A Constant Resistance Analysis and Control of Cascaded Buck and Boost Converter for Wireless EV Chargers

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Abstract—**This paper presents a new constant resistance control technique for a cascaded buck and boost converter, which is suitable for wireless energy transfer pickup systems in variable load applications such as battery or ultra-capacitor charging. In order to achieve high efficiency, an impedance matching network is commonly used in the contactless energy transfer systems especially for low coupling coefficient circuits. The proposed control technique avoids a divergence of the designed impedance matching system considering the load variation. This is important to secure high wireless energy transfer efficiency under voltage and current changes at the load terminals. The transfer function of the converter is presented with theoretical calculations describing the small-signal model. The system model is used to control the resistance in the cascaded buck and boost converter for electric vehicle (EV) charging applications in a 2 kW prototype.**

Keywords—buck and boost; cascaded; constant resistance control; converter; EV charger; wireless

I. INTRODUCTION

Contactless energy transfer has experienced recently a growing attention for its numerous potential applications such as smartphone charging platforms [1]-[2], medical implant devices [3]-[4], and electric vehicle charging [5]-[6]. In order to reach high efficiency the whole system must be carefully designed [7]-[8]. An impedance matching network is important to improve the system performance and is usually used at both transmitter and receiver sides. However, due to load variation during charging, the contactless system overall impedance diverges from the designed characteristic, which means that the designed impedance matching may be not working effectively causing a decrease in the system efficiency as compared to the designed performance values.

A conventional EV contactless energy transfer system consists of two stages; a transmitter and receiver platform as shown in Fig. 1. The role of the first stage with impedance matching network is to deliver energy to the second stage. The dc output voltage is provided to the load by the second stage with an impedance matching network, a high-frequency rectifier, and a non-isolated dc/dc converter. Since there is no standard about battery charging control established by the Society of Automotive Engineers – SAE [9], some of the wireless systems control the output at the receiver side, and others offer control at the transmitter side.

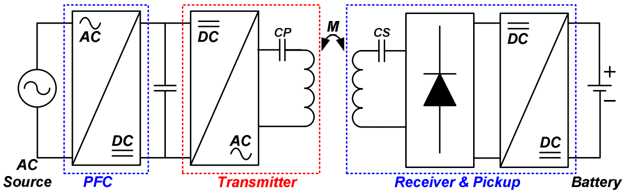

Fig. 1. Standard EV wireless power transfer system.

Several pickup circuit topologies, compensation strategies, and control algorithms are explored in the literature [10]-[21]. Due to the coupling coefficient factor, the transmitter and receiver resonant frequency may not match within a small to middle coil distance variation. This frequency mismatch results in a large drop in the delivered power. For this problem, discrete tuning [15], variable capacitor [16], variable inductance [17], and a more flexible solution, namely, a parallel compensated pickup with tristate boost converter topology [18] are proposed for mid-range wireless applications. Although, the coupling coefficient factor is investigated considering the distance variation between transmitter and receiver, the load condition is not considered in these papers. Controllable ac voltage output for pickup is presented in [19]. The transient response of the receiver side is limited with a variation of load or the coupling coefficient because of larger reactive power in the receiver part of resonant

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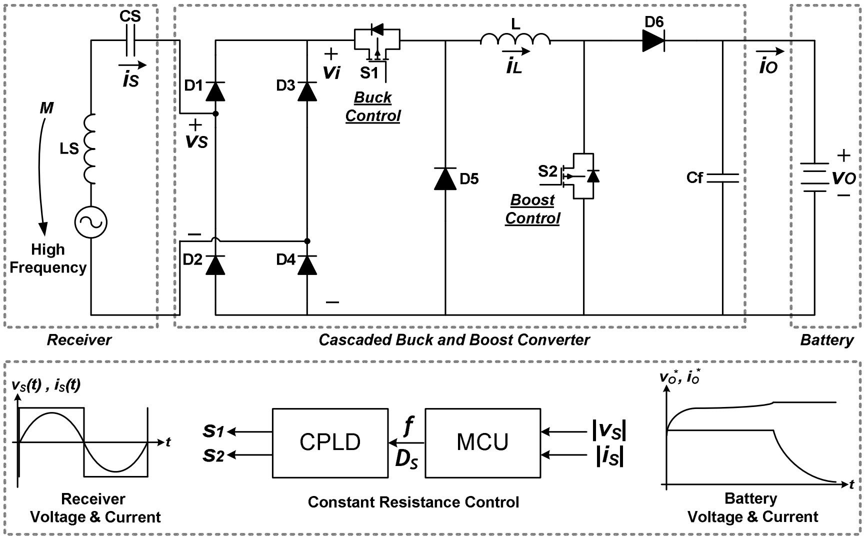


Fig. 2. Wireless EV battery charger receiver, cascaded buck and boost converter pickup with a battery, and the proposed control scheme.

tank. This makes the system power transfer capability inefficient and requires very nonlinear control algorithms. In [20]-[21], researchers have investigated multi-pickup bidirectional inductive power transfer by a power frequency controller and a synchronization technique for EV battery chargers. However, battery charging conditions are not considered and analyzed.

