Design of a Nonisolated Fuel Cell Boost Charger for Lithium Polymer Batteries With a Low Output Ripple

Van-Long Tran, Ngoc-Tham Tran, Sun-Ho Yu, Yongjin Park, and Woojin Choi, Member, IEEE

Abstract—In the design of a fuel cell charger, it is important to find a suitable topology and to design the converter to guarantee the performance of both the fuel cell and the battery. Most of the chargers developed so far have used step-down converters. However, since a small fuel cell stack can only generate a low voltage, it is necessary to use a step-up converter to charge batteries. In this paper, a nonisolated boost charger topology with an additional output inductor for a proton exchange membrane fuel cell is presented to meet the strict ripple requirements for the battery charge, and its control method using a proportional-integral (PI) controller is detailed. The feasibility of the boost charger and its control method is then verified through the experimental results.

Index Terms—Proton exchange membrane (PEM) fuel cell, lithium-polymer battery, nonisolated boost charger, proportional-integral (PI) controller.

I. INTRODUCTION

NOWADAYS, portable electronic devices such as portable computers, media players and smart phones are becoming more and more developed and diversified. The energy density requirement for the power sources of these devices is ever on the increase. Many technology companies are working to find ways to enhance the run time of these mobile devices. However, battery technology has not caught up with the development of electronic devices with the higher power consumption [1], [2].

To meet the energy and power density demands of mobile applications, it is desirable to achieve a specific energy of more than 500 W · h/kg, an energy density of more than 1000 W · h/L and a specific power of no less than 50 W/kg. In addition, the typical power levels in mobile applications vary from 1 to 60 W with a run time varying from 10 to 100 h [3]. Unfortunately, this requirement can be barely achieved with the most advanced battery technology developed so far.

The small fuel cell is emerging as a promising solution for power hungry devices to provide a sufficient run time. They are being developed and improved faster to catch up with the developments in the portable electronics sector. However, since a fuel cell requires start-up power for its balance-of-plant and takes some time to generate power, it would be desirable to use it as an auxiliary power source for charging batteries. For portable power systems, it is essential that they must be designed in light and compact forms including the power electronics [4], [5].

Most of the chargers developed so far have used step-down converters to adjust the high ac voltage to the low dc voltage suitable for charging batteries. However, since fuel cells exhibit low voltage characteristics, a boost type converter is required to charge the batteries. Among the many different topologies, the nonisolated boost converter can be a good candidate for a battery charger due to its compactness, lightweight, simplicity of the circuit and low cost [6], [7]. However, the nonisolated boost converter is rarely used for charge applications in spite of its advantages due to its inherent high ripple current at the output [8], [9]. In addition, the ripple current is barely filtered out by the output capacitor of the nonisolated boost converter, rather it is absorbed by the battery due to the even larger capacitance in the equivalent circuit of the battery. This ripple current has an undesirable effect on battery life because it interacts with the internal ac impedance of the battery thereby causing internal heating [10], [11]. As a result, battery manufacturers make strict recommendations in terms of the current ripple as well as the voltage ripple on the battery terminal during charging to guarantee the desired life of the battery. In case of a Li-Polymer battery, a maximum of 5% current ripple and 1% voltage ripple are allowed [11], [12]. In order to meet these requirements for a battery with a conventional nonisolated boost converter, the reactive components in the circuit have to be unnecessarily large, which is not acceptable. There have been many approaches to mitigate the ripple between the inverter and grid by employing a filter such as L, L–C, L–C–L, etc., in order to meet the strict filtering tolerances suggested by the standards such as IEEE 519-1992 and IEEE P1547.2-2003. Among the methods inserting an inductor in between the inverter and grid would be a simplest means to compensate the modulation effect and harmonics from the inverter to the grid [13]–[15].

