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A NEW TECHNIQUE FOR BRIDGELESS CHARGING OF EV's BATTERIES WITH UNITY POWER FACTOR BASED ON BORDERLINE CONTROL

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Original scientific research

This paper presents a new bridgeless switching converter which is used as an electrical vehicle charger. It connects directly to the utility plug and its output DC voltage varies in the range of 350 V to 650 V. We employ the borderline or peak current control here to correct the charging power factor. This control technique produces lower high-frequency conduction noise rather than other similar techniques, which guarantees the electro-magnetic compatibility (EMC). A clamp capacitor connected in series with source utility brings a DC voltage shift at input nodes, thus converter input voltage remains always positive and there is no need to any active or passive bridge. Averaged instant value of the converter input current is sinusoidal and is in phase with the source voltage. Also, this converter can draw the sinusoidal current at any phase difference with the input AC source. In the other word, the proposed charger is capable of bi-directional power delivery that is an important feature especially in the intelligent charging applications. This charger is a member of synchronous boost family, also it has lower components count and then lower production cost. Finally, the proposed converter and control technique are simulated and validated using Power Simulator (PSim6) software. Very good agreements between the theoretical and simulation results are achieved.

Keywords: *borderline current control; bridgeless charger; electrical vehicle; unity power factor*

Nova tehnika punjenja akumulatora električnih vozila bez premošćenja jedinstvenim faktorom snage temeljenim na graničnoj kontroli

Izvorni znanstveni članak

Ovaj rad predstavlja novi prespojni konverter bez premošćenja koji se koristi kao električni punjač vozila. Povezuje se izravno na utikač a izlazni DC napon varira u rasponu od 350 V do 650 V. Ovdje koristimo regulator graničnog ili vršnog opterećenja za ispravljanje faktora punjenja akumulatora. Ova kontrolna tehnika stvara nižu buku provođenja visoke frekvencije nego druge slične tehnike, što jamči elektro-magnetsku kompatibilnost (EMC). Električni kondenzator spojen u seriju s izvorom korisnosti donosi promjenu napona DC na ulaznim čvorovima, stoga ulazni napon konvertera ostaje uvijek pozitivan i nema potrebe za bilo aktivnom ili pasivnom premosnicom. Prosječna vrijednost ulazne struje konvertera je sinusoidna i u fazi je s početnim naponom. Također, ovaj pretvarač može izvući sinusoidalnu struju u bilo kojoj fazi razlike u odnosu na ulazni AC izvor. Drugom riječju, predloženi punjač je sposoban za dvosmjernu isporuku električne energije što je važna osobina posebno u inteligentnim aplikacijama punjenja. Ovaj punjač spada u grupu sinhronih pojačanja, također ima manji broj komponenti, pa stoga i nižu proizvodnu cijenu. Konačno, predloženi konverter i regulacijska tehnika su simulirani i provjereni pomoću Simulator (PSim6) softvera. Postignuto je vrlo dobro slaganje između teorijskih i rezultata simulacije.

Ključne riječi: *električna vozila; granična kontrola struje; jedinični faktor snage; punjač bez premošćenja*

1 Introduction

Due to lack of fossil sources, many researchers have focused on electrical vehicles (EV's) nowadays. Power factor correction (PFC) is an important aspect of AC/DC switching chargers. Low power factor reduces the power to be absorbed from the source utility, also high total harmonic distortion (THD) of line current leads to electro-magnetic interference (EMI) problems [1÷3]. From this point of view, many attempts have been done to improve the interface systems which develop the power factor of the standard switching converters. Power factor correction techniques must emulate a resistor at the source side also by maintaining a regulated voltage at output node. By supposing the sinusoidal line voltage, this means that the control block must order to sink a sinusoidal current. Then a suitable sinusoidal reference is needed and control function must force the input current to follow it as like as possible. Fig. 1, shows the converter input current in the borderline or peak current mode control [4].

