A High Efficiency Isolated DC/DC Converter Using Series Connection on Secondary Side

Satoshi Miyawaki*, Jun-ichi Itoh*, and Kazuki Iwaya**
* Nagaoka University of Technology, 1603-1 Kamitomioka-cho Nagaoka City Niigata 940-2188, Japan
** DENSEI-LAMBDA, Ltd., 2701 Tokawa Settaya Nagaoka City Niigata 940-1195, Japan

***Abstract*-- This paper proposes a new circuit topology for a high efficiency isolated buck-boost DC/DC converter. The proposed converter consists of a high efficiency resonance half-bridge converter and a series converter. This proposed circuit regulates the output voltage by the series converter, which provides only the differential voltage between the input voltage and the output voltage. Therefore, the circuit achieves high efficiency when the input voltage is closed to the nominal input voltage, since only the resonance converter will operate. Experimental results are shown in order to demonstrate the advantages of the proposed converters in comparison with a conventional converter. The experimental results confirmed that the proposed circuit, which converts 48 V input to 12 V, achieves 94.0% maximum efficiency point at the nominal input voltage region.**

***Index Terms*—DC/DC converter, Isolated converter, Series voltage compensation, Current resonance**

I. INTRODUCTION

Recently, high efficiency and high power density of power supplies are increasingly desired for telecom applications and microprocessor boards. In addition, these power converters have to supply larger output current with very low output voltage for the loads. In order to achieve high efficiency and high power density, the power system is divided into several converters, such as point-of-load converter, bus converters and front end converter. In this system, the power is distributed to each of the device by a DC voltage line [1-5].

The DC bus converter, which regulates the constant DC voltage for output side, is required at the input point of each device, because the DC bus voltage will fluctuate due to the bus impedance when the load condition had changed. The DC bus converter is also used to obtain other levels of DC voltage from the DC bus voltage. Therefore, high efficiency DC/DC converters are required for these bus converters.

Resonant type half-bridge converters, which use a resonance between the leakage inductance of transformers and the DC capacitor, are one of the most effective circuit topologies to obtain high efficiency. However, it is difficult to regulate the output voltage in wide range while there is a fluctuation in the input voltage because the switching timing is constrained by the resonance period. Therefore, a resonant-type half-bridge converter is generally connected to a voltage control converter, such as a buck chopper [6-7]. As a result, the converter loss increases because all the power passes through two converters; the voltage control converter and the resonant converter.

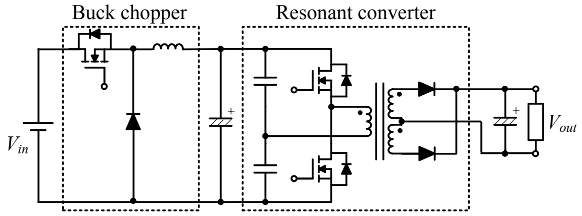
This paper proposes a new topology for an isolated DC/DC converter using series voltage compensation. The input voltage fluctuation is compensated by the auxiliary circuit that outputs only the fluctuation of the output voltage [8-11]. One of the advantages of the proposed circuit is that high efficiency can be achieved when the input voltage is closed to the nominal input voltage because the power of the auxiliary circuit becomes very small in comparison to the input power. Generally, the large fluctuations of the DC bus voltage are not generated for long time periods, and as a result, the converter loss can be reduced.

Firstly, an approach uses to obtain high efficiency with the proposed series compensation method is introduced in this paper. Secondly, the circuit configuration and control strategy are described. Finally, some experimental results are given in order to demonstrate the advantages of the proposed converter.

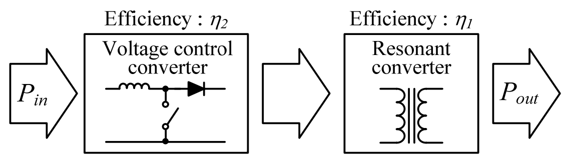
II. CIRCUIT CONFIGURATIONS

A. Conventional circuit

Fig. 1 shows a configuration of a conventional DC/DC converter. The conventional circuit consists of a resonant half-bridge converter and a voltage control converter, such as a buck boost chopper. The fluctuation of the input voltage is constantly controlled by the buck chopper. The output side is isolated by the resonant half-bridge converter to the input side. This system has two stages of the power flow from input to output, as shown by Fig.



