High Efficiency DC-DC Converter using a Series-Parallel Compensation Method for a Fuel cell

Koji Orikawa, Jun-ichi Itoh
NAGAOKA UNIVERSITY OF TECHNOLOGY
1603-1 Kamitomioka-cho
Nagaoka city Niigata, Japan
Tel./Fax: +81 / (258) .47.9533.
E-Mail: itoh@vos.nagaokaut.ac.jp
URL: http://itohserver01.nagaokaut.ac.jp/itohlab/index.html

Keywords

«DC power supply», «Converter control», «Fuel cell system»

Abstract

This paper proposes a novel DC-DC converter for a hybrid power supply using both a fuel cell and a battery. In the proposed circuit, the power converter with the battery is connected in series to the fuel cell. The output voltage is controlled by a series converter that regulates only the differential voltage between the fuel cell voltage and the output voltage. The power rating of conventional buck-boost DC-DC converters are dominated by the input voltage or the output voltage. In contrast, since the voltage rating of the proposed circuit requires the differential voltage between the fuel cell voltage and the output voltage, the power rating of the proposed circuit is smaller than that of the conventional converters.

In addition, in order to suppress large current ripple in the fuel cell, a parallel converter is added to the series converter. The experimental results confirmed that the proposed circuit could achieve 98.8% at the maximum efficiency point in the small differential voltage region.

I. Introduction

Recently, most mobile electronic devices use batteries as a power source. The mobile electronic devices are developed with increasingly high performance and functionality, accompanied by increasing power consumption and the demand for longer operation times. The efficiency of DC-DC converters become an important issue in terms of longer operation times for these devices. Resonant type converter, which use zero voltage switching or zero current switching, is one of the most effective circuit topologies to obtain high efficiency [1-2]. However, the conventional DC-DC converter needs to convert all the power regardless of the output voltage because the conventional converter is connected in parallel to a power supply and a load.

On the other hand, the fuel cell systems are being developed as a new power supply for mobile devices. Many circuit topologies of DC-DC converters for fuel cell applications have been studied in order to obtain high efficiency [3-5]. In Ref. [3], cascade converter topologies, which compensate differential voltage between the fuel cell voltage and the output voltage, is a good solution to obtain high efficiency. However, one of the problems of these converters is that the fluctuation of the output current is the same as the fluctuation of the fuel cell current due to the series connection. The output power of a fuel cell should be constant, because quick power fluctuations of a fuel cell reduce its life time. As a result, the series converter reduces the life time of the fuel cell although the output voltage can be controlled.

A fuel cell requires a battery or an electric double layer capacitor (EDLC) to compensate the dynamic response, because it cannot respond to quick load fluctuations. A hybrid power supply using both the fuel cell and battery also requires high efficiency, downsizing, and quick response to load fluctuations.

Nowadays, hybrid power supplies using both the batteries and fuel cells are being actively studied [6-9]. One of the popular circuit configurations consists of two boost choppers for the fuel cell and battery, and a buck chopper for output voltage regulation. When the load condition causes a change in the terminal voltage of the fuel cell, the operation of the buck chopper regulates the output voltage effectively. The buck mode operation is also used to save the power consumption of the load circuit. The battery supports the control response of the fuel cell through the boost chopper. However, this system can not achieve high efficiency because the power is converted twice between the fuel cell and the output, resulting in an increased of power loss.

In this paper a novel DC-DC converter is proposed for a hybrid system using both the fuel cell and battery. The proposed system consists of a series converter and a parallel converter to control the input current and the output voltage respectively. The same concept has been proposed for an uninterruptible power system (UPS) [10] to control the input current and the output voltage. The input current is controlled by a parallel converter and the output voltage is controlled by a series converter. This paper applies the same concept to a DC-DC converter using both the fuel cell and battery.

In the proposed circuit, the series converter generates a positive and negative voltage to achieve boost and buck operation. As a result, high efficiency is obtained, because the power rating of the DC-DC converter can be drastically reduced [11]. On the other hand, the parallel converter with a battery compensates the quick response according to the load fluctuations. A control strategy is also proposed to achieve both the quick response of the load and slow power fluctuation of the fuel cell. Finally, the experimental results are presented to demonstrate the advantages of the proposed converter in comparison with a conventional circuit.