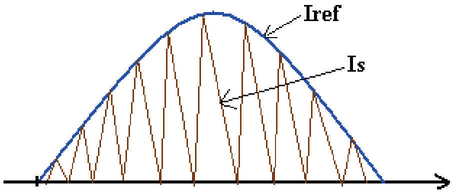

Figure 1 Borderline (peak current mode) control technique

As seen, the source current (I_S) sets when it reaches zero and resets when it reaches the reference signal (I_{ref}). The converter operates between the borders of continuous current mode (CCM) and discontinuous current mode (DCM) [5]. This technique has some advantages such as:

- No need of external compensation ramp
- Possibility of switch current limiting
- Low distorted input current
- No need of current error amplifier
- Decreasing the reverse recovery effect
- It acts as a first order system easing the feedback control design
- Lower conduction noise contents due to variable switching frequency
- Its manner is near to zero voltage switching (ZVS)

There are some commercial IC's such as ML4812 and TK 84812 designed especially for this control technique [6]. Input current distortion can be decreased by changing the current reference or by introducing a tiny DC offset. By inserting a little delay before turning on the main switch, the transistor can use the sine oscillation occurring between drain and source to bring the converter to operate in a near zero voltage switching (ZVS) condition [7, 8].

In this paper, a synchronous boost converter is employed as a step up charger for EV batteries which is controlled by peak current mode (borderline) technique. It also offers bidirectional power delivery. In the next sections, first we analyze the proposed converter design then we describe the control strategy. Finally, proposed converter system is simulated using Power Simulator (PSim6). Very good agreements between the theoretical results and simulation are achieved.

2 Proposed converter analysis

The power stage of the proposed charger is depicted in Fig. 2. The AC source is connected to converter input nodes via a bias capacitor. Capacitor (C_i) is serried with source to clamp its voltage, and then the converter input voltage (V_i) always remains positive.

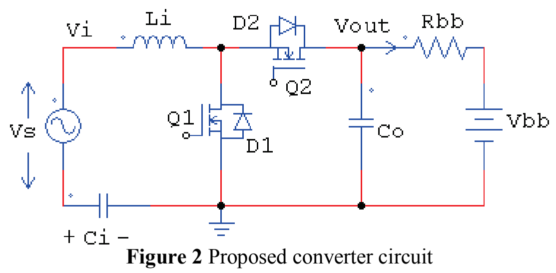

Figure 2 Proposed converter circuit

Transistors are driven in the complementary manner, so Q1 and D2 act in the positive half cycles of source voltage (mode 1), also Q2 and D1 act in the negative half cycles (mode 2). In mode 1, power is transferred from source and C_i to batteries bank (BB) while the average input current follows V_S and is inphase with it. During mode 2, power flows through BB to source utility, but the delivered power is greater than the received one. Toggling between mode1 and mode2 (or instant charging and discharging modes) helps to hold batteries in a fresh mood and long life time. The major goal of the controller is to create a resistive behavior at the point at which the converter interfaces the utility line [9]. This resistance is denoted as the emulated resistance and will be as follows:

$$V_S(t)=V_{Sm}\sin(\omega t);\ I_S(t)=I_{Sm}\sin(\omega t) \tag{1}$$

$$R_{em}=\frac{V_{Sm}}{I_{Sm}};\ I_S(t)=\frac{I_{ref}(t)}{2}. \tag{2}$$

C_i value can be defined using the following equations.

$$V_i(t)=V_S(t)+V_{Ci}(t);\ V_{Ci}(t)=\frac{1}{j\omega C_i}I_{Sm}\sin(\omega t) \tag{3}$$

$$V_i(t)>0\Rightarrow C_s>\frac{1}{\omega R_{em}} \tag{4}$$

Clamp capacitor of C_i must be initially charged before the system turns on. To define the initial voltage of $V_{Ci}(0)$, first consider the following 4 cases of switching regions.

