Loss Evaluation of a Series-Parallel Compensation DC-DC Converter for a Small Fuel Cell System

Koji Orikawa, Jun-ichi Itoh
Nagaoka University of Technology
Department of Electronics and Information Engineering
E-mail: itoh@vos.nagaokaut.ac.jp

Abstract — This paper proposes a novel DC-DC converter for hybrid power supplies using both fuel cell and battery. The output voltage is controlled by a series converter that regulates only the differential voltage between the fuel cell voltage and the output voltage. Although the load condition is changed, the variation of the fuel cell current is suppressed by a battery through operation of the parallel converter. The experimental results confirmed that the proposed circuit could achieve maximum efficiency point of 98.8% in the small differential voltage region. In addition, the loss analysis clarified the relations among the ripple current of the inductors, the inductor voltage and the inductors losses. As a result, it is confirmed that the proposed circuit achieves the minimum loss of the copper loss and the iron loss in the inductors when the differential voltage is small.

I. Introduction

Recently, most mobile electronic devices use batteries as a power source. The mobile electronic devices are developing with increasingly high performance and functionality, accompanied by higher power consumption and the demand for longer operation times. Fuel cell systems have being developed as a new power supply for mobile devices to achieve these demands. A direct methanol fuel cell (DMFC) has possibility to achieve high power density as a power supply for mobile devices. However the fuel cell system has some problems as follows.

(1)Output voltage fluctuation according to the load condition

The fuel cell has large internal impedance.

(2)Low dynamic response

The fuel cell does not allow the regeneration from the load and needs long starting time.

(3)Short lifetime

The output power of a fuel cell should be constant, because quick power fluctuations of a fuel cell reduce its life time.

The DC-DC converters are required in the fuel cell system in order to control the output voltage. The efficiency of DC-DC converters become an important issue in terms of to provide longer operation times for these devices. Many circuit topologies of DC-DC converters for fuel cell applications have been studied in order to obtain high efficiency [1-5]. A 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]. 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. As a result, the series converter reduces the life time of the fuel cell although the output voltage can be controlled.

In order to compensate the dynamic response, a battery or an electric double layer capacitor (EDLC) is used in a fuel cell system. A hybrid power supply using both the fuel cell and battery also requires high efficiency, downsizing, and quick response to the load fluctuations. 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. In the proposed circuit, the series converter generates a positive and negative voltage to achieve boost and buck operation individually. As a result, high efficiency is obtained, because the power rating of the DC-DC converter can be drastically reduced [10]. 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. In addition, analysis and measurement of power loss in each part of the proposed circuit is implemented to clarify the reason for high efficiency. Overall, the validity of the series-parallel compensation method is confirmed.

II. CONCEPT OF PROPOSED CIRCUIT

A. Series compensation

Fig. 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. For example, in a conventional buck-boost chopper, which consists of a energy storage reactor and a single switching device, 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}.

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

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 efficiency will be decreased.

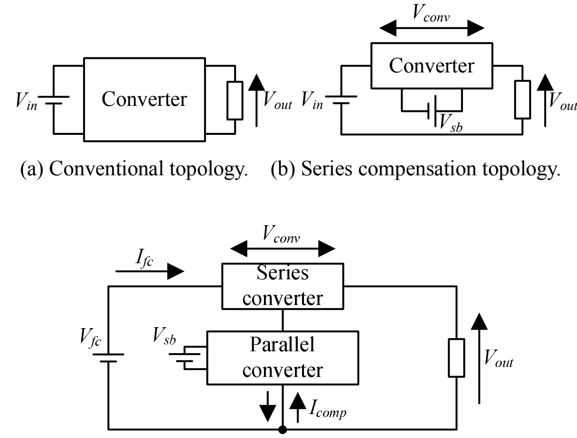
Fig. 1(b) shows a block diagram of the series compensation converter, which is connected in series to the power supply. The series converter outputs only the differential voltage between the fuel cell voltage and the output voltage. Therefore, when the fuel cell voltage is close to the output voltage, 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 will decrease 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

Fig. 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}.

$$V_{out} = V_{fc} \pm V_{conv} \qquad (2)$$

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.



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

(c) Proposed circuit.

