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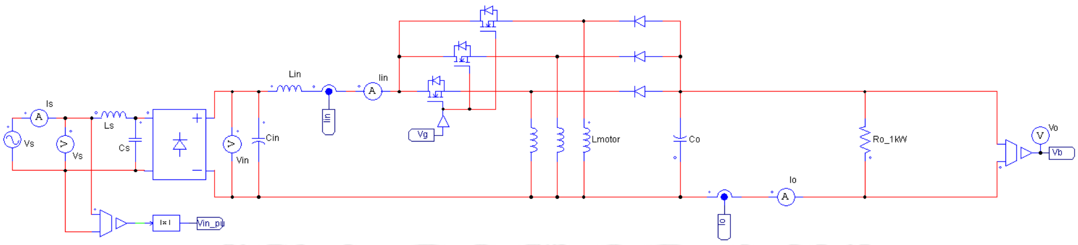
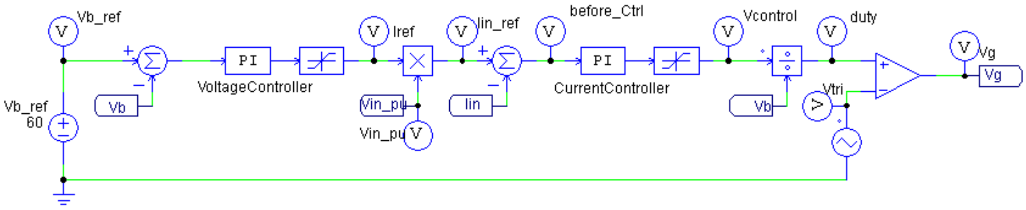
วงจรจำลองการทำงาน



ภาพที่ ก.1 วงจรกำลังการจำลองการทำงานโดยให้สวิตซ์กำลังทั้ง 3 ตัวทำงานพร้อมกัน



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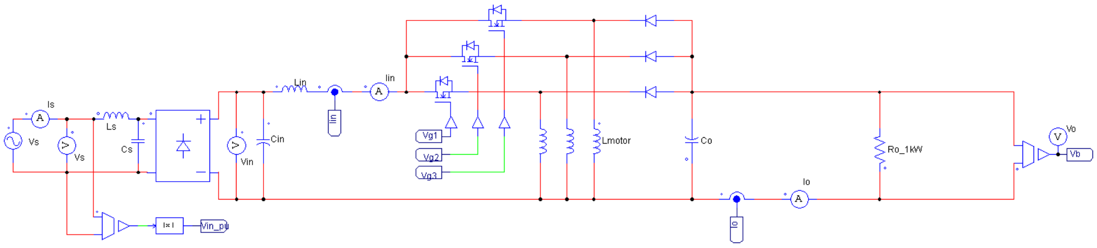

ภาพที่ ก.3 วงจรกำลังการจำลองการทำงานโดยให้สวิตซ์กำลัง
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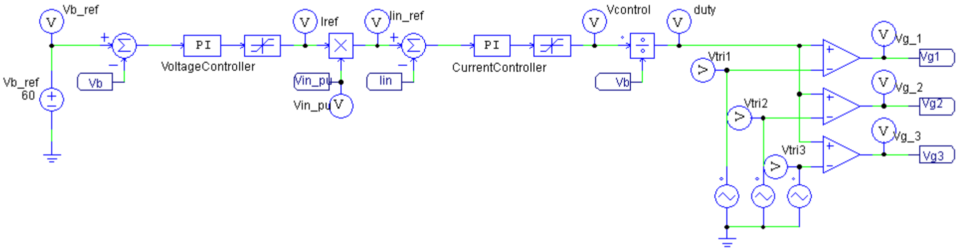

ภาพที่ ก.4 วงจรควบคุมการจำลองการทำงานโดยให้สวิตซ์กำลัง
ทำงานแบบอินเตอร์ลีฟ

ภาคผนวก ข

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An Off-line Battery Charger Based on Buck-Boost Power Factor Correction Converter for Plug-in Electric Vehicles

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Abstract

This paper presents an off-line battery charger based on the buck-boost power factor correction (PFC) converter for plug-in electric vehicles (EV). The integrated battery charger is obtained from the traditional three-phase voltage source inverter (VSI) for EV, which operates as buck-boost converter with power factor correction ability. The PFC controller is regulates the battery voltage and controls the supply current of the converter to achieve unity power factor which is very simple and gives good performance. The proposed buck-boost PFC converter is operating in buck mode and boost mode, which is alternatively carried out according to the relationship between the rectified input voltage and battery voltage. The practicality and performance of the battery charger of the proposed converter topology has been verified via simulation.