II. CONCEPT OF PROPOESD CIRCUIT

A. Series compensation

Figure 1(a) presents a block diagram of a conventional buck-boost chopper. These converters convert all the input power, which is not dominated by the relations between the input and output voltage. In particular, when the input voltage V_{in} is close to the output voltage V_{out}, the duty ratio D of a single stage buck boost chopper is obtained by (1), using switch on time t_{on}, and off time t_{off}.

$$D = \frac{t_{on}}{t_{on} + t_{off}} = \frac{V_{out}}{V_{in} + V_{out}} = 0.5 \tag{1}$$

In this case, switching devices should be operated regardless of the relations between the input voltage and the output voltage. Besides, the energy for the output should be charge by an intermediate reactor or capacitor. As a result, the converter efficiency will decrease.

Figure 1(b) shows a block diagram of the series compensation converter, which is connected in series to the power supply. The series converter outputs only the differential voltage between the fuel cell voltage and the output voltage. Therefore, when the fuel cell voltage is close to the output voltage, the output power of the series converter becomes smaller. The small output power means a small loss even if the efficiency is not so high. In particular, when the fuel cell voltage agrees with the output voltage, the output power is directly provided by the fuel cell without switching operation; therefore, high efficiency is obtained by the series compensation circuit, although fluctuation of the output current directly becomes a fluctuation of the fuel cell current due to the series connection, which decreases the lifetime of the fuel cell. A voltage ripple of the fuel cell occurs due to the internal impedance in the fuel cell.

B. Series-parallel compensation

Figure 1(c) shows a block diagram of the proposed series-parallel compensation converter. In the proposed circuit, the parallel converter is connected in parallel to the fuel cell. When the output power is constant, the parallel converter does not operate, and the series compensation method can obtain high efficiency. The output voltage V_{out} is obtained by (2), using series converter output voltage V_{conv} and the fuel cell voltage V_{fc}.

$$V_{out} = V_{fc} \pm V_{conv} \tag{2}$$

When the load condition is changed, the parallel converter will compensate the quick variation of the fuel cell current. The fluctuation of the output power is compensated by the battery through the operation of that parallel converter. In addition, when the battery voltage is decreased or overcharged, either the battery will be charged from the fuel cell or the battery supplies the power to the load through the operation of that parallel converter.

III. PROPOSED CURCUIT

A. Circuit configuration

Figure 2 shows the circuit configuration of the proposed circuit based on Fig. 1(c). The series converter uses a boost converter and a step-down converter. The series converter generates a positive and negative voltage according to the boost mode and buck mode, respectively. The output of the parallel converter is connected to the negative terminal of the fuel cell. The proposed circuit requires only two reactors, but the conventional circuit uses three reactors. To suppress the ripple current of the fuel cell, an inductor is connected in series to the fuel cell. The reactor is used as a boost reactor too when the boost mode is selected.

Figure 3(a) shows a block diagram of the proposed circuit for series compensation mode. In this case, the series converter works as a H-bridge converter. Figure 3(b), (c) present a block diagram of the proposed circuit for series-parallel compensation mode. When the load condition is changed, only the parallel converter operates. The series converter compensates the differential voltage between the fuel cell voltage and the output voltage, and the parallel converter compensates the quick variation of the fuel cell current. The battery voltage must be higher than the fuel cell voltage to prevent a rush current from the fuel cell to the battery.

B. Design of the proposed circuit

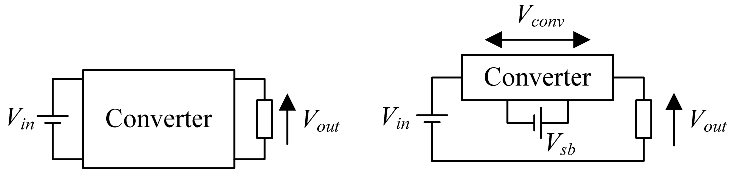
In the proposed circuit, the ripple current of the inductors becomes maximum value when the differential voltage between the fuel cell voltage and the output voltage is at maximum. The value of the ripple current of the inductor do influence on the lifetime of the fuel cell. The ripple current of the inductor Δi_{fc} is obtained by (3), using switch on time t_{on}.