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

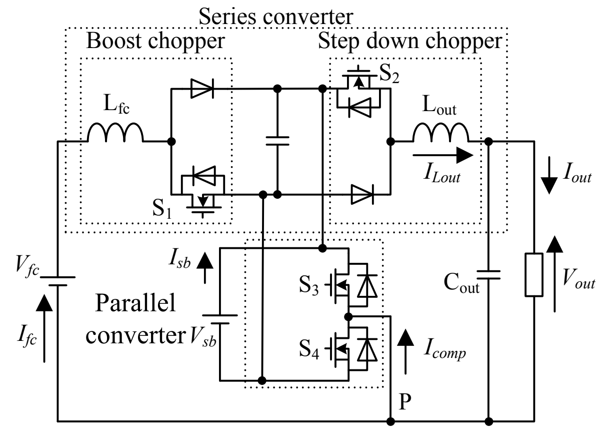


Fig. 2. Configuration of proposed circuit.

III. PROPOSED CIRCUIT

A. Circuit configuration

Fig. 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 the 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, where the conventional circuit needs to use three reactors. To suppress the ripple current of the fuel cell, an inductor is connected in series to the fuel cell. Further, the reactor is used as a boost reactor too when the boost mode is selected.

Fig. 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. Fig. 3(b) and (c) presents a block diagram of the proposed circuit for series-parallel compensation mode. When the load condition is changed, only the parallel converter will operate. 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}.

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

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).

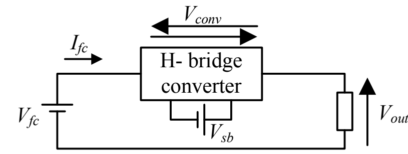
$$L_{fc} = \frac{V_{fc}}{\Delta i_{fc} f_{sw}} \frac{V_{out} - V_{fc}}{V_{sb}} = \frac{4}{0.5 \times 100 \times 10^3} \frac{7.2 - 4}{11} = 23.3 \mu H \quad (4)$$

IV. Control Strategy

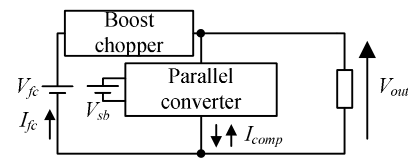
Fig. 4 shows control diagrams of the proposed circuit. The proposed control method has two loops; the inner loop is for controlling the fuel cell current and the parallel converter current. As for the outer loop, it is for the output voltage control.

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, since 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 switches S_3 and S_4 are for the parallel converter. The parallel converter works only when the load is 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.

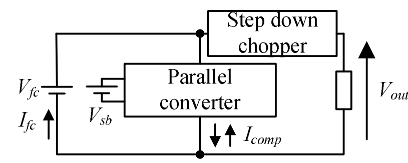
The current command is divided into the fuel cell current command and the compensation current command. Low pass filters (LPF) and high pass filters (HPF) are used to divide the current command. The LPF is used to separate the fundamental current fluctuation, for the slow response of the fuel cell. The HPF is used to separate the transient current



(a) Series compensation mode.



(b) Boost mode (Load change).



(c) Step down mode (Load change).

Fig. 3. Block diagram of proposed circuit.

TABLE I
Specifications for Proposed Circuit

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

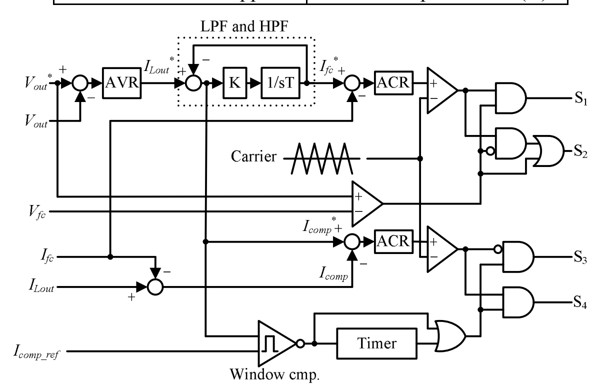


Fig. 4. Control diagrams for the proposed circuit.

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 (5), using the fuel cell current I_{fc} and the parallel converter current I_{comp}.

$$I_{Lout} = I_{fc} + I_{comp} \quad (5)$$

The fuel cell current command I_{fc}^* and the parallel converter current command I_{comp}^* are obtained by (6) and (7)

$$I_{fc}^* = \frac{1}{1+sT} I_{Lout}^* \quad (6)$$

$$I_{comp}^{*} = \frac{sT}{1+sT} I_{Lout}^{*} \tag{7}$$

where T is the time constant of the filter and I_{Lout}^{*} is the output current command. Therefore, the output current is obtained by (8).

$$I_{Lout} = G_1(s) I_{fc}^{*} + G_2(s) I_{comp}^{*} \tag{8}$$

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 (9) when both current regulator designs for the fuel cell and parallel converter are the same.

$$I_{Lout} = G(s) I_{Lout}^{*} \tag{9}$$

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 decrement of efficiency in the proposed circuit.

