source of energy to the load, and it works in the same manner as a traditional Cuk converter. The diodes$(D_1 and\ D_2)$are switched in opposite phases during the positive and negative half cycles. Nevertheless, the two switches$(SW_1 and SW_2)$are mutually exclusive are triggered at the same instant in each half cycle. The output stage is arranged in the same manner as a conventional Cuk converter and contains an output inductor $L_0(L_0 = L_1 = L_2)$and an output diode $D_0(D_0 = D_1 = D_2)$partitioned into two segments so that it functions in a switched inductor system. Output inducers will be taken to have the same values in this study. The buck converter is used to refill the battery like other two-stage systems. The voltage of the dc-link goes by the nameV_{dc}. The equations are then used to come up with the expression of voltage gain (M) of proposed BLSI Cuk converter. In this case, M is the DC voltage gain of the BLSI converter, and d is the duty ratio used to achieve the required step- down output voltage. The suggested BLSI converter is 50 times better in the PFC stage than the traditional buck-boost converters (M=$\frac{d}{(1-d)}$). The BLSI converter is planned to have higher duty cycle and higher inductance in DC-DC circuit than the DC-link voltage.

$$M = \frac{V_{dc}}{V_m} = \frac{d}{2(1-d)} \tag{1}$$

$$V_{ds}(t) = V_m + 2V_{dc} \tag{2}$$

Consequently, switch capacity is either over utilized or converter switches in the proposed charger architecture have adequate free working margin. Since the battery voltages and input are fixed, it means that the recommended BLSI Cuk converter has to run on a higher dc-link voltage, to achieve maximum use of the switch voltage rating. In the case of conventional single stage and two stage designs, as the DC-link voltage is increased, the power passes across the middle stage more in response to the constant input AC current. This leads to the second stage battery-side buck converter which in turn is able to provide a larger charging current to the battery.

3. CONTROL OF THE PROPOSED BLSI CONVERTER

3.1. PI Controller

In order to prevent inadequate utilization of the switch capacity, the convertors in the proposed charger should have adequate margin of operation. Since the battery voltages and input are fixed, the BLSI Cuk converter is set with a higher DC-link voltage to achieve the peak switch voltage rating. This greater DC-link voltage than in standard single and two stage designs enhances power passing through the middle stage with the same input AC current. The battery-side buck converter (second stage) is therefore able to give a larger charging current to the battery.

3.2. Super Twisting Sliding Mode Controller (STSMC)

ST-SMC controller was used in place of PI Controller in this work as indicated in Fig.2, at bi-directional converter, to overcome limitations as slow dynamic response and not being robust.ST-SMC Structure:

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The controller compares the target battery current and the actual current first. There are two control terms in its structure, then:

- The super-twisting term
- The correction based on integration.

The first control component is computed on the upper path of the diagram as a square root of the product of the absolute error (repeated by its sign). This is in turn scaled by the gain $-\lambda_3 = -0.7$and applied in causing a rapid corrective response to the tracking error. The second-order correction is the lower path, that is, the error gets multiplied by a gain $\lambda_4 = 0.91$ and then time-integrated to give a smooth and stable regulation.

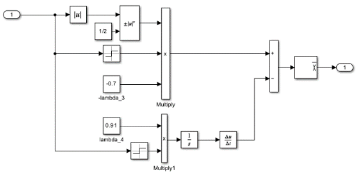

Fig.2. ST-SMC Controller

Important Equations:

Super-twisting term

$$u_1(t) = -\lambda_3 . |s(t)|^{1/2} . sign(s(t)) \quad (3)$$

Integration-based term

$$u_2(t) = \int \lambda_4 . sign(s(t)) \quad (4)$$

Unlike the classical sliding mode control, the final control scheme of the Super-Twisting Sliding Mode Controller (ST-SMC) reduces chattering to a large degree, and at the same time provides a reliable, finite time settlement of a sliding surface s(t) of a system. The input of the control consists of two quantities a nonlinear discontinuous term and an integral-based term.

The square root and sign of the sliding surface are added in the first term, which makes the nonlinear action of control and makes the convergence to the desired trajectory fast. The sign function is then integrated to get the second term which serves as a dynamic correction mechanism and enhances robustness of the model to the external disturbances and model uncertainties. With these elements combined, high-frequency switching is not necessary, and operation of the control becomes smooth.

4. Results and Discussions

The proposed EV charger is tested in the MATLAB/Simulink platform to determine its performance using PI and STSM controllers. In both cases, the conditions of input and output are kept the same so that a fair comparison could be made. It is assumed that it is a battery system of 48 V and 100 AH with switches rated at up to 800 V and 80A With PI controller operation, the steady-state operation results indicate a voltage stress of approximately 400 V to the switch and a current stress of approximately 30 A at a power level of 650 W. This ascertains that the proposed charger functions rather efficiently within the safe range of the switch ranking. The voltage stress on the switch is almost half that on conventional buck chargers, resulting in lower device ratings and lower cost. The charger can be used with a higher switch voltage (200 V) and at the same switch capacity to run closer to full switch utilization and allow quicker charging. The STSM-controlled charger further reduces the voltage and current stress, switching and conduction losses and this result in improved efficiency and allows the battery to charge at a significantly faster rate