Case I:

$$\left\{(0\le\omega t\le\frac{\pi}{2})\ \text{and}\ (T_1=\text{on})\right\}\ \text{or}\ \left\{(\frac{3\pi}{2}\le\omega t\le 2\pi)\ \text{and}\ (T_2=\text{off})\right\}$$

$$\frac{dI_S(t)}{dt}>>\frac{dI_{ref}(t)}{dt} \tag{5}$$

Case II:

$$\left\{(0\le\omega t\le\frac{\pi}{2})\ \text{and}\ (T_1=\text{off})\right\}\ \text{or}\ \left\{(\frac{3\pi}{2}\le\omega t\le 2\pi)\ \text{and}\ (T_2=\text{on})\right\}$$

$$\frac{dI_S(t)}{dt}<<\frac{-dI_{ref}(t)}{dt} \tag{6}$$

Case III:

$$\left\{(\frac{\pi}{2}\le\omega t\le\pi)\ \text{and}\ (T_1=\text{on})\right\}\ \text{or}\ \left\{(\pi\le\omega t\le\frac{3\pi}{2})\ \text{and}\ (T_2=\text{off})\right\}$$

$$\frac{dI_S(t)}{dt}>>\frac{-dI_{ref}(t)}{dt} \tag{7}$$

Case IV:

$$\left\{(\frac{\pi}{2}\le\omega t\le\pi)\ \text{and}\ (T_1=\text{off})\right\}\ \text{or}\ \left\{(\pi\le\omega t\le\frac{3\pi}{2})\ \text{and}\ (T_2=\text{on})\right\}$$

$$\frac{dI_S(t)}{dt}<<\frac{dI_{ref}(t)}{dt} \tag{8}$$

By expanding the equations of (5) to (8), it is possible to define the maximum and minimum values of C_i initial voltage which are stated in the following equations.

$$\frac{V_{out}-V_{C_i}(0)}{V_{Sm}}\ge\left(\sqrt{1+\left(\frac{2\omega L_i}{R_{em}}+\frac{1}{R_{em}\omega C_i}\right)^2}-\frac{1}{R_{em}\omega C_i}\right) \tag{9}$$

$$\frac{V_{C_i}(0)}{V_{Sm}}\ge\left(\sqrt{1+\left(\frac{2\omega L_i}{R_{em}}+\frac{1}{R_{em}\omega C_i}\right)^2}+\frac{1}{R_{em}\omega C_i}\right). \tag{10}$$

3 Control technique analysis

As mentioned before, the converter seen in Fig. 2 is applied as a charger with unity power factor using borderline control technique. The overall system circuit is shown in Fig. 3.