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 a negative influence on the lifetime of the fuel cell, the time constant should be set to a few seconds.

Fig. 5 shows the efficiency of the proposed circuit to confirm the effectiveness of the 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.

Fig. 6(a) and (b) show comparisons of the fuel cell current and the output voltage with and without parallel compensation when the load condition is changed. In Fig. 6(a), the voltage drops over 14% 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. 6(b) shows that the variation of the fuel cell current is suppressed by the parallel compensation. The output voltage drops within 7% is achieved.

VI. Loss analysis

In order to evaluate the power loss of the proposed circuit, the loss measurement and analysis for each part have examined. In the proposed circuit, the copper loss and the iron loss of the inductors depends on the ripple current of inductors and the inductor voltage, respectively. It should be noted that theoretical calculation of the inductors loss for a fundamental

TABLE II
EXPERIMENTAL CONDITIONS

Fuel cell voltage V_{fc}	4 to 10 (V)
Output voltage V_{out}	7.2 (V)
Battery voltage V_{sb}	11 (V)
Switching frequency f_{sw}	100 (kHz)
Input inductor L_{fc}	30 (μH)
Output inductor L_{out}	30 (μH)
Output capacitor C_{out}	801 (μF)
AVR response	0.1 (kHz)
ACR response	1 (kHz)
LPF time constant T	2.2 (ms)
Load change	2 to 20 (W)

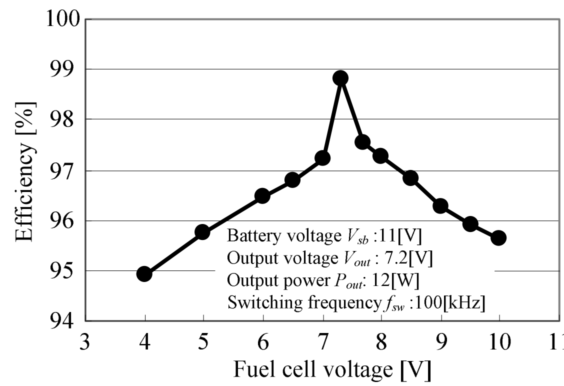
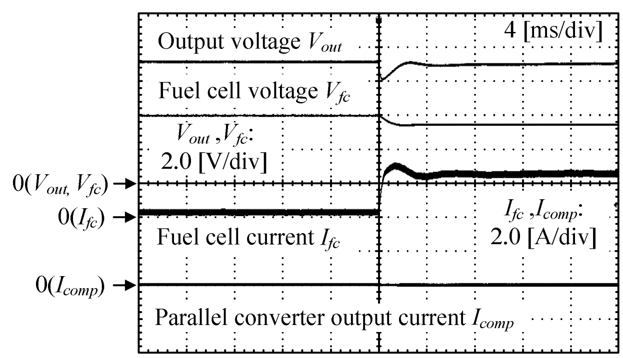
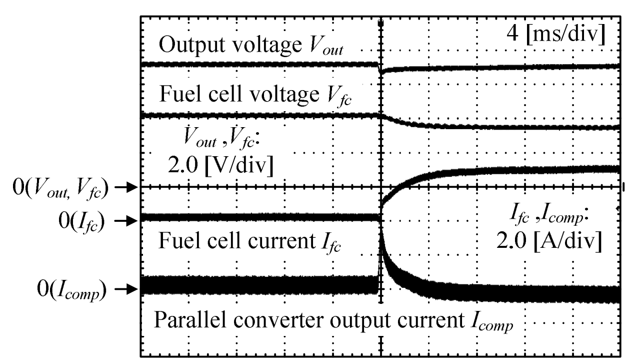


Fig. 5. Efficiency of the proposed circuit.



(a) Series compensation only.



(b) Series compensation with series-parallel compensation.

Fig. 6. Voltage waveforms and current waveforms for increasing power condition.

frequency component is indicated because it is difficult to calculate the PWM loss of the inductor. In addition, the loss analysis for the switching loss and the conduction loss of the MOSFETs are presented in this section.