$$\Delta i_{fc} = \frac{V_{fc}}{L_{fc}} t_{on} = \frac{V_{fc}}{L_{fc} f_{sw}} D_{boost} = \frac{V_{fc}}{L_{fc} f_{sw}} \frac{V_{out} - V_{fc}}{V_{sb}} \tag{3}$$

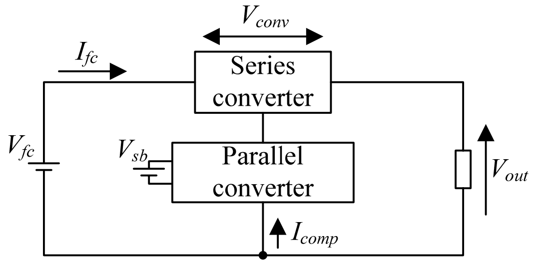
where L_{fc} is an inductor of the fuel cell side, and D_{boost} is the duty ratio in boost mode.

Table I shows the specifications for the proposed circuit. In case of Table I, the ripple current of the inductor becomes the maximum value when the fuel cell voltage is 4 V in boost mode. The value of the ripple current of the inductor is limited to 30% of the output current, and then the ripple current is 0.5 A since the output current is 1.67 A at the output power 12 W. In this condition, from (3), the inductance of the fuel cell side is calculated by (4).

$$L_{fc} = \frac{V_{fc}}{\Delta i_{fc} f_{sw}} \frac{V_{out} - V_{fc}}{V_{sb}} = \frac{4}{0.5 \times 100 \times 10^3} \frac{7.2 - 4}{11} = 23.3[\mu H] \tag{4}$$



(a) Conventional circuit. (b) Series compensation.



(c) Proposed circuit.

Fig. 1: Block diagrams of proposed converter in comparison with a conventional circuit.

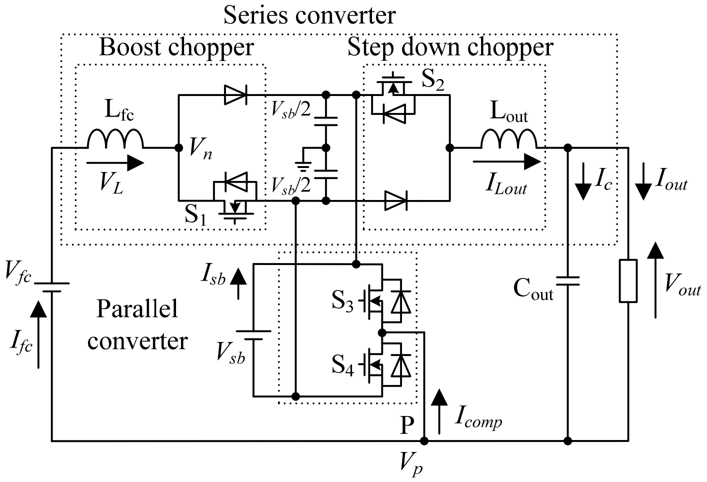
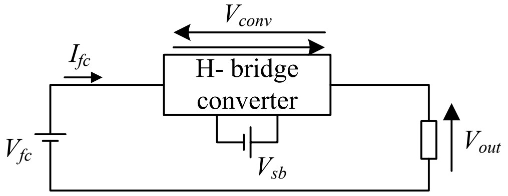
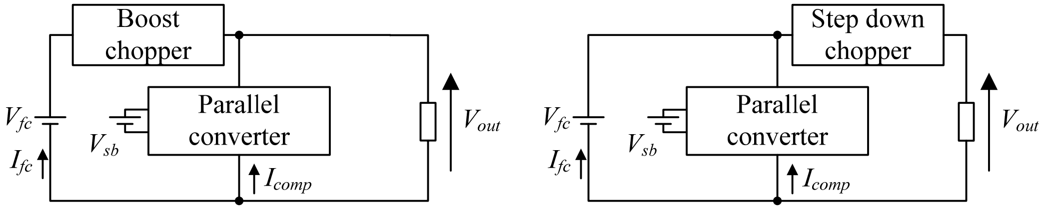


Fig. 2: Configuration of proposed circuit.