In this paper, a new constant resistance control is applied to the cascaded buck and boost converter in order to increase system efficiency for wireless EV battery chargers. This simple control has brought a novel aspect for reflected constant impedance to the transmitter side considering battery charging effects. EMI problems can be reduced with this new control approach that provides transmitter side control at a constant frequency and regulates the output with phase shift or dc link control. The proposed control is examined at light and full load conditions by modeling the battery as a variable load for the cascaded buck and boost converter. The converter model controllability is tested deriving the circuit behavior and transfer function of the converter extracted for the constant resistance approach. The impact of low harmonic components is investigated by using small signal analysis for reduction of the low frequency harmonics in the converter output voltage. The system performance is confirmed with experimental results for a cascaded buck and boost converter at 2 kW in the laboratory conditions. The circuit control system and the theoretical analysis with verification of the converter are discussed in more detailed in the following chapters.

II. CASCADED BUCK AND BOOST CONVERTER

Single switch step-up and down converter topologies, such as inverting buck-boost, SEPIC, and Cuk converter, have disadvantages of reverse output polarity and relatively high voltage and current stresses on the switch comparing to the buck and boost converter topologies [22]-[23]. The cascaded buck and boost converter as shown in Fig. 2 can achieve low switching stresses splitting voltage and current in two active switches, and results in low energy storage requirement and high performance efficiency operating independently in buck or boost mode [24]-[25]. Also, the converter has wide input voltage range capability [26] that is important for wireless EV charger receiver pickup applications in order to reach high efficiency.

The converter consists of a high frequency rectifier followed by a series connected buck converter and boost converter sharing a single filter inductance. Two active switches run in two operation modes, buck or boost, according to the system control. The buck operation mode is controlled when the rectified input voltage is greater than the output voltage. In the boost operation mode, the peak voltage of the input is smaller than the output voltage. This can be summarized that

$$\frac{|v_S|}{V_O} = \begin{cases} \dfrac{1}{D_{S1}}, & D_{S2} = 0 \quad \rightarrow \quad buck\,operation \\ 1 - D_{S2}, & D_{S1} = 1 \quad \rightarrow \quad boost\,operation \end{cases} \tag{1}$$

where D_{S1} and D_{S2} are the control switches duty cycles for S_1 and S_2, respectively. The cascaded buck and boost converter average model can be simplified by using the input dc voltage transfer function in terms of duty cycle equation as

$$\frac{|v_S|}{V_O} = \frac{1 - D_{S2}}{D_{S1}} \tag{2}$$

III. BATTERY AND CONTROL SCHEME

Battery is the main energy storage device for EVs, HEVs, and PHEVs. Electricity is produced releasing the energy stored in the battery chemicals [27]-[28]. The battery life, power, and energy density depend on energy storage capability, which is important for charge and discharge characteristics to be able to fast and secure recharge. In order to obtain a high-performance charging of the battery, charging conditions should be observed, controlled, and protected.

The battery life and performance are influenced by many factors, such as temperature, battery aging, over charging/discharging, charging rate, charger efficiency, and charging current ripples. These factors could deteriorate battery capacity, decrease charge acceptance, lower voltage, cause faster temperature rise and frequent self-discharge. These issues underscore the importance of the battery charger system and control.

The applied battery charging method is first constant current (CC) and then voltage limit control (CV) until the battery is fully charged. The charging profile of a battery is shown in Fig. 3. While the battery charging, the battery effective load resistance increases with control methods CC-CV as shown in green color in the figure. This changes the wireless converter quality factor and slips the resonant frequency, resulting in divergence of the designed impedance matching system.

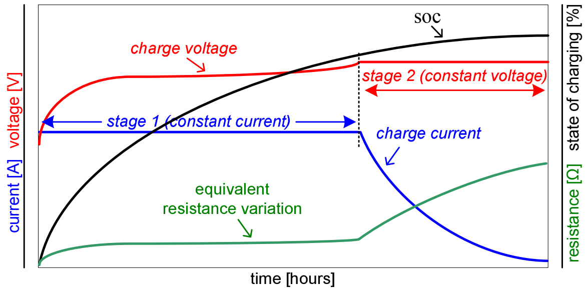


Fig. 3. Charging characteristic of a lithium-ion battery.