(a) Circuit diagram.



(b) Power flow diagram.

Fig. 1. Conventional circuit using a buck chopper and a resonant converter.

1(b). The total efficiency of the conventional circuit η_c is obtained from (1), using both the resonant converter efficiency η_1 and the buck chopper efficiency η_2.

$$\eta_c = \eta_1 \eta_2 \tag{1}$$

All the power passes through both converters despite the relation between the input voltages; therefore, the converter efficiency is decreased.

B. Series connection on primary side

Fig. 2 shows the configuration of the DC/DC converter using series connection in the primary side which has been proposed by authors in [11]. This system consists of two power converters; main circuit and auxiliary circuit, which are connected in series to the output side using a transformer.

The main circuit is that the resonant type half-bridge converter with isolation transformer. Zero current switching (ZCS) is implemented by the resonance circuit between the leakage inductance of the transformer and the resonance capacitor in the DC part, in order to achieve high efficiency.

The auxiliary circuit is a full-bridge converter uses for regulating the output voltage. The output voltage of the auxiliary circuit is added to the output of the main circuit by the transformer. That is, the auxiliary circuit compensates only the fluctuation voltage, against the output voltage commands. Therefore, the converter loss is decreased.

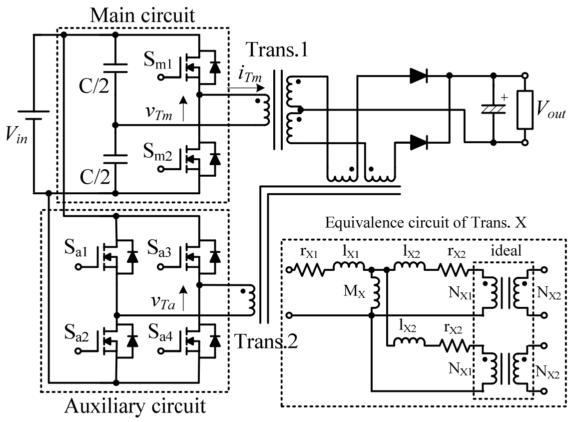
The problem of this circuit is that the auxiliary circuit is connected on the primary side. Thus, by using series connection on primary side, the voltage rating of the switching device in auxiliary circuit is dominated by the input voltage V_{in}. Here, when the specification of the turns ratio in the main circuit transformer is $2N_{11}<N_{12}$, the output voltage is lower than the input voltage. In this condition, the switching loss in the auxiliary circuit is increased. In addition, the wire turns of the transformer in the auxiliary circuit needs to be increased.

C. Series connection on secondary side

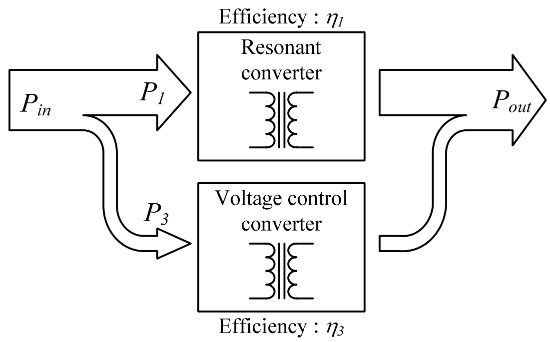
Fig. 3 shows the configuration of the proposed converter using series connection on secondary side. Like the series compensation on primary side, the proposed system consists of two power converters, which are connected in series to the output side using a transformer. However, the auxiliary circuit is connected on the secondary side. In this circuit, the switching loss in auxiliary circuit can be reduced in comparison to the series compensation on primary side.