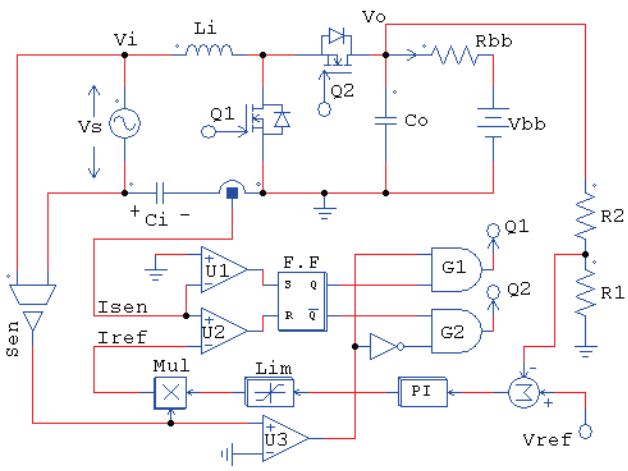

Figure 3 Proposed converter overall circuitry

As seen above, comparator (U_3) enables and disables the drive signals of Q_1 and Q_2 depending on the source voltage sign using G_1 and G_2 AND gates respectively. Difference between reference and output voltages is fed to a PI compensator which modulates the reference current amplitude that I_S must follow it, then the converter delivers the power according to output batteries need. PI control then is connected to a limiter block to avoid the unwanted oscillations when the system starts-up or at the transient instants. Since the converter output voltage is so much greater than the control block signaling voltage, R_1 and R_2 resistors are employed here as a voltage divider. When the sensed current reaches zero, U_1 gate sets the RS flip-flop and when it reaches the reference level of I_{ref}, U_2 comparator resets the flip-flop so the current always stays among the bands. Amplitude of I_{ref} signal changes depending on the error signal fed by PI controller, or in other words, depending on the power absorbed by EV batteries. A little dead time is needed between Q_1 and Q_2 signals to prevent it from short circuit.

The proposed converter values are stated in Tab. 1. Simulation is based on these values; also equivalent series resistors (ESR) of inductor and capacitor are taken into account to simulate the converter veritably.

Table 1 Circuit components value

Part’s	Value
V_S	110 V, 60 Hz
L_i, r_{Li}	0,5 mH, 0,05 Ω
C_i, r_{Ci}	2,2 mF, 0,05 Ω
C_o, r_{Co}	3,3 mF, 0,07 Ω
V_{out}, $V_{battries}$	400 V, 380 V
PI controller	$\kappa = 3$, $\tau = 25$ ms

Here, the Ziegler-Nichols method is used for PI controller tuning [10]. This method makes a syllogistic assumption on the system model but does not require that the model be specifically known. Zeigler-Nichols formula for controller tuning is based on the plant step response. In this method we first step-up the source voltage then by studying the output voltage change, the PI coefficients are selected [11]. Fig. 4 shows the output voltage behavior affected by the source voltage step change.

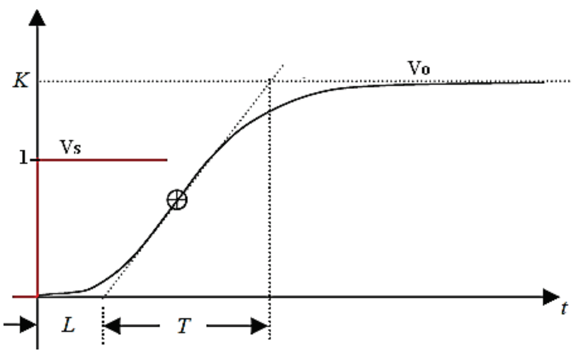

Figure 4 Output voltage responce to source voltage change

Then the proportional and integral coefficients of the controller can be calculated using the following formula:

$$\kappa = 0{,}9\frac{T}{L};\quad \tau = \frac{L}{0{,}3} \tag{11}$$

This technique is completely simple and efficient which considers the plant as a black box. Also the output response is typical of a first order system or a second order system with dominant pole approximation or a plant made up of series of first order systems. It should be noted that the figure shown above is also typical of over damped second order system.

Fig. 5, shows the converter source current (I_S) along with utility voltage (V_S) that both are sinusoidal and inphase.