A. Copper loss of the inductors

Copper loss occurs in the winding resistance of the inductors. The copper loss of the inductors is expressed by (10)

$$P_{ind\_copper} = R_{LDC} I_{OUT}^2 + R_{LAC} I_{LAC}^2 \tag{10}$$

where R_{LDC} is a DC component resistance of the inductor, R_{LAC} is a AC component resistance of the inductor, I_{out} is an output current, I_{LAC} is RMS value of the ripple current of the inductor.

The current waveform of the inductor can be approximated to a triangular shape when the resistance component of the inductor is negligible. Therefore, RMS value of the ripple current of the inductor I_{LAC} is obtained by (11) from Ref. [11]

$$I_{LAC} = \frac{1}{2\sqrt{3}} \frac{\left|V_{fc} - V_{out}\right|}{\left(L_{fc} + L_{out}\right) f_{sw}} D \tag{11}$$

where D is the duty ratio of the series converter. Then, the duty ratio D is given by (12)

$$D = 1 - \frac{\left|V_{fc} - V_{out}\right|}{V_{sb}} \tag{12}$$

Fig. 7 shows RMS value of the ripple current. In the small differential voltage region, the ripple current of the inductors are reduced, as shown in Fig. 7. Finally, the copper loss of the inductors is obtained by (13)

$$P_{ind\_copper} = R_{LDC} I_{OUT}^2 + R_{LAC} \frac{\left(V_{fc} - V_{out}\right)^2}{12\left(L_{fc} + L_{out}\right)^2 f_{sw}^{\ 2}} D^2 \tag{13}$$

B. Iron loss of the inductors

Iron loss occurs in the core of the inductor [12]. Fig. 8 shows the voltage waveforms of the input inductor. The voltage waveform of the inductor is changed according to the differential voltage. Fig. 9 shows the RMS value of the input inductor voltage and output inductor voltage respectively. In the proposed circuit, the inductor voltage becomes smaller when decreasing the differential voltage between the fuel cell voltage and the output voltage, as shown Fig. 9. That is, in the small differential voltage region, the iron loss becomes small because the RMS value of the inductor voltage is reduced.

Secondly, the relations between the inductor voltage and the iron loss are clarified. Note that it is difficult to calculate the iron loss of the inductor used in DC-DC converters because DC current flows through the inductor. In this paper, only the eddy-current loss and the hysteresis loss which are caused by the voltage of the switching frequency component are evaluated. In the proposed circuit, a flux change of the core of the inductors is expressed by (14)

$$B_m = \frac{\sqrt{2} V_{dis\_rms}}{N A_e f_{sw}} \tag{14}$$

where B_m is the magnetic flux density, V_{dis_rms} is the distortion RMS value of the inductor voltage, N is the number of wire turns, A_e is the effective cross section of the core.

The material of the core is PC40 which is a kind of ferrite. Iron loss of the inductor consists of the eddy-current loss and

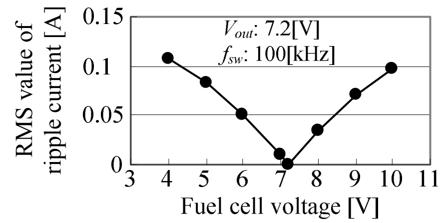
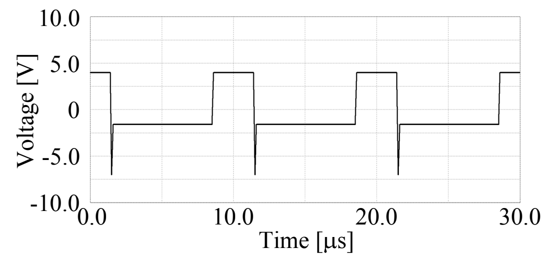
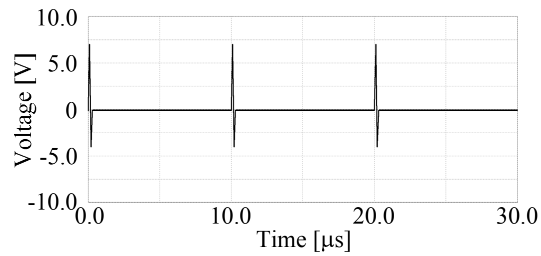


Fig. 7. RMS value of ripple current of the inductors.



(a) V_{fc}=4V.



(b) V_{fc}=7V.

Fig. 8. Voltage waveforms of the input inductor L_{fc}.