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Keywords: Battery chargers, buck-boost converter, power factor correction, electric vehicle, ac motor drives ;

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1. Introduction

The development of electric vehicles (EV) has proliferated rapidly in recent years. The battery has become the most significant power source for the EV propulsion systems, electric motors, power converters, and controllers. Its cost, energy and power density, memory effect, and charging time are still practical applications. In addition, the charging time and battery life time depend highly on the characteristics of the battery charger [1]-[3].

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The battery charger system has an important role in the battery and EV technology. In general, the plug-in EV battery charger system can be classified as on-board and off-board charging systems with unidirectional /bidirectional converter [4], [5]. There are advantages and disadvantages with both charging systems. In on-board charging systems, the batteries can be recharged anywhere from household utility outlets. However, it is limited in power output because of the size and weight limitations defined by EV design. The off-board charging system can be designed for high charging power levels and is less constrained by the size and weight. However, this system is limited in power output only by the ability of the batteries to accept the charge. Moreover, the springiness to charge at different locations is restrained.

The integrated EV battery chargers into the electrical drive system have been reported in the literature. Reference [6] presented the integrated battery chargers using the inductor of induction motor during charging time to constitute a dc/dc boost PFC converter with the three-phase VSI. The battery voltage of this system should be more than maximum line-to-line peak voltage to guarantee unity power factor operation. In [7], a single-phase integrated charger for an electrical scooter with an interior permanent magnet motor traction drive was presented. The battery system operated as a dc/dc boost PFC converter where the motor works as a coupled inductor, which used the three-phase VSI as a switch in the charging mode.

In this paper, an off-line battery charger based on the buck-boost PFC converter is proposed for plug-in EV. The proposed converter modified the structure of the three-phase VSI and motor drive into a battery charger system. The PFC controller technique for the integrated battery charger is used to the line frequency current shaping control scheme. Finally, simulation results are shown to verify the performance of the proposed battery charger for EV.

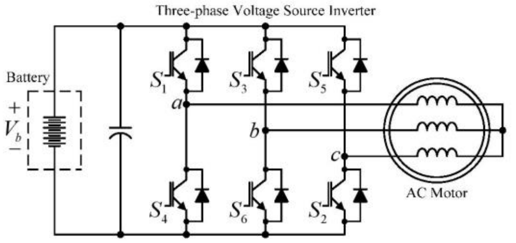

Fig. 1. Traditional three-phase voltage source inverter for electric vehicles.

2. The proposed circuit configuration

A basic configuration for the traditional three-phase VSI powered by a battery for EV is shown in Fig. 1. It consists of a three-phase ac motor, a three-phase VSI and a battery pack. In addition, some methods are an inverter accompany with a bidirectional dc/dc converter [8].

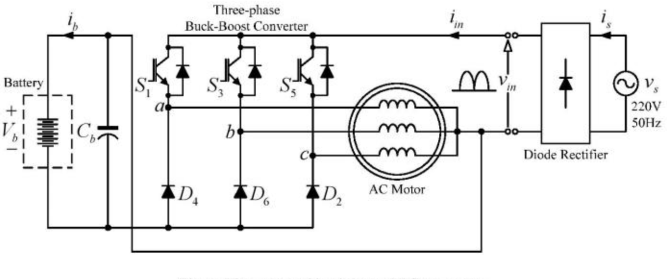

Fig. 2. The proposed buck-boost PFC converter.

The buck-boost converter with the PFC controller for EV battery charger system is shown in Fig. 2. The proposed system modified the structure of the traditional three-phase VSI, which used the inductor ac motor during battery charging time to constitute a buck-boost converter. The proposed circuit describes the three-phase buck-boost converter obtained from the ac motor drive. The positive dc-link of inverter and the neutral point of the ac motor terminals are the input terminal of the buck-boost converter for battery charger system, which includes a single-phase diode rectifier. The high side power switches of the inverter are operated as a simple switch and the low side power switches of the inverter are not enabled, which are operated as a diode switch.