It should be noted that the voltage rating of the switching device in the auxiliary converter is lower than the main circuit because the output voltage is lower than the input voltage. That is, the conduction loss of the auxiliary circuit can be decreased.

The switching frequency of the main circuit is constrained by the resonance frequency. From the equivalent circuit of the transformer shown in Fig. 3(a), the resonant inductance of the proposed circuit L is obtained from (2), using the leakage inductance l_{xx},

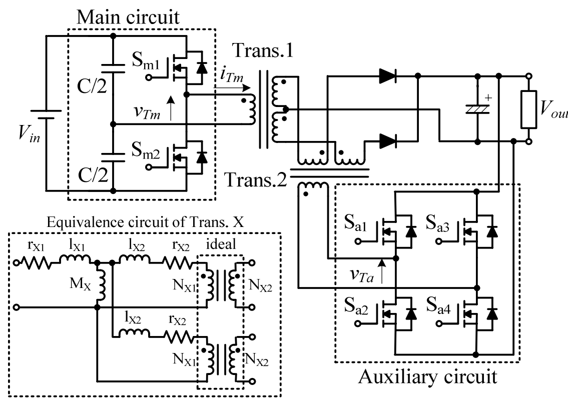


(a) Circuit diagram.

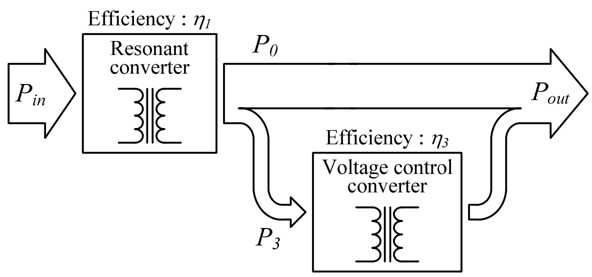


(b) Power flow diagram.

Fig. 2. Proposed circuit using series connection on primary side.



(a) Circuit diagram.



(b) Power flow diagram.

Fig. 3. Proposed circuit using series connection on secondary side.

mutual inductance M_{xx} and the number of wire turns N_{xx}.

$$L = l_{11} + \frac{M_1 (l_{12} + L_{T2})}{M_1 + (l_{12} + L_{T2})} \tag{2}$$

where $L_{T2} = \left(\frac{N_{11}}{N_{12}} \right)^2 \left(\frac{N_{22}}{N_{21}} \right) \left(l_{21} + \frac{l_{22} M_2}{l_{22} + M_2} \right)$

The resonance frequency of the proposed circuit f_0 is obtained by

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

The reason of high efficiency in the proposed circuit is as follows. The power P_{out} is obtained by adding the auxiliary converter power P_3 to the directly power P_0, as shown by Fig. 3(b). The total converter efficiency of the proposed circuit η_p is obtained by (4), using the auxiliary circuit efficiency η_3 and the power ratio $k=P_3/P_0$.

$$\eta_p = \eta_1 \frac{1 + k\eta_3}{1 + k} \tag{4}$$

Therefore, the total efficiency η_p of the proposed circuit is higher than the conventional circuit where the relation of efficiency for each circuit is given by