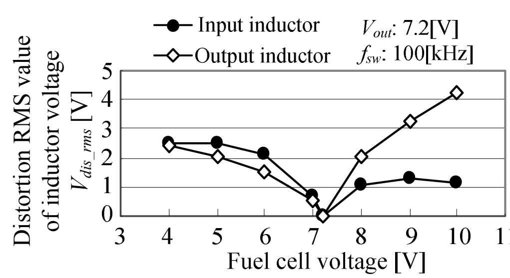


Fig. 9. Distortion RMS value of inductor voltage.

the hysteresis loss is expressed by (15) from Ref. [13]

$$P_{ind\_iron} = 4.50 \times 10^{-4} \times B_m^{2.5} \times f_{sw}^{1.55} \times V_c \tag{15}$$

where V_c is the effective volume of the core.

C. Loss analysis of the experimental result

Fig. 10 shows the calculation results of the sum of the copper loss and the iron loss of the inductors respectively. Fig. 10 confirms that the copper loss and the iron loss of the inductors become small in the small differential voltage region. In addition, the iron loss is drastically changed according to the fuel cell voltage.

Fig. 11 shows the result of the loss analysis including the switch loss. The switching loss and the conduction loss of the MOSFETs are obtained as follows; the switching loss is calculated by the measured current and voltage. The conduction loss is calculated by the measured current using on-resistance which is obtained from the data sheet of the switching device.

The analysis results confirmed that the copper loss and the iron loss of the inductors are reduced when the fuel cell voltage is close to the output voltage. From the loss analysis, the major loss in the proposed circuit is comprises by the loss of the inductors, the switching loss of the MOSFETs and the loss in the body diode, which is used as the free wheeling diode (FWD) of the series converter. It should be noted that in order to reduce the FWD loss during the dead-time period, the low voltage forward drop diode is connected in parallel to the FWD.

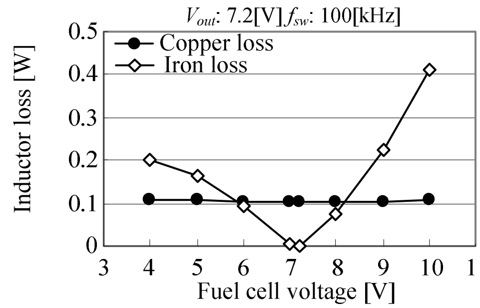


Fig. 10. Iron loss and copper loss of the inductors.

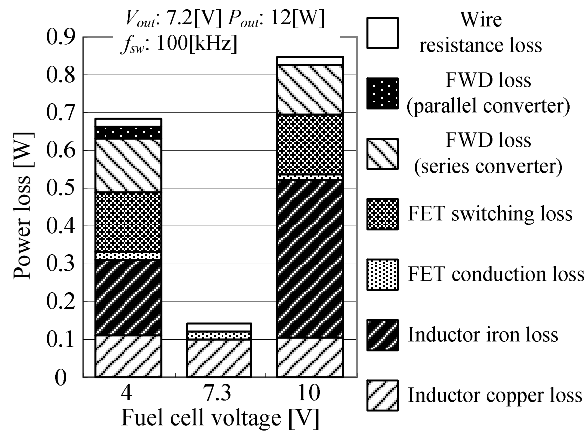


Fig. 11. Loss analysis of the experimental result.

VII. 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. The design of the proposed circuit was also clarified by using the ripple of the inductors.

The experimental results confirmed that the proposed circuit could achieve a maximum efficiency of 98.8% in the small differential voltage region. The loss analysis clarified the relations among the ripple current of the inductors, the inductor voltage and inductors loss. Moreover, the copper loss and the iron loss of the inductors became small in the small differential voltage region are as well been confirmed. 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.

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] 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

[11] Y. Katayama, M. Edo, T. Denta, T. Kawashima, and T. Ninomiya, “Optimum Design of CMOS DC-DC Converter for Mobile Applications,” *IEEJ Trans. IA*, Vol.124, No.10, pp.1043-1052 (2004-10) (in Japanese)

[12] S. Iyasu, T. Shimizu, and K. Ishii, “Iron Loss Calculation Method of Filter Inductor Core on a Single –Phase PWM Voltage Source Inverter,” *IEEJ Trans. IA*, Vol.127, No.3, pp.217-225 (2007-3) (in Japanese)

[13] Carl Nelson, “LT1074/LT1076 Design Manual”, Linear Technology Corporation, pp.33-36