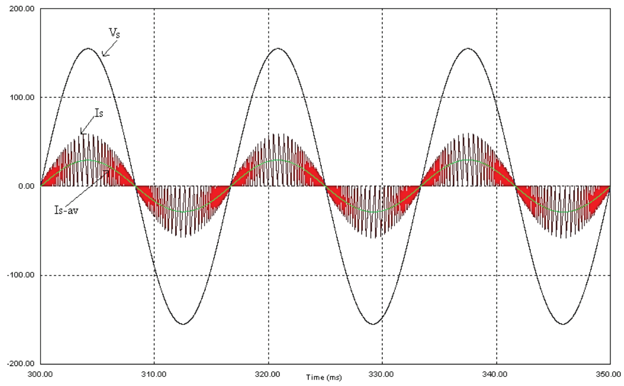

Figure 5 Source voltage and current

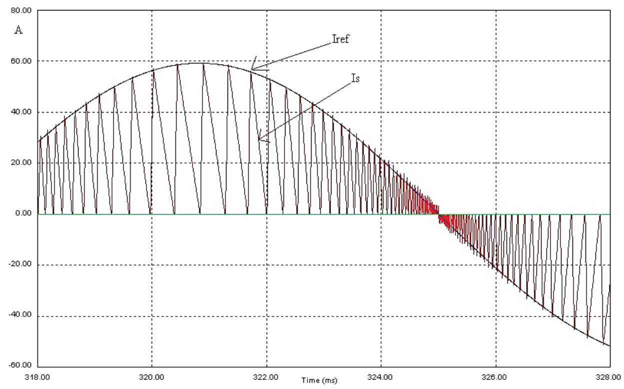

Figure 6 Enlarged image of source current and its reference

Fig. 6 shows the enlarged image of the source current (I_S) and its reference signal (I_{ref}).

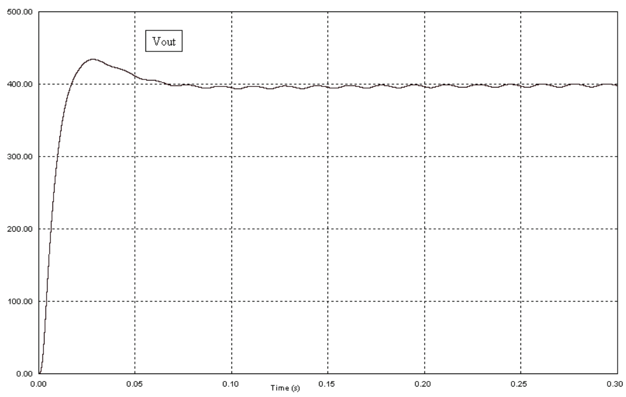

Figure 7 Charger output voltage at start-up moment

Fig. 7 illustrates the converter output DC voltage at start-up moment which exhibits a response time of about 70 ms. As seen, it has fast response behavior and by changing R_{bb} (shown in Fig. 3) or V_{out}, it is possible to change the charging current of batteries bank (BB) and to vary the charge waiting time.

To study the dynamic response of the proposed technique, converter output voltage is stepped at time 0,5 s intentionally. Fig. 8 illustrates the source current and output voltage along with each other respectively. Their quiescent time is about 0,2 s.

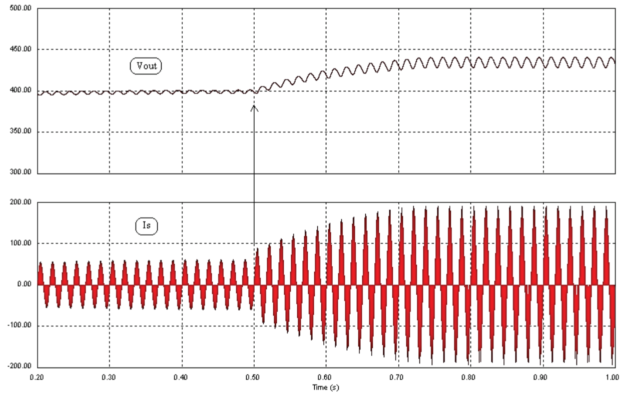

Figure 8 Converter output voltage which steps up about 35V

The main goal of feedback circuit is to control the loop gain such that its crossover frequency stays on a desired location with enough phase and gain margins to achieve a good dynamic response, stability, line and load regulation [12]. Fig. 9, shows the error signal of PI block.