(a) Series compensation mode.



(b) Boost mode with parallel compensation.

(c) Step down mode with parallel compensation.

Fig. 3: Block diagram of proposed circuit.

Table I: Specifications for proposed circuit.

Fuel cell voltage V_{fc} (V)	4 to 10
Output power P_{out} (W)	12
Output voltage V_{out} (V)	7.2
Battery voltage V_{sb} (V)	11
Switching frequency f_{sw} (kHz)	100
Inductor current ripple (A)	30% of output current

IV. CONTROL STRATEGY

Figure 4 shows control diagrams of the proposed circuit. The proposed control method has two loops; the inner loop is for controlling the fuel cell current and the parallel converter current. As for the outer loop, it is for the output voltage control.

Operation between the series and parallel converter is constrained by the load condition in order to reduce the converter loss. In boost mode, the series converter works as a boost converter. That is, the switch S_2 maintains at on state. The difference voltage is then controlled by PWM modulation of S_1. In this case, the battery supplies the power to the load, because the differential voltage is positive. In buck mode, the series converter operates as a buck converter; switch S_1 maintains at off state. The differential voltage is then controlled by PWM of S_2. In this case, the battery is charged from the fuel cell, because the differential voltage is negative. Boost and buck modes are selected by the control signal of the series converter according to the relations between the fuel cell voltage and the output voltage. The switch S_3 and S_4 are for the parallel converter. The parallel converter works only when the load fluctuated. The parallel converter will be started when the load fluctuation is detected by the window comparator and is stopped after the time spends longer than the time constant of the LPF and HPF.

A. Output voltage control

The output voltage command of the series converter is calculated from the difference between the output voltage command and the fuel cell voltage. Where the voltage drop of the inductance and the on-resistance of FET can be negligible, the modulation index α for the series converter is obtained by (5), using the fuel cell voltage V_{fc} and the battery voltage V_{sb}, and the output voltage command V_{out}^*.

$$\alpha = 2\left(\frac{\left|V_{out}^* - V_{fc}\right|}{V_{sb}} - 1\right) \tag{5}$$

In order to improve the response and compensate the voltage error, the output voltage is regulated by an automated voltage regulator (AVR) using a proportional-integral (PI) controller. Then the output current command for the inner loop is output by the AVR.

Figure 5 shows control diagrams of the output voltage. When the response of the current control is much faster than the voltage control, the transfer function from the output voltage command to the output voltage V_{out} is obtained by (6):

$$\frac{V_{out}}{V_{out}*} = \frac{\frac{K_p}{C_{out}T_i}\left(1 + sT_i\right)}{s^2 + \frac{K_p}{C_{out}}s + \frac{K_p}{C_{out}T_i}} \tag{6}$$

where symbol "*s*" is Laplace operator, K_p is the proportional gain and T_i is the integral time constant of the PI regulator. Then, the K_p and T_i are given by (7), (8)

$$K_p = 2\zeta\omega_{v\_n}C_{out} \tag{7}$$

$$T_i = \frac{2\zeta}{\omega_{v\_n}} \tag{8}$$

where ζ is a damping factor, ω_{v_n} is a natural angular frequency for the output voltage control.

B. Current control

The current command is divided into the fuel cell current command and the compensation current command. Low pass filters (LPF) and high pass filters (HPF) are used to divide the current command. The LPF is used to separate the fundamental current fluctuation, for the slow response of the fuel cell. The HPF is used to separate the transient current fluctuation for the fast response of the battery. The HPF functions simultaneously with the LPF filter, as shown in Fig. 4. The time constants of the LPF and HPF are set to the same value.