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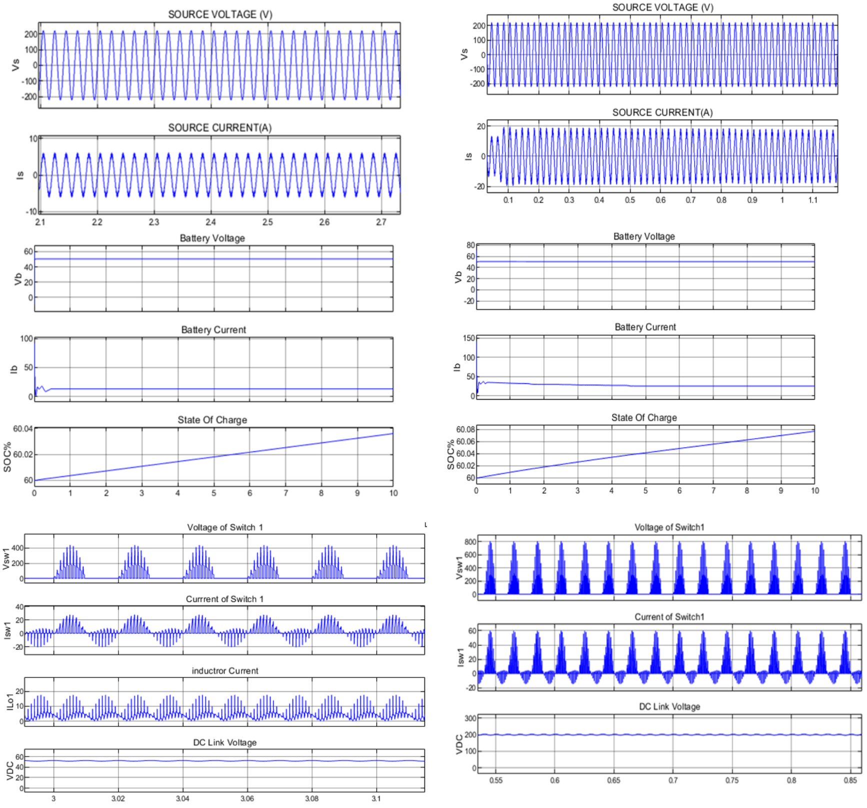
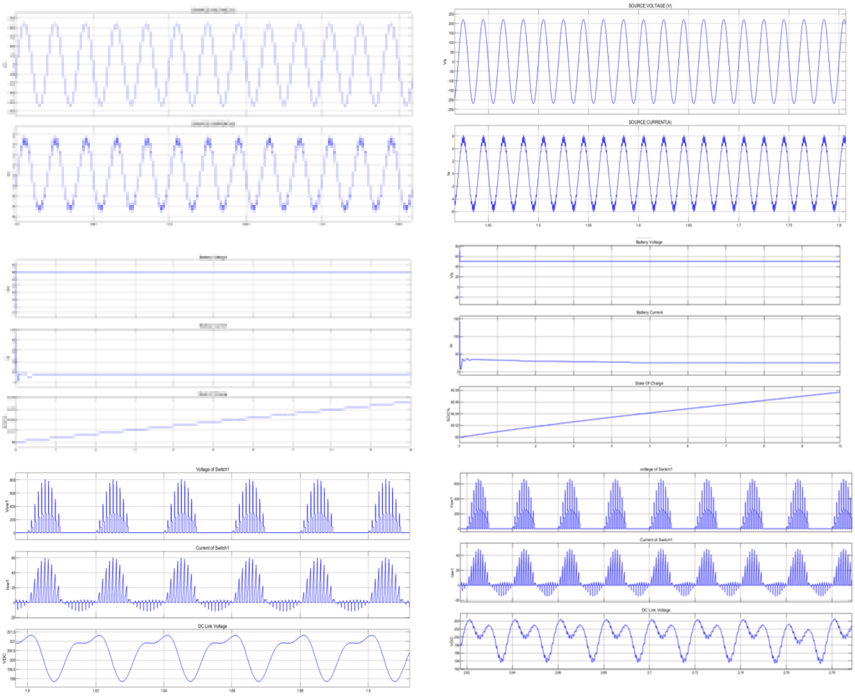


(a) **(b)**

Fig.3.Simulation waveforms of proposed fast charger with PI controller for (a) V_{dc} = 50V (b) V_{dc} = 200V



(a) (b)

Fig.4.Simulation waveforms of proposed fast charger with STSMC controller for (a) V_{dc} =50V(b) V_{dc} =200V

4.1 Comparison Analysis

Table 1 shows the voltage stress and current stress comparison between the fast charging PI controller and the STSMC controller.

Table 1. Voltage stress and current stress across the switches of fast charger with PI and the STSMC controller

S.NO	Charger type	Parameter			
		For 50V		For 200V	
		Voltage stress	**Current stress**	**Voltage stress**	**Current stress**
1	Fast Charger with PI controller	400V	30A	800V	60A
2	Fast Charger with STMC controller	400V	28A	650V	50A

5. CONCLUSION

This work presents a high-performance on-board fast charging architecture for light electric vehicles using a Bridgeless Switched Inductor (BLSI) based Cuk converter. The proposed topology improves switch utilization by operating at a higher DC-link voltage, thereby enabling enhanced power transfer without increasing semiconductor ratings. Simulation studies confirm that the converter operates safely within device limits while achieving improved charging performance. Under identical operating conditions, the PI-controlled system exhibits a switch voltage stress of 400 V and current stress of 30 A at 50 V operation. When the DC-link voltage is increased to 200 V, the stress levels rise significantly. In contrast, the Super Twisting Sliding Mode Controller (STSMC) demonstrates reduced current stress (28 A at 50 V and 50 A at 200 V) along with improved dynamic response and better robustness against disturbances. The comparative analysis clearly indicates that the STSMC provides superior regulation, lower stress variation, and faster convergence when compared to the conventional PI controller. The bridgeless input structure and switched-inductor configuration further contribute to reduced conduction losses and enhanced efficiency. Overall, the proposed fast charging system achieves improved power density, better switch utilization, and reduced charging time without increasing hardware complexity. Therefore, the presented architecture offers a practical and efficient solution for next-generation on-board EV fast charging applications.

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