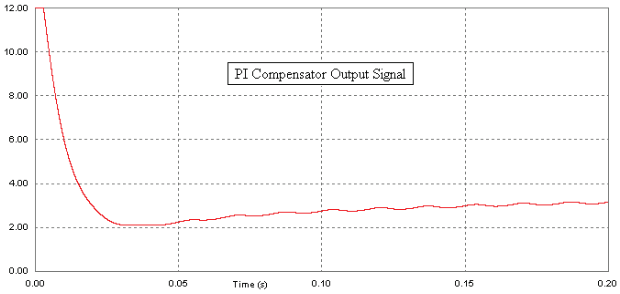

Figure 9 Error signal of PI compensator

Maximum of switching frequency (F_S) and duty cycle (D) change help to select the transistors and to design the converter perfectly. Fig. 10 shows the way to extract the F_S and D from switching signal, which is described in the equation presented below.

$$F_S=\frac{1}{T}=\frac{1}{t_{on}+t_{off}};\quad D=\frac{t_{on}}{T}=\frac{1}{1+\dfrac{t_{off}}{t_{on}}}. \tag{12}$$

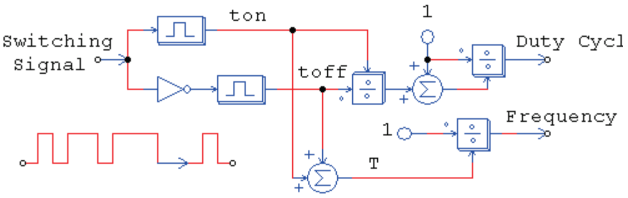

Figure 10 Calculation of F_S and D based on the switching signal

Based on the calculation block of Fig. 10, the transistors switching frequency and duty cycle have been computed and illustrated in Fig. 11 and Fig. 12 respectively. These curves help the design engineer to select the circuit parts such as semiconductor switch correctly with proper frequency and power rates which then leads to saving money and to increasing the system reliability. This aspect is important especially in the manufacturing stage which is studied in some works such as [13, 14].

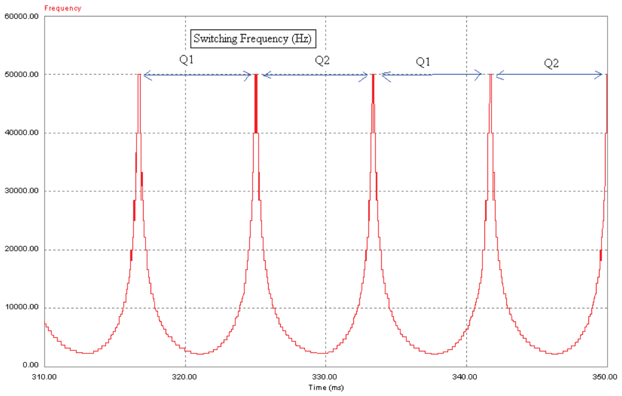

Figure 11 Switching frequency

Switching frequency varies between 3 kHz and 50 kHz.

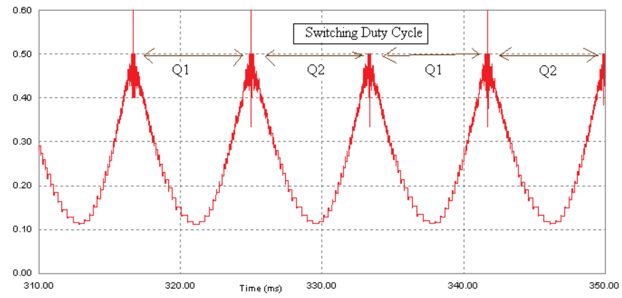

Figure 12 Switching duty cycle

Switching duty cycle varies between 0,1 and 0,5.

4 Conclusion

In this paper, we have proposed a new switching charger for electrical vehicle batteries. It is based on the bridgeless synchronous boost converter and has unity power factor. Borderline current mode control is used as power factor correction technique. This technique offers some advantages rather than the other ones as stated in the sections before. The input bridge is eliminated, instead of it one bias capacitor is put in series with the source utility to clamp the input voltage always positive. This charger has a low number of components and then has lower production cost. But there is one disadvantage; it needs a rather large bias capacitor which must be pre-charged before setting the system on. PF and THD obtained here are 0,98 and 4,5 % respectively. Finally, the proposed system is simulated and validated using Psim6.

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