The method can also be used for the battery charger to satisfy the strict ripple requirements suggested by the battery manufacturer by making the dc–dc converter as a unipolar current source. In [16] and [17], an additional inductor is employed in between the buck converter and the load to attenuate the output ripple effectively. However, the stability of the converter can hardly be insured without the cost of the complexity in the control due to the instability which may be caused by the L–C–L filter at the output.
In this paper, an output inductor is employed in between the nonisolated boost converter and the battery in order to reduce the ripples and attenuate the high frequency harmonics generated by the switching. It may be disadvantageous that the volume, weight, and cost of the converter are increased little bit. However, it is advantageous since this can prevent the need to employ a transformer or an unnecessarily large output capacitor to meet the ripple requirements for the charging of a battery. In addition, unlike the conventional methods since the additional inductor and the output capacitor form a $\text{C–L}$ filter, it is also advantageous that the proposed method does not require a complex control algorithm to eliminate the resonant component. The control-to-output transfer functions are derived including the equivalent circuit model of a lithium-polymer battery. Unlike the conventional boost converter, PI controllers can be used to control the output current and voltage to implement constant current (CC) and constant voltage (CV) mode charging. The experimental results verify the feasibility and validity of the boost charger and its control method.

II. Structure of the PEM Fuel Cell Boost Charger for Lithium Polymer Batteries

Fig. 1 shows a block diagram of the small proton exchange membrane fuel cell (PEMFC) charge system for the lithium-polymer batteries of portable devices. The PEM fuel cell stack is composed of ten cells and its output voltage varies from 6 to 10 V with a maximum power of 180 W as shown in Fig. 2. The Li-Po battery pack configuration is 3S3P. This means that three cells are in series and three strings of these are in parallel with an 11.1 V nominal voltage and a 12 A nominal current. The charger is required to charge the battery at a 6 A (0.5 C) charge current and a 12.6 V charge voltage using the typical CC/CV charge mode.

Fig. 3 shows the charge profile of a Li-Po battery pack using the CC/CV mode charge method by using a dc power supply. This method offers a fast charge for the Li-Po battery and guarantees the maximum lifetime of the battery. The charge process starts with the CC mode which continues until the battery voltage reaches the limited charge voltage. Then, the battery is switched to the CV mode which continues until the charge current decreases to below 0.03 C [12], [18]. A simple $R–C$ equivalent circuit model of a Li-Po battery can be derived by using (1) and (2) [19], [20]. The model will be included in deriving the control-to-output transfer function of the converter for the battery charge.

As shown in (1), due to the huge capacitance in the equivalent circuit model of a Li-Po battery, the output ripple current can barely be filtered out by the output capacitor. Thus, it can be easily seen that in order to use the nonisolated boost converter for battery charge applications, some modifications are required to meet the output ripple current limit for a battery during charging to avoid employing an unnecessarily large output capacitor.

$$C_b = \sum_{n=1}^{\infty} \frac{(I_{n+1}+I_n)}{2} \frac{\Delta t_n [s]}{12.6[V] - 10.8[V]} = 21500 \text{ F} \tag{1}$$

$$R_b = \frac{\tau}{C_b} = \frac{2490}{21500} = 0.116 \text{ Ω} \tag{2}$$
a commercially available electrolytic capacitor from Samyoun is found to be 49 mΩ with a 1000 μF capacitance [22]. Thus, in order to satisfy the output ripple requirements, it is necessary to use at least 12 capacitors connected in parallel, which results in an unnecessarily bulky converter.

In the boost charger, an additional inductor is adopted between the output capacitor and the battery in order to reduce the size and cost of the output filter as shown in Fig. 4. In the boost converter with an additional output inductor, it is necessary to connect only three capacitors in parallel considering the rated RMS value of the ripple current of the previous selected capacitors (2.25 A) since the RMS ripple current of the output capacitor can be calculated as 6.3 A by using:

\[ I_{C(RMS)} = I_o \sqrt{\frac{D}{1-D}}. \]  

(5)

The output inductor plays a major role in satisfying the output ripple requirement in the boost charger, and its detailed design procedure is as follows:

\[ \Delta v_o = \Delta i_o R_b \]  

(6)

\[ \Delta v_o^\% = \Delta i_o^\% \left(1 - \frac{V_{C_1}}{V_o}\right). \]  

(7)

Due to the huge capacitance in the battery equivalent circuit model, the relationship between the output voltage ripple and the output current ripple can be derived as (6) and (7).