IV. THE CONSTANT RESISTANCE SMALL SIGNAL MODEL

Considering the voltage fluctuation from the PFC through wireless link and the pickup converter, the input voltage of the cascaded buck and boost converter varies with the sinusoidal line voltage. In case of the input voltage variation, a large output voltage changes can be prevented by a satisfactory input transient response and this is desired for the wireless EV charger pickup converter because of the battery safety. Therefore, the converter small signal analysis in the input line fluctuation is investigated for the constant resistance analysis considering buck and boost operation modes.

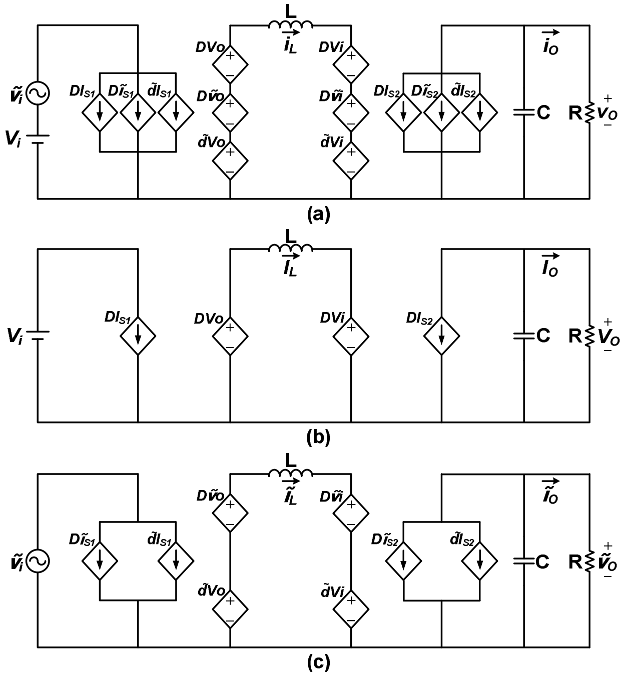


Fig. 4. Circuit models of the cascaded buck and boost converter a) linear model, b) linear dc model, c) linear small signal model.

The linear switch model of the converter is described in [29] and [30] as shown in Fig. 4.a. The second order ac terms can be neglected with the average linearization and with the replacing linear model components in dc terms, the dc model of the converter is formed as shown in Fig. 4.b. Then, the linear small signal model of the converter is obtained with the first order ac components as in Fig. 4.c. The transfer functions of input admittances are given below using the state space averaging method [31]-[32].

The transfer function of input admittance for buck mode is

$$Y_{in-buck} = \frac{D_{S1}^{2}\frac{s}{L}}{s^{2}+\frac{s}{L}+\frac{1}{LC_{f}}} \tag{3}$$

The transfer function of input admittance for boost mode is

$$Y_{in\_boost} = \frac{\frac{s}{L}}{s^{2}+\frac{s}{L}+\frac{\left(1-D_{S2}\right)^{2}}{LC_{f}}} \tag{4}$$

V. PROPOSED CONSTANT RESISTANCE CONTROL

The constant resistance control for the cascaded buck and boost converter is shown in Fig. 5. The pulse width modulator adjusts the inductor current amplitude and regulates the ratio between input voltage and current as seen in the scheme. The control loop forms the reference equivalent load resistance value based on the pick-up voltage and current $|v_{S(t)}|$ and $|i_{S(t)}|$, and determines the duty cycle value. The feedback of the input voltage and current is filtered to reduce the high frequency harmonic components. Then, the obtained reflected input equivalent load resistance value is hold at the constant value. The inductor current $i_{L(t)}$ maintains this value increasing or decreasing according to the reference value Z_i^*.

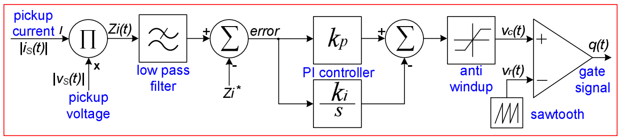


Fig. 5. Block diagram of the proposed constant resistance control.

The designed converter has a ripple voltage fluctuation around 120 Hz, caused by the rectified grid voltage. Due to deterioration effect of ripple into the controller performance, a low pass filter is needed. For this purpose, the low pass filter having 4 Hz cut off frequency is implemented in the microprocessor.

VI. EXPERIMENTAL RESULTS

To check the performance of the constant resistance control, experimental results are obtained to verify load characteristics. The step load change from 10 Ω to 12 Ω is given in Fig. 6.a and a transient state is shown in Fig. 6.b. The transition between buck and boost modes is plotted in Fig. 6.c, and Fig. 6.d, for the load variation 50 Ω to 100 Ω. The other step load performance in steady state and transient from 200 to 250 are presented in Fig. 6.e and Fig. 6.f. As seen in all figures, the voltage and current ratio on the input is secured at a constant value and the proposed control algorithm performs well. The designed prototype converter picture is given in Fig. 7.