$$\frac{1 + k\eta_3}{1 + k} > \eta_2 \tag{5}$$

III. Control Strategy

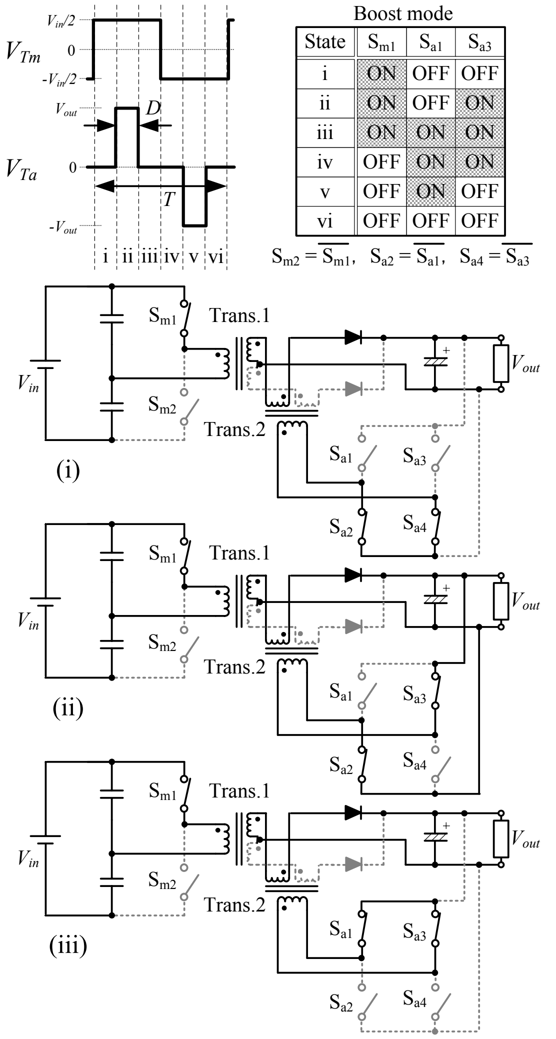
In the proposed circuit, the main circuit is controlled under an optimum condition as the resonant converter. In order to obtain the maximum efficiency, the resonant converter operates at 50% duty cycle based on resonance frequency f_0. Therefore, the main circuit can achieve zero current switching (ZCS) at any time.

Fig. 4 shows the operation mode and the waveforms in the primary side of the transformer in the boost mode. The switching timing of the auxiliary circuit is synchronous with the main circuit. The auxiliary circuit can output three different voltage levels; $+V_{out}$, $-V_{out}$, and zero voltage. In the boost mode; i.e. when the input voltage is decreased, the auxiliary circuit outputs positive phase voltage to the output voltage of the main circuit without preventing the resonance operation in the main circuit. Similarly, in the buck mode; i.e. when the input voltage is increased; the auxiliary circuit outputs negative phase voltage to the output voltage of the main circuit.

The output voltage is controlled by changing the pulse width D of the auxiliary circuit. If the voltage drop from the leakage inductance and winding resistance are negligible, the pulse width of the auxiliary circuit D is obtained by (6), using the switching (resonance) cycle T and the output voltage command V_{out}*.

$$D = \frac{T}{2} \cdot \frac{N_{21}}{N_{22}} \cdot \left(\frac{V_{out}^*}{V_{out}} - \frac{N_{12}}{2N_{11}} \cdot \frac{V_{in}}{V_{out}} \right) \tag{6}$$

Fig. 5 shows the control block diagram of the proposed circuit. The duty cycle of the main circuit is set to 50%. In the auxiliary circuit, the output pulse width D is calculated by an automatic voltage regulator (AVR). The phase shift gain is then calculated according to D. The phase shift is used to decrease the switching loss in the auxiliary circuit. According to the relation between the output and input voltages, the mode selector determines the operation mode. It should be note that the proposed converter has the reference voltage mode, which means that the auxiliary circuit stops when the input voltage is almost the same as the nominal input voltage, in addition to the buck and boost mode operation.



State	S_{m1}	S_{a1}	S_{a3}
i	ON	OFF	OFF
ii	ON	OFF	ON
iii	ON	ON	ON
iv	OFF	ON	ON
v	OFF	ON	OFF
vi	OFF	OFF	OFF

Fig. 4. Corresponding of the switching pattern and operation mode.

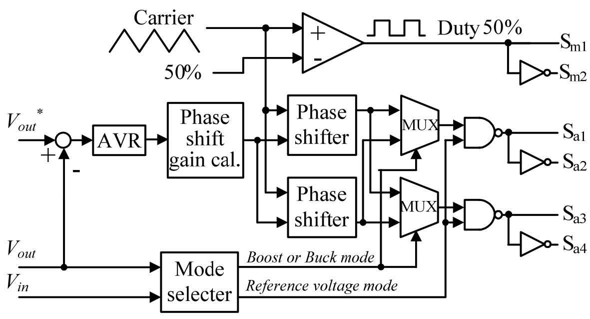


Fig. 5. Control block diagram of the proposed circuit.