The voltage at the output capacitor can be shown as (8) by using Kirchhoff’s voltage law (KVL)

\[ v_c(t) = v_o(t) + v_{Lc}(t). \]  

(8)

The magnitude of the ripples can be expressed as (9) during the switch-on time period

\[ L_o \frac{\Delta i_o}{DT_s} + \Delta v_o = \Delta v_c. \]  

(9)

Thus, the required output inductor to meet the output voltage ripple and output current ripple limit can be calculated based on (9) as

\[ L_o = \frac{(\Delta v_c - \Delta v_i)D}{\Delta i_o f_s}. \]  

(10)

The specifications for the fuel cell charger and all of the converter parameters calculated by using the previous equations are summarized in Table I.

### III. Steady-State Characteristics of the Boost Charger

Fig. 4 shows an equivalent circuit of the nonisolated boost converter with an additional output inductor when the switch is ON and OFF. The basic operation of the nonisolated boost converter with an additional inductor is the same as the conventional one. In this circuit, only the equivalent series resistor (ESR) of the Li-Po battery and the output capacitor are shown for simplicity of the analysis since the equivalent resistors of the other components are small and do not affect the circuit operation much. It is well known that the input inductor has to be designed based on the desired output ripple current value of the PEM fuel cell stack [21]. The minimum inductance value required to limit the fuel cell output current ripple at a certain value can be calculated by using

\[ L = \frac{V_o D}{I_o \Delta i_o f_s}. \]  

(3)

In addition, the relationship between the output capacitor and its voltage ripple can be found as (4) by performing the circuit analysis while the switch is ON, which is the same the conventional nonisolated boost converter

\[ \Delta v_c = \frac{(V_o - V_{C_1})D}{CR_b f_s} + \left(\frac{I_o}{f_s} + \frac{\Delta i_o}{2}\right) R_c. \]  

(4)

It can be noticed from (4) that the output voltage ripple can be easily reduced by paralleling the capacitors since it is proportional to the ESR of the capacitor and inversely proportional to the capacitance. Since the first term of the right side of (4) is smaller than the second term, the output voltage ripple mainly depends on the ESR of the capacitor. Thus, in order to satisfy a 0.5% (63 mV) output voltage ripple the ESR of the output capacitor must be far less than 4.2 mΩ since the maximum average current of the front-end inductor \( (L) \) is calculated as 15 A when the fuel cell stack delivers the maximum output power at the minimum output voltage, 6 V. The minimum ESR value of

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TABLE I
SPECIFICATION OF THE BOOST CHARGER FOR Li-Po BATTERY

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rating</td>
<td>90 W</td>
</tr>
<tr>
<td>Input voltage, $V_S$</td>
<td>6–10 V</td>
</tr>
<tr>
<td>Charge voltage, $V_c$</td>
<td>12.6 V</td>
</tr>
<tr>
<td>Charge current, $I_o$</td>
<td>6 A</td>
</tr>
<tr>
<td>Switching frequency, $f_S$</td>
<td>300 kHz</td>
</tr>
<tr>
<td>Input inductor, $L_o$</td>
<td>45 μH</td>
</tr>
<tr>
<td>Output inductor, $L_o$</td>
<td>0.7 μH</td>
</tr>
<tr>
<td>Output capacitor, $C_o$</td>
<td>3000 μF</td>
</tr>
<tr>
<td>Battery resistor, $R_b$</td>
<td>0.116 Ω</td>
</tr>
<tr>
<td>Battery capacitor, $C_b$</td>
<td>21 500 F</td>
</tr>
<tr>
<td>Output voltage ripple, $\Delta V_{o}$</td>
<td>63 mV (0.5%)</td>
</tr>
<tr>
<td>Output current ripple, $\Delta i_L$</td>
<td>60 mA (0.5%)</td>
</tr>
<tr>
<td>Output current ripple of the PEMFC, $\Delta i_\ell$</td>
<td>300 mA (2.5%)</td>
</tr>
</tbody>
</table>