The frequency responses of the LPF and HPF do not influence the output current response, as explained by the following. The relations between each current can be expressed by (9), using the fuel cell current I_{fc} and the parallel converter current I_{comp}.

$$I_{Lout} = I_{fc} + I_{comp} \tag{9}$$

The fuel cell current command I_{fc}^* and the parallel converter current command I_{comp}^* are obtained by (10) and (11)

$$I_{fc}^* = \frac{1}{1 + sT}I_{Lout}^* \tag{10}$$

$$I_{comp}^* = \frac{sT}{1 + sT}I_{Lout}^* \tag{11}$$

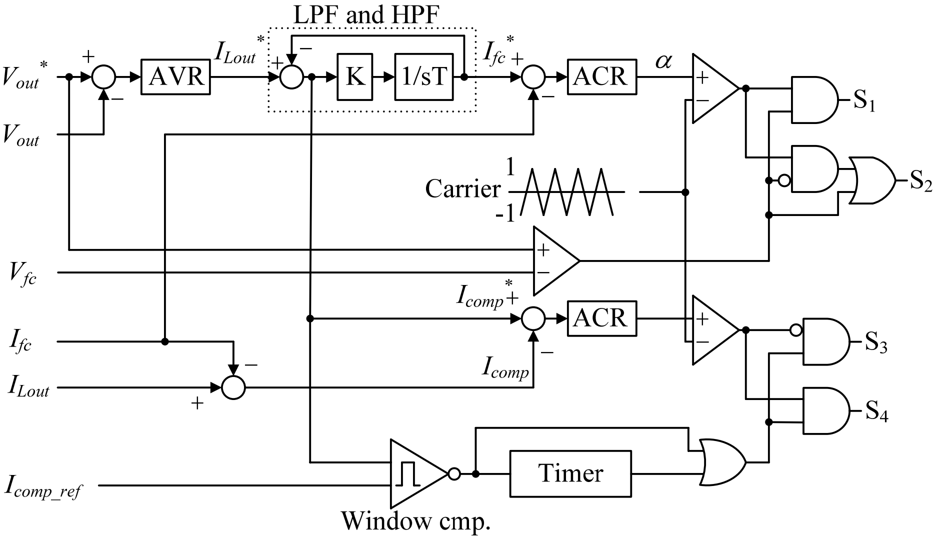


Fig. 4: Control diagram for the proposed circuit.

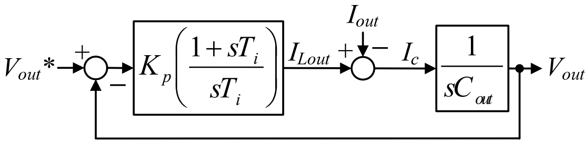


Fig. 5: Control diagrams of the output voltage.

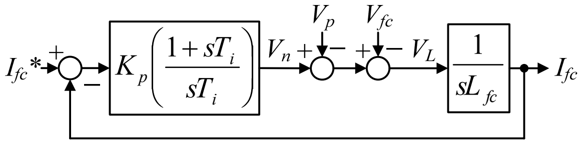


Fig. 6: Control diagrams of the fuel cell current.

where T is the time constant of the filter and I_{Lout}^* is the output current command. Therefore, the output current is obtained by (12).

$$I_{Lout} = G_1(s) I_{fc}^* + G_2(s) I_{comp}^* \tag{12}$$

where $G_1(s)$ and $G_2(s)$ are the transfer functions of the fuel cell current control and the parallel converter current control, respectively.

In addition, the output current is expressed by (13) when both current regulator designs for the fuel cell and parallel converter are the same.

$$I_{Lout} = G(s) I_{Lout}^* \tag{13}$$

where $G(s)$ is the transfer function of the output current control. That is, the time constant of the LPF or HPF does not appear in the transfer function of the output current control. In addition, the operation of the parallel converter is started by variation of the parallel converter current command I_{comp}^*. Then, operation of the parallel converter is stopped by a timer which is used to prevent a decrease in the efficiency of the proposed circuit.

Figure 6 shows control diagrams of the fuel cell current. The transfer function from the reference of the fuel cell current to the fuel cell current is described by (14).

$$\frac{I_{fc}(s)}{I_{fc\_ref}(s)} = \frac{\frac{K_p}{L_{fc}T_i}(1+sT_i)}{s^2 + \frac{K_p}{L_{fc}}s + \frac{K_p}{L_{fc}T_i}} \tag{14}$$

Then, the proportional gain K_p and the integral time constant T_i are given by (15), (16)

$$K_p = 2\zeta\omega_{i\_n}L_{fc} \tag{15}$$

$$T_i = \frac{2\zeta}{\omega_{i\_n}} \tag{16}$$

where ω_{i_n} is a natural angular frequency of the fuel cell current control. The natural angular frequency of the fuel cell current control and the parallel converter current control should be set to the same value. It is noted that the natural angular frequency of the current control is set to over than ten times of the voltage control in order to avoid the influence of the current control for the output voltage control.