IV. Operational Mode Analysis

The proposed circuit is clarified in order to the stability of operation and operational mode is analyzed using a simple equivalent circuit. Fig. 6 shows the equivalent circuit of the proposed circuit under the boost operation. In the AC signal analysis, the switching operation of the main circuit and the rectifier part at the output side is expressed as a square wave power source, which has the amplitude of the input and output voltage at the frequency of the switching frequency respectively. The capacitors of the half-bridge converter can be represented as one resonance capacitor with ideal transformers. Moreover, the full-bridge converter in the auxiliary circuit is represented as three different voltage levels; $+V_{out}$, $-V_{out}$, and zero voltage. Note that the excitation inductance of the transformer is disregarded in the mode analysis because it is much larger than the leakage inductance. The resonance frequency is dominated by the leakage inductance.

Fig. 7(a) and (b) show the simplified equivalent circuit which is separated into the main circuit side and auxiliary circuit side, according to the superposition principle. The separation of the equivalent circuit is achieved by focusing on the transformer input current i_{Tm} of the main circuit. The equivalent circuit is obtained from the perspective of the main circuit, when the input of the auxiliary circuit is short-circuited. Similarly, the equivalent circuit is obtained from the perspective of the auxiliary circuit, when the input of the main circuit is short-circuited; i_{Tm} is obtained by

$$i_{Tm} = i_{Tm\_m} + i_{Tm\_a} \tag{7}$$

where i_{Tm_m} is the input current on the main circuit side as shown in Fig. 7(a) and i_{Tm_a} is the input current on the auxiliary circuit side as shown in Fig. 7(b). Consequently, the equation of the entire circuit can be obtained by deriving each equation from each of the circuit equation in Fig. 7. The input current i_{Tm_m} and i_{Tm_a} are obtained from (8) and (9).

$$i_{Tm\_m} = e^{-\frac{1}{\tau}t}\left[\begin{array}{l} \frac{1}{2}\cdot\frac{V_{in}}{\omega L}\sin(\omega t) - \frac{\alpha V_{out}}{\omega L}\sin(\omega t) \\ + i_{m(k)}\left\{\cos(\omega t) - \frac{1}{2Q}\sin(\omega t)\right\} \\ - q_{m(k)}\omega\left(1+\frac{1}{4Q^2}\right)\sin(\omega t) \end{array}\right] \tag{8}$$

$$i_{Tm\_m} = e^{-\frac{1}{\tau}t}\left[\begin{array}{l} \frac{1}{2}\cdot\frac{V_{in}}{\omega L}\sin(\omega t) - \frac{\alpha V_{out}}{\omega L}\sin(\omega t) \\ + i_{m(k)}\left\{\cos(\omega t) - \frac{1}{2Q}\sin(\omega t)\right\} \\ - q_{m(k)}\omega\left(1+\frac{1}{4Q^2}\right)\sin(\omega t) \end{array}\right] \tag{9}$$

where $\tau = \frac{2L}{R}$, $\omega = \sqrt{\frac{1}{LC} - \left(\frac{1}{\tau^2}\right)}$, $Q = \frac{\omega L}{R}$

$$R = R_1 + \left(\frac{\alpha}{\beta}\right)^2 R_2,\ L = L_1 + \left(\frac{\alpha}{\beta}\right)^2 L_2$$

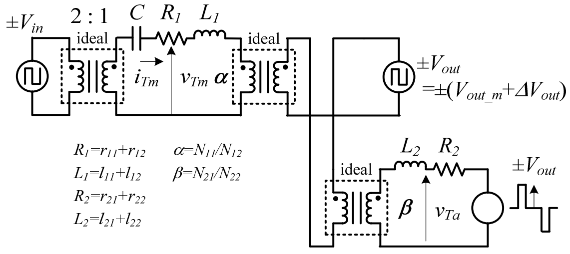