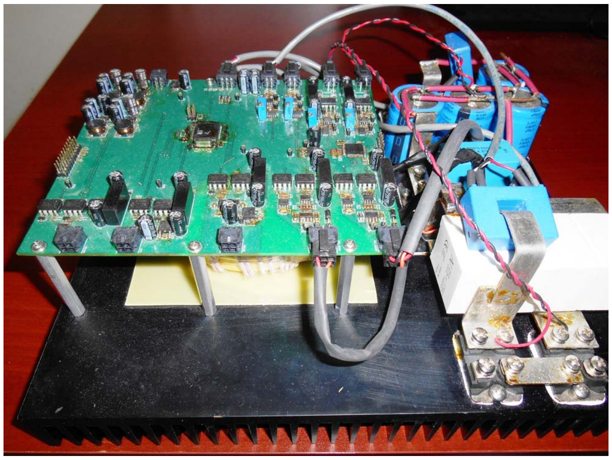
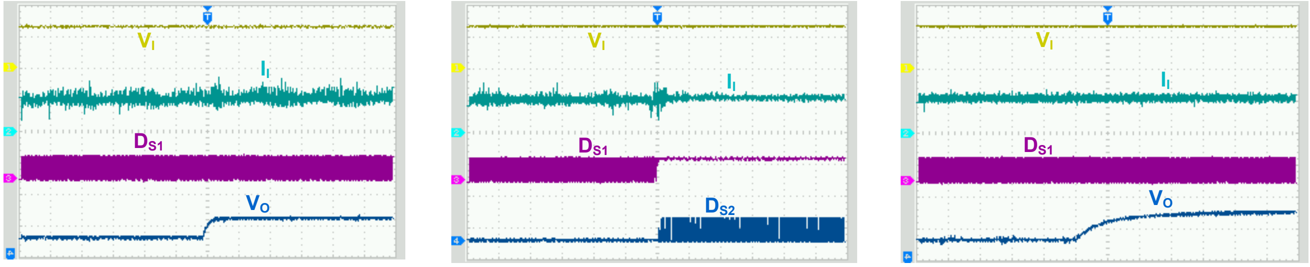


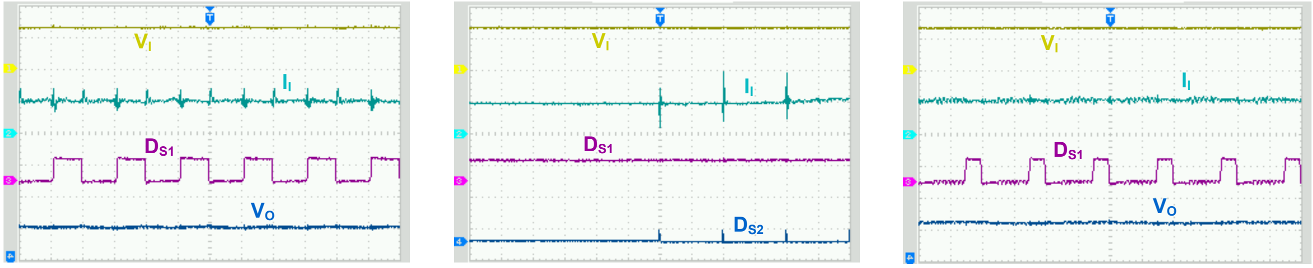
Fig. 7. The designed and built prototype of the converter.

VII. CONCLUSIONS

In this study, a new constant resistance control is presented for wireless EV battery charger systems. The control method is



a) 10 Ω to 12 Ω c) 50 Ω to 100 Ω e) 200 Ω to 250 Ω



b) 10 Ω to 12 Ω d) 50 Ω to 100 Ω f) 200 Ω to 250 Ω

Fig. 6. The converter input voltage and current (V_I), (I_I), buck / boost duty cycle (D_{S1}), (D_{S2}), a), b), e), f) for V_I *(40 V/div)*, I_I *(1 A/div)*, D_{S1} *(20 V/div)*, V_O *(5 V/div)*, c), d) for V_I *(40 V/div)*, I_I *(1 A/div)*, D_{S1} *(20 V/div)*, D_{S2} *(20 V/div)*.

proved by using a cascaded buck and boost converter at the pickup side. The theoretical equation of the system is explained by a small signal model. The experimental results are provided to verify the design with 2 kW output power. Light and full load conditions are examined by modeling the battery as a variable load for the cascaded buck and boost converter. The converter model controllability is tested deriving the circuit behavior and transfer function of the converter extracted for the constant resistance approach.

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