V. EXPERIMENTAL RESULTS

The proposed circuit was tested under the experimental conditions shown in Table II. The response of the current regulator was designed as much higher than that of the LPF. It should be noted that the time constant was set to a shorter time in this experimental condition in order to confirm the effectiveness of the parallel converter. In order to reduce negative influence on the lifetime of the fuel cell, the time constant should be set to a few seconds.

Figure 7 shows the efficiency of the proposed circuit to confirm the effectiveness of series compensation. The experimental results confirmed that the proposed circuit could achieve 98.8% at the maximum efficiency point in the small differential voltage region. The output voltage is kept constant by the PI regulator. It should be noted that the output voltage waveform has no low frequency component and the fluctuation is in a steady state load.

Figure 8 shows the result of the loss analysis. In order to evaluate the power loss of the proposed circuit, the loss measurement and analysis for each part have examined. When the fuel cell voltage agrees with the output voltage, the maximum efficiency of the proposed circuit is obtained. This

Table II: Experimental conditions.

Fuel cell voltage V_{fc} (V)		4 to 10
Output voltage V_{out} (V)		7.2
Battery voltage V_{sb} (V)		11
Switching frequency f_{sw} (kHz)		100
Input reactor L_{in} (μH)		30
Output reactor L_{out} (μH)		30
Output capacitor C_{out} (μF)		801
ACR response (kHz)		1
LPF time constant (ms)		2.2
Load change (W)	Fig. 9(a), (b)	2 to 20
	Fig. 10(a), (b)	20 to 2

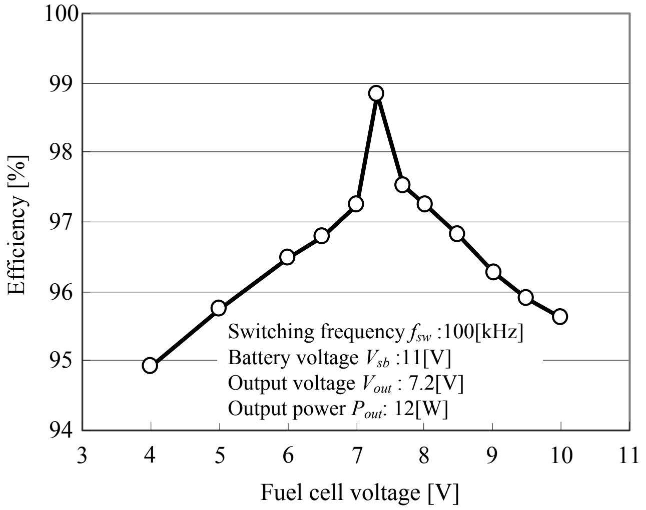


Fig. 7: Efficiency of the proposed circuit.

reason is that the output power is directly provided by the fuel cell without any switching operation. That is, the switching loss is zero. Besides, the proposed circuit provides higher efficiency than the conventional circuit even if each switch is controlled. This reason is explained as follows; in the small differential voltage region, the ripple current of the inductors are reduced because the reactor voltage is small. Therefore, the losses of the inductors are smaller than the conventional circuit. Especially, the iron loss in both the inductors becomes smaller.