3. Operation of the buck-boost PFC converter

From the schematic diagram in Fig. 2, it can be shown that the simplified equivalent circuit of the buck-boost PFC converter as illustrated in Fig. 3. The two equivalent circuits of each operational mode in the switching period of the proposed converter are shown in Fig. 4, which operate in the continuous condition mode (CCM). At initial condition, the current flowing through inductors in ac motor L_{motor} are zero, the main switches $S\ (S_1, S_3, S_5)$ and diodes $D\ (D_4, D_6, D_2)$ are off-state, and the capacitor C_b is charged to sum of the input voltage V_{in} and the output battery voltage V_b. It is assumed that all the components in the converter are ideal. The operating principle of the buck-boost PFC converter during the switching period can be described as follows:

Mode 1: In Fig. 4 (a), the main switches S are conducting. The diodes D are reverse biased. The input voltage V_{in} supplies energy to the inductors L_{motor}. Also, the energy is transferred from capacitor C_b to the battery.

Mode 2: In Fig. 4 (b), the main switch S is turned off. The diode D is forward biased. Therefore, the voltage across the inductor is $-V_b$, thereby causing the inductor to be magnetized in the opposite direction.

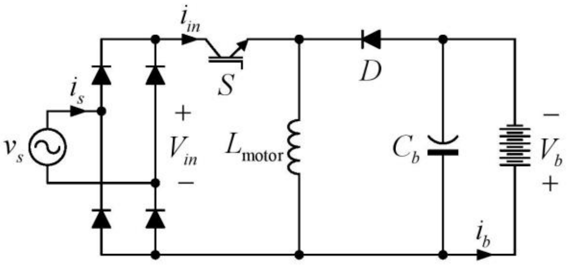

Fig. 3. The simplified equivalent circuit of the buck-boost PFC converter.

In the steady state operation of the proposed converter, the integral of the inductor voltage over time period must be zero. This implies that the average voltage across the inductor over the time period is zero ($V_L = 0$). Therefore, the dc voltage conversion ratio of the buck-boost PFC converter can be represented as

$$\frac{V_b}{V_{in}} = \frac{d}{1-d}, \tag{1}$$

where d is the duty cycle of the converter for $0 \le d < 1$, defined by $d = t_{on} / T_s$, T_s is the switching period, and t_{on} and t_{off} are the turn-on and turn-off times of the main switches, respectively.

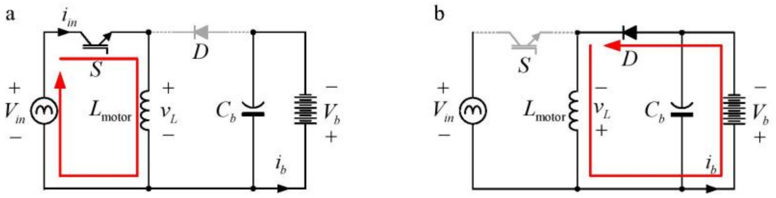

Fig. 4. The equivalent circuit for different operation modes of the proposed converter.

(a) Mode 1; (b) Mode 2.

4. Power Factor Correction control scheme

The block diagram of the line frequency current shaping control for the buck-boost PFC converter is shown in Fig. 5. The proposed PFC controller consists of an external voltage control loop, which is used to regulate the battery voltage. It also consists of an internal current control loop, which is used to control the reference input current and shapes the input current of the converter to achieve unity power factor.

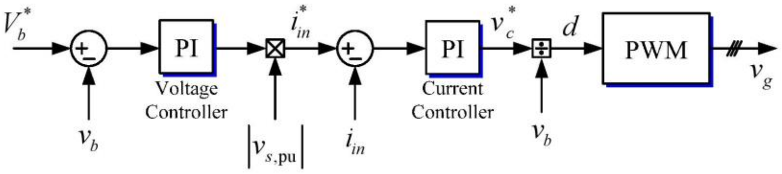

Fig. 5. Block diagram of the buck-boost PFC converter control.

4.1. Voltage Controller

The main voltage PI controller regulates the battery voltage V_b . The output signal of the PI voltage controller corresponds to the maximum value of the input current, which is multiplied by an absolute sinusoidal voltage waveform $|v_{s,pu}|$ with the same frequency and phase of the supply voltage v_s . It generates the reference for the input current control loop I_{in}^* . The external voltage control loop has a very low bandwidth compensator and has a voltage reference.

4.2. Current Controller

In the current control loop, the input current reference I_{in}^* is given by voltage controller. The current regulator is the PI current controller for obtaining a good tracking of the current reference. The current loop is a fast controller, which has twice the supply frequency (100 Hz) and is designed so as to track the rectified supply voltage waveform. The current controller sets the desired duty cycle d , which is compared with the triangular carrier voltage to get the gating pulse PWM signal for the switches (S_1, S_3, S_5) of the proposed converter.