By replacing the control parameters, input and state variables with a dc steady-state value and a small time-varying component; neglecting the small-signal and the dc products; and treating the dc steady-state values as constant parameters, (11)–(14) can be rewritten as

$$
\frac{d\tilde{v}_L}{dt} = \tilde{v}_s - (1 - \tilde{d}) \left( \tilde{v}_o + L_o \frac{d\tilde{i}_o}{dt} \right) \frac{L}{L}
$$

$$
\frac{d\tilde{v}_c}{dt} = \frac{d}{dt} \left( \tilde{v}_o + L_o \frac{d\tilde{i}_o}{dt} - R_c \tilde{i}_c \right) = \tilde{i}_c \frac{C}{C}
$$

$$
\tilde{i}_c = (1 - \tilde{d})\tilde{i}_L - \tilde{i}_o
$$

$$
\tilde{v}_o = \frac{1}{C_b} \int \tilde{i}_o dt + \tilde{i}_o R_b.
$$

By taking the Laplace transformation of (15)–(18), (19) to (22) can be obtained as follows:

$$
\tilde{i}_L = \tilde{v}_s - (1 - D)\tilde{v}_o + V_o \tilde{d} - sL_o(1 - D)\tilde{i}_o
$$

$$
\tilde{v}_c = \tilde{v}_o + sL_o \tilde{i}_o - R_c \tilde{i}_c = \frac{\tilde{v}_e}{sC}
$$

$$
\tilde{i}_c = (1 - D)\tilde{i}_L - I_L \tilde{d} - \tilde{i}_o
$$

$$
\tilde{v}_o = \tilde{i}_o \left( R_b + \frac{1}{sC_b} \right).
$$

Since the average voltage of the output inductor is equal to zero, (13) can be rewritten as

$$
I_L = \frac{I_o}{1 - D} = \frac{V_o - V_{C_b}}{R_b (1 - D)}.
$$

The control-to-output voltage transfer function of the boost charger can be obtained as (24) by substituting (20)–(23) into (19)

$$
G_{v_o \mid V_s = 0} = \frac{\tilde{v}_o}{\tilde{d}} \bigg|_{V_s = 0} = \frac{G_{v_o} (1 + \frac{\omega}{\omega_{ESR}}) \left( 1 + \frac{\omega}{\omega_{RHPZ}} \right)}{b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0}
$$

where

$$
G_{v_o} = \frac{V_o}{1 - D} \omega_{RHPZ} = \frac{R_b}{L \left( 1 - \frac{V_o}{V_{C_b}} \right)} (1 - D)^2; \quad \omega_h = \frac{1}{R_b C_b};
$$

$$
\omega_{ESR} = \frac{1}{R_c C}\frac{b_o}{1}; \quad b_1 = R_c C + R_b C_b;
$$

$$
b_2 = \frac{L(C + C_b)}{(1 - D)^2} + R_b R_c C C_b + L o C b
$$

$$
b_3 = \frac{(R_b + R_o)LCC_b}{(1 - D)^2} + R_c L o C C_b; \quad b_4 = \frac{LL_o C C_b}{(1 - D)^2}.
$$

Due to the huge capacitance in the equivalent circuit model of the battery, the voltage variation at $C_b$ during a small period of time can be neglected. Thus, the control-to-output current transfer function of the boost charger can be easily derived with (22) as

$$
\frac{\tilde{i}_o}{\tilde{d}} = \frac{1}{R_b} \times \tilde{v}_o \tilde{d}.
$$

The control-to-output current transfer function of the boost charger can be written as (26) by using (24) and (25)

$$
G_{i_o \mid V_s = 0} = \frac{\tilde{i}_o}{\tilde{d}} \bigg|_{V_s = 0} = G_{i_o} \times \frac{\left( 1 + \frac{\omega}{\omega_{ESR}} \right) \left( 1 + \frac{\omega}{\omega_{RHPZ}} \right)}{b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0}
$$

where

$$
G_{i_o} = \frac{V_{C_b} + I_o R_b}{R_b (1 - D)}
$$

Fig. 5. Small-signal model of the nonisolated boost charger in CCM.
In order to verify the control-to-output transfer functions of the boost charger with an additional output inductor and the battery model, Bode plots of the control-to-output voltage and control-to-output current transfer functions were drawn by using PSIM software as shown in Fig. 6. The Bode plots shown in the solid lines were drawn by using (24) and (26), and the Bode plots shown in the dotted lines were drawn by using the ac sweep function in PSIM. As seen in Fig. 6, the results are well matched with each other, thereby verifying the correctness of the derived transfer functions.

Fig. 7 shows Bode plots of the control-to-output voltage transfer function for the conventional boost converter with a pure resistive load and the boost charger with an additional output inductor and the battery model, where both converters have the specifications given in Table I. As shown in Fig. 7, the phase change of the conventional boost converter is stiff at the resonant frequency due to a double pole located at the origin as shown in Fig. 8. As a result, the crossover frequency is typically selected in a narrow band between a third and a fifth of the right-half-plane-zero (RHPZ) frequency, where the phase lag is around $-180^\circ$ to guarantee the stability of the system under load changes [24], [25]. In addition, a 3-pole/2-zero (Type III) controller should be used to provide enough phase margin at the crossover frequency in the design of the controller for the conventional boost converter.

However, in the boost charger with an additional output inductor and a battery model, it is observed that the resonant peak and the stiff phase change have been smoothed as shown in Fig. 7. This is mainly due to the small ESR of the battery model which causes a pole-zero doublet (at $6.38 \times 10^{-5}$ Hz) close to the origin together with the huge capacitance in the model as shown in Fig. 8. As a result, in between a third and a fifth of the RHPZ frequency on the Bode plot of the boost charger with an additional output inductor, the phase margin is around 60–90° which is enough to make the closed system stable. Thus, the controller does not require a zero at the crossover frequency to boost the phase. It only requires one pole at the origin in order to increase the gain in the low frequency band, and one zero to place the crossover frequency at the desired position. Thus, unlike the design of the controller for the conventional boost converter, a PI controller can be used to compensate the loop for the control of the output current and output voltage, thereby successively implementing the CC/CV charge function in the boost charger with an additional output inductor. Since the additional output inductor causes a pole, it provides a stronger high frequency attenuation and also helps limit the ringing on the switch node.

It should be noticed that in the boost charger the RHPZ frequency is varied according to the variation of the input voltage...
Fig. 9. Li-Po battery voltage curve in CC/CV charge mode.

Fig. 10. Variation of the RHPZ frequency of the control-to-output current transfer function in the boost charger with an output inductor according to the variation of the input voltage and the terminal voltage of the battery.

Fig. 11. Variation of the RHPZ frequency in the control-to-output voltage transfer function of the boost charger with an output inductor according to the variation of the input voltage and the terminal voltage of the battery.

and terminal voltage of the battery over a whole charge period as in (24) and (26). In order to design the controller properly, it is necessary to observe the variation of the RHPZ frequency at each charge mode to guarantee the stability of the system. This issue will be discussed in detail in the following section.

V. DESIGN OF THE CONTROLLER CONSIDERING VARIATIONS OF THE RHPZ FREQUENCY OF THE BOOST CHARGER

Fig. 9 illustrates the popular CC/CV mode charge profile for a lithium-polymer battery. It is well known that the CV mode charge is required to fully charge the battery due to the existence of the ESR of the battery. Thus, the changeover voltage from the CC mode to the CV mode has to be calculated based on the value of the CC charge current (6 A in this case), the ESR (116 mΩ) and the nominal voltage of the battery. It can be easily derived from (23) as

\[ V_{CB} = V_o - I_o R_b = 12.6 - 6 \times 0.116 = 11.9 \text{ V}. \]  

(27)

In order to observe the variation of the RHPZ frequency of the control-to-output current transfer function of the boost charger, equation (28) has been derived by rewriting (26)

\[ f_{RHPZ} = \frac{V_o^2}{2\pi L V_o (V_o - V_{CB})}. \]  

(28)

Fig. 10 shows the variation of the RHPZ frequency in the control-to-output current transfer function of the boost charger with an additional output inductor according to the variation of the input voltage and the terminal voltage of the battery drawn by using (28). As can be seen in Fig. 10, the lowest value of the RHPZ frequency is 1.6 kHz when the input voltage is at its minimum value (6 V) and the terminal voltage of the battery reaches 11.9 V at the end of the CC charge mode. Thus, the bandwidth of the charger in the CC mode has to be lower than 1.6 kHz/3 to guarantee the stability of the system.

Similarly, in order to observe the variation of the RHPZ frequency in the control-to-output voltage transfer function of the boost charger, equation (29) has been derived by rewriting (24)

\[ f_{RHPZ} = \frac{R_b V_o^2}{2\pi L (V_o - V_{CB})}. \]  

(29)

Fig. 11 shows the variation of the RHPZ frequency in the control-to-output voltage transfer function of the boost charger with an additional output inductor according to the variation of the input voltage and terminal voltage of the battery drawn by using (29). As can be seen in Fig. 11, the lowest value of the RHPZ frequency is 1.6 kHz when the input voltage and terminal voltage of the battery are at their minimum values (6 and 11.9 V) at the beginning of the CV charge mode. Thus, the bandwidth of the charger in the CV mode has to be lower than 1.6 kHz/3 to guarantee the stability of the system. In conclusion, the bandwidth of the charger has to be lower than 1.6 kHz/3 in both the CC and CV charge modes and the phase margin in this case is about 60° as shown in Fig. 6. Since the phase margins are already enough to make the closed-loop stable at the crossover frequency in both charge modes, a PI controller can be applied to the boost charger with an additional output inductor and R–C battery model.

VI. DESIGN OF THE OUTPUT VOLTAGE AND OUTPUT CURRENT CONTROLLER OF THE BOOST CHARGER USING A PULSE WIDTH MODULATION ANALOG IC MAX745

A commercial IC MAX745 provides all of the functions necessary for implementing the charger of the Lithium battery packs. It provides separate CC and CV charge functions.
to fully charge the battery. The input voltage of the IC ranges from 6 to 24 V, and its pulse width modulation (PWM) operates at 300 kHz [26]. This is suitable for implementing the fuel cell charger to charge a 9 cell Li-Po battery (3S3P) pack at 6 A (0.5 C).

Fig. 12 shows a block diagram of the CC/CV charge control algorithm for the boost charger with a MAX745 PWM controller. Each loop works independently according to the state of charge of the battery. It should be pointed out that unlike the conventional boost converter, PI controllers are used to control the current and voltage. In the charge process, a comparator (comp1) compares the saw-tooth waveform ($V_m$) to the output of the voltage controller ($G_{vc}$) or the current controller ($G_{ic}$) to generate a PWM signal for gating the semiconductor switch. Another comparator (comp2) compares the output of the two controllers and the charge mode is selected depending on the magnitude of the output from the controller. When the output of the current controller is smaller than that of the voltage controller, the system will work in the CC mode and vice versa. While the current is in regulation, the output voltage of $G_{vc}$ is clamped at less than $G_{ic} + 80$ mV to prevent the battery voltage from overshooting when the charge mode is turned over to the CV mode [26].

In order to implement an external PI controller for the Max 745 IC, the internal error amplifiers, GMI and GMV, need to be voided by applying the same current and voltage feedback signals to their positive terminals. Then, the output of each external PI controller can be applied to the CCV and CCI pins of the IC, respectively, as shown in Fig. 13. The reference signals for the current and voltage controls are utilized by the PWM logic block to generate the PWM waveforms for the MOSFET switch.

Figs. 14 and 15 show the design of the PI controller for the boost charger with the additional inductor using MATLAB software. For the design of the control-to-output voltage and control-to-output current loops, PI controllers are used to improve the gain at the low frequency range and to place the crossover frequency at the desired position in the frequency domain. In the output voltage control loop, the phase margin is 56.1° at a crossover frequency of 501 Hz, and in the current control loop the phase margin is 56.2° at a crossover frequency of 502 Hz. Both loops can be successfully stabilized with PI controllers.
VII. OPERATION OF THE PEM FUEL CELL BOOST CHARGER

The presented fuel cell charger has four main operation modes. Each operation mode can be described simply by using Fig. 16 as follows.

1) Mode 0 (charge only): In this mode, the boost charger charges the battery by CC/CV mode until it gets fully charged. The power from the fuel cell is used only for charging the battery.

2) Mode 1 (charge and supply): In this mode, the charger can charge a battery and supply power to the load. When the load current \( I_{\text{Load}} \) is smaller than the rated charge current (6 A, 1 C), the charger supplies power to the load and the rest of the available power is used for charging the battery. In this case, the output voltage is the same as the battery terminal voltage which varies from 11.1 to 12.6 V.

3) Mode 2 (supply only): When the load current becomes equal to the charge current (6 A), all of the power from the charger is supplied to the load while no power is used for charging the battery. This mode of operation also occurs after the battery is fully charged since no power is required to charge the battery.

4) Mode 3 (hybrid supply): When the load current is higher than the charge current (6 A), the power from the charger is not sufficient to supply the load. In this case, the charger supplies power to the load together with the battery.

VIII. EXPERIMENT RESULTS OF THE BOOST CHARGER WITH A PEMFC STACK

Fig. 17 shows the experimental setup for testing the boost charger with a PEMFC stack, a Li-Po battery pack, and an electronics load.

Fig. 18 shows the ripples of the charge current and charge voltage of the Li-Po battery when it is being charged by the PEMFC stack and the boost charger with an additional output inductor. As shown in the figures, both the output current and the voltage ripples are less than 0.5% which can satisfy the ripple requirements recommended by the manufacturer of the Li-Po battery.

Fig. 19 shows the CC/CV charge profiles of the Li-Po battery pack with a 6 A (0.5 C) charge current and a 12.6 V charge voltage when it is being charged by the boost charger and the PEMFC stack under the mode 0 operation. As shown in Fig. 19, the boost charger works fine and it takes about 3 h to fully charge the battery when it is discharged completely. When the charging current of the battery pack decreases to 0.24 A (0.02 C), the charge process is complete.

Fig. 20 shows the dynamic characteristics of the boost charger when an output current load is applied to the charger during the CV mode. At the beginning of the charge, the battery is being charged by the CC mode and the CV mode is followed. At \( t_1 \), a 12 A current load is applied to the system while the battery is being charged in the CV mode. The mode of operation switches from modes 0 to 3 in this case. As shown in Fig. 20, since
the output current of the charger is limited by 6 A, the battery discharges 6 A to supply the 12 A load together with the fuel cell.

Fig. 21 shows the dynamic characteristics of the boost charger when a pure resistive load (4.2 Ω) is applied during the mode 0 (CV mode charge) operation.

As shown in Figs. 20 and 21, the charge system can work properly under varying load conditions.

IX. CONCLUSION

In this paper, a nonisolated boost charger topology for PEM fuel cell applications has been presented and its feasibility and validity have been verified through experiments. Due to the additional inductor, the output current and voltage ripple can be successfully attenuated to meet the suggested ripple limits with a small number of capacitors connected in parallel. Unlike the conventional nonisolated boost converter, the boost charger with an additional output inductor can be controlled by a PI controller, which can be easily implemented by using a commercially available PWM IC such as a MAX745.

REFERENCES


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