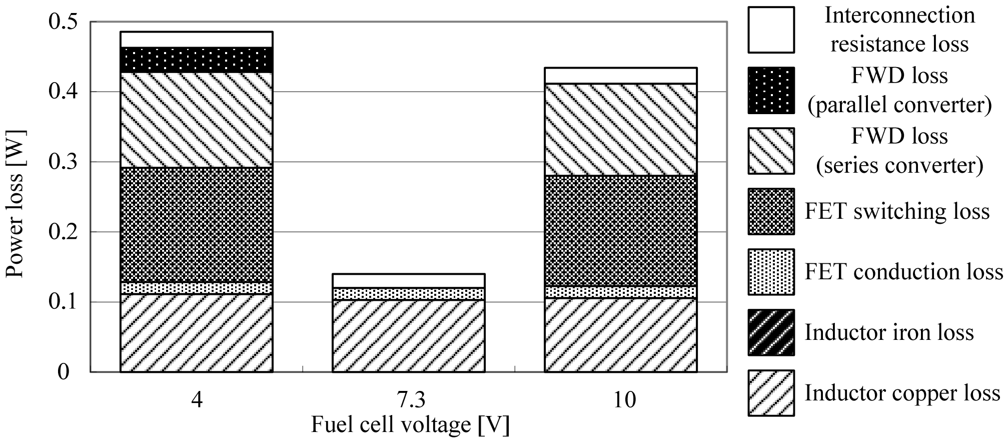


Fig. 8: Loss analysis.

Figure 9 and Figure 10 show comparisons of the fuel cell current and the output voltage with and without parallel compensation when the load condition is changed. In Fig. 9(a), the voltage drop of over 14% occurs at the point of the load change when the output power is increased by the load, where only series compensation applied. In addition, the fuel cell current is changed at high speed. In contrast, Fig. 9(b) shows that the variation of the fuel cell current is suppressed by parallel compensation. The output voltage drop of within 7% is achieved.

On the other hand, Fig. 10(a) shows the waveform without parallel compensation when the output power is decreased by the load. In this case, in Fig. 10(b), the variation of the output voltage is also suppressed by operation of the parallel converter. It should be noted that the spike current occurs due to the initial value of the integrator in the ACR of the parallel converter. This problem can be solved by improving the initial operation of the parallel converter.

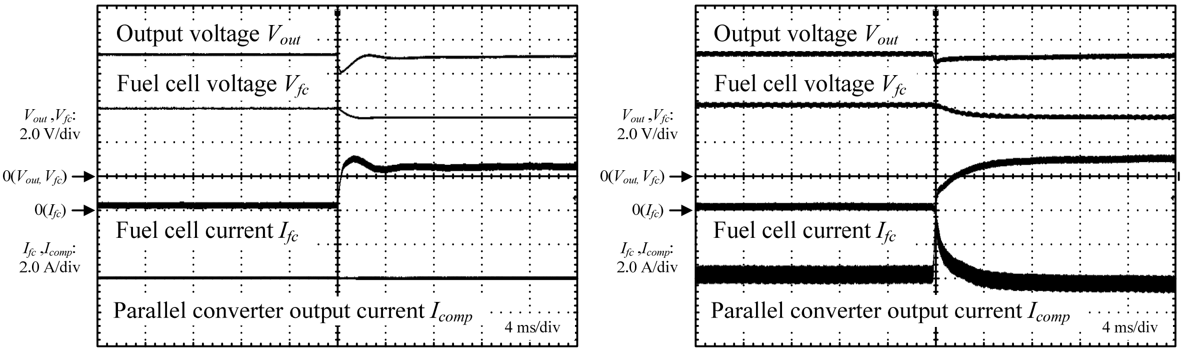
Overall, the experimental results confirm the validity of the series–parallel compensation method.

VI. Conclusion

A series-parallel compensation type DC-DC converter has proposed to achieve high efficiency, downsizing and longer lifetime of a fuel cell-battery hybrid system. When the output power is almost constant, the series converter provides only the differential voltage between the fuel cell voltage and the output voltage, while the parallel converter suppresses the variation of the fuel cell current. In addition, the control strategy combined a LPF and a HPF to suppress the quick load fluctuation has proposed. The share rate between the fuel cell and battery is controlled by time constant of the LPF and HPF. Besides, the design of control parameter for the ACR and AVR was discussed based on the control model of the proposed circuit. The design of the proposed circuit was also clarified using the ripple of the inductors.