5. Design of the buck-boost PFC converter

In this section, the proposed buck-boost PFC converter is designed with circuit parameters for off-line battery charger. According to (1), the battery voltage V_b of the buck-boost PFC converter is given as

$$V_b = \frac{2\sqrt{2}dV_s}{(1-d)\pi}, \tag{2}$$

where V_{in} is the rectified supply voltage, $V_{in} = 2\sqrt{2}V_s / \pi$, and V_s is the rms of supply voltage.

From (2), the duty cycle of the buck-boost PFC converter can be derived as

$$d = \frac{V_b\pi}{\left(2\sqrt{2}V_s + V_b\pi\right)}. \tag{3}$$

The minimum of the inductor $L_{\min}$ design is under the condition that the buck-boost converter operates in CCM, which can be expressed as

$$L_{\min} = \frac{3(1-d_{\min})V_b}{2f_sI_L}, \tag{4}$$

Therefore, the minimum inductor value of the proposed converter can be design according to equation (4) where the inductor motor in ac motor is higher than the minimum inductor ($L_{\text{motor}} \geq L_{\min}$).

6. Simulation result

The proposed off-line battery charger using the buck-boost PFC converter for plug-in EV is verified through PSIM circuit simulator software. The simulation configuration was shown in Fig. 6. The system parameters used in the simulation are listed in Table 1. The lithium-ion battery bank is formed by four series connected to 12V/80AH batteries, which used resistive load for simulating the charged battery condition.

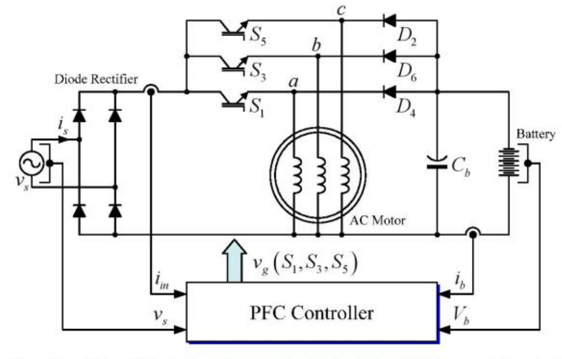

Fig. 6. Configuration of the off-line battery charger using the buck-boost PFC converter for electric vehicles.

Table 1. Circuit Parameters in Simulation.

Parameters	Value
Supply voltage, V_s	220 V(rms)
Supply frequency, f_1	50 Hz
Inductors of ac motor, L_{motor} (per phase)	1.5 mH
Switching frequency, f_s	20 kHz
Nominal battery voltage, $V_{b,nom}$	48 V
Rated charge battery voltage, V_b	60 V
Rated power, P_o	1 kW

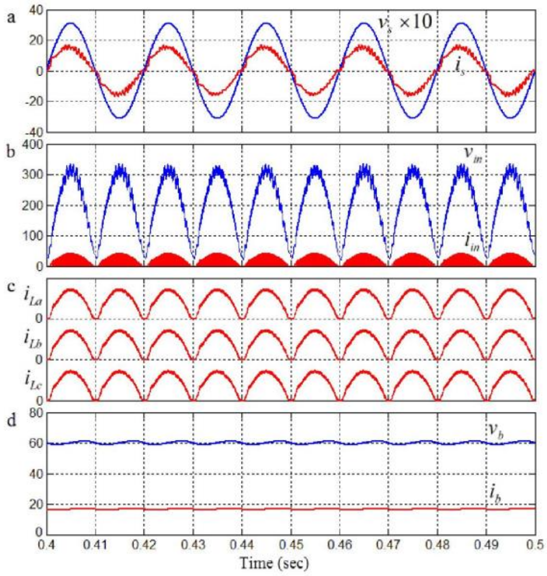

Fig. 7. Simulated waveforms of the off-line battery charger using the buck-boost PFC converter for electric vehicles.

(a) supply voltage v_s and current i_s ; (b) dc input voltage v_{in} and current i_{in} ;

(c) ac motor inductor current i_{La}, i_{Lb}, i_{Lc} (20A/div); (d) battery voltage v_b and current i_b .

Fig. 7 shows the simulation results of the off-line battery charger using buck-boost PFC converter for EV in steady state condition during time interval 0.4-0.5 sec. Fig. 7 (a) shows the supply voltage v_s and current i_s of the buck-boost PFC converter. It is noted that the supply current i_s is sinusoidal and catching up with the supply voltage so that the high power factor is achieved. Fig. 7 (b) shows the rectified input voltage v_{in} and current i_{in} .The inductor currents i_{La}, i_{Lb}, i_{Lc} are illustrated in Fig. 7 (d). It can be seen that the proposed buck-boost PFC converter has the small inductor-current ripple. Fig. 7 (d) shows the battery voltage v_b and current i_b , which can be stably regulated by voltage controller to be 60 V.

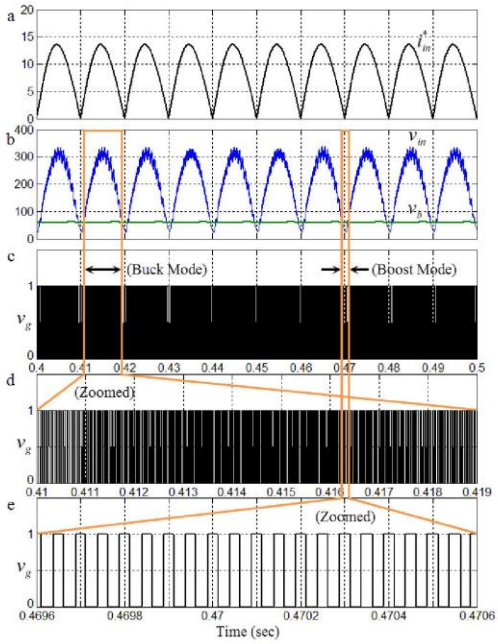

Fig. 8. Simulated waveforms of the buck-boost operation for plug-in charging.

(a) input current reference i^*_{in} ; (b) dc input voltage v_{in} and battery voltage v_b ; (c) gating pulse PWM signal v_g ; (d) zoomed gating pulse PWM signal in buck operation; (e) zoomed gating pulse PWM signal in boost operation.

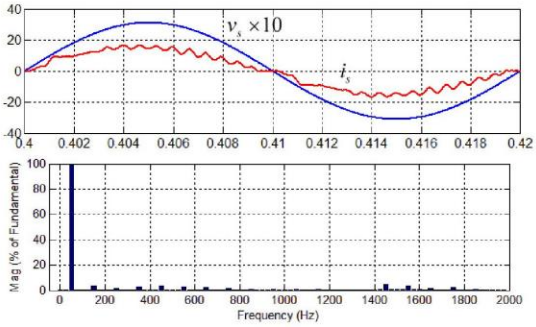

Fig. 9. Simulated waveforms of supply voltage v_s ; current i_s and current spectrum (THDi=4.95%).

The proposed buck-boost PFC converter which is operating in buck mode and boost mode are shown in Fig. 8. Fig. 8 (a) shows the input current reference i_{in}^{*} for current controller. Fig. 8 (b) shows the rectified input voltage v_{in} and battery voltage v_b. As can be seen in these results, the proposed converter operation has been simulated under two conditions, buck or boost switching mode. The buck mode is operated when the value of the rectified input voltage v_{in} is higher than battery voltage v_b and the boost mode is operated when the value of the rectified input voltage v_{in} is lower than the battery voltage v_b. Fig. 8 (c) shows the gating pulse PWM signal v_g for the buck-boost PFC converter under two mode conditions (buck mode and boost mode), which are illustrated in the zoomed gating pulse PWM signal in Fig. 8 (d) and (e), respectively. It can be seen that buck-boost operation is alternatively carried out by the resultant control voltage reference according to the rectified input voltage/battery voltage relationship.

Finally, Fig. 9 shows the supply voltage v_s, current i_s, and current spectrum waveform of the proposed converter. The supply current is in phase with the supply voltage, which is close to unity power factor. The power factor value is about 0.99 under full power recharge and the total harmonic distortion of the supply current (THDi) value is 4.95%.

7. Conclusion

An off-line battery charger based on the buck-boost PFC converter for plug-in EV was proposed in this paper. The battery charger system is obtained from the voltage source inverter and motor dive system, which operates as a buck-boost converter with power factor correction ability. The feasibility and reliability of the proposed converter for plug-in battery chargers in electric vehicles has been verified by the simulation. Simulation results confirmed the good performance of the battery charger and high input power factor. As stated above, the proposed system can be applied to a very wide range of battery sizes and higher power applications.

Acknowledgements

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