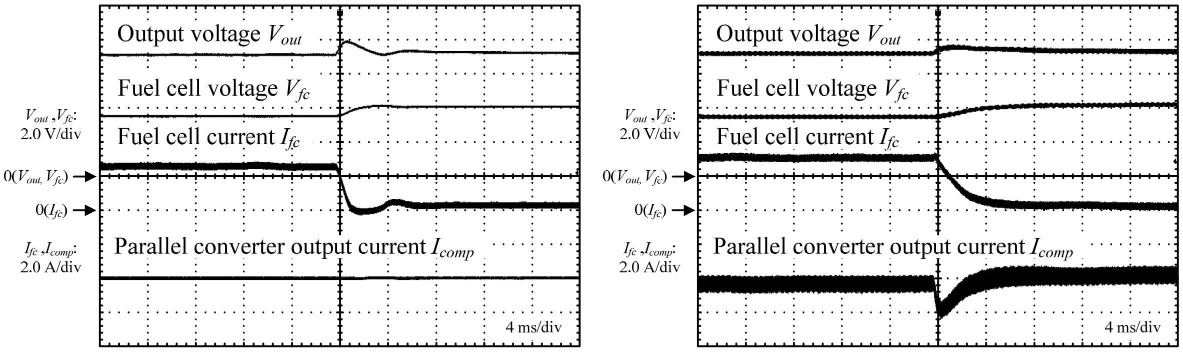
The experimental results and the loss analysis confirmed that the proposed circuit could achieve a maximum efficiency of 98.8% in the small differential voltage region. In addition, the proposed converter suppressed the variation of the fuel cell current and achieved an output voltage drop of within 7% for the effect of load change.

Overall, the experimental results confirmed the validity of the series-parallel compensation method.



(a) With series compensation only. (b) With series-parallel compensation.

Fig. 9: Voltage waveforms and current waveforms for increasing power condition.



(a) With series compensation only. (b) With series-parallel compensation.

Fig. 10: Voltage waveforms and current waveforms for decreasing power condition.

References

[1] Yilei Gu, Zhengyu Lu, and Zhaoming Qian: Three Level LLC Series Resonant DC/DC Converter, Proc. of IEEE-APEC04, pp. 1647- 1652

[2] Eui-Sung Kim, Dong-Yun Lee, and Dong-Seok Hyun: A Novel Partial Series Resonant DC/DC Converter with Zero-Voltage/Zero-Current Switching, Proc. of IEEE-APEC00, pp. 93- 98

[3] Jiann-Fuh Chen, Wei-Shih Liu, Ray-Lee Lin, Tsorng-Juu Liang, and Ching-Hsiung Liu: High-Efficiency Cascode Forward Converter of Low Power PEMFC System, Proc. of IEEE-IPEMC06

[4] Changrong Liu, Amy Johnson, and Jih-Sheng Lai: A Novel Three-Phase High-Power Soft-Switched DC/DC Converter for Low-Voltage Fuel Cell Applications, *IEEE Trans. Industry Applications*, pp. 1691- 1697, 2005

[5] Xin Kong, Ashwin M. Khambadkone: Analysis and Implementation of a High Efficiency, Interleaved Current-Fed Full Bridge Converter for Fuel Cell System, *IEEE Trans. Power Electronics*, pp. 543- 550, 2007

[6] H. Tao, A. Kotsopoulos, J. L, Duarte, and M. A. Hendrix: A Soft-Switched Three Port Bidirectional Converter for Fuel Cell and Supercapacitor Applications, Proc. of IEEE-PESC05, pp. 2487- 2493

[7] Naehyuck Chang: Fuel Cell and Battery Hybrid System for Portable Electronics Applications, 10th Annual International Conference SMALL FUEL CELLS 2008 – Portable & Micro Fuel Cells for Commercial & Military Applications, 2008

[8] Zhenhua Jiang, Lijun Gao, and Roger A. Dougal: Flexible Multiobjective Control of Power Converter in Active Hybrid Fuel Cell/Battery Power Sources, Proc. of IEEE-PESC04, pp. 3804- 3811

[9] Wei Chen, Zhengyu Lu: A Novel ZVS Push-Pull Type LLC Series Resonant Dc-Dc Converter for Hybrid Fuel Cell Power Systems, Proc. of IEEE-PESC08, pp. 1651- 1656

[10] Youichi Ito, Satoru Ishiguma, Isao Takahashi, and Hitoshi Haga: New power conversion technique to obtain high performance and high efficiency for single-phase UPS, Proc. of IEEE-IAS01, pp. 2383- 2388

[11] Jun-ichi Itoh, Takashi Fujii: A New Approach for High Efficiency Buck-Boost DC/DC Converters Using Series Compensation, The 39th IEEE Power Electronics Specialists Conference, pp. 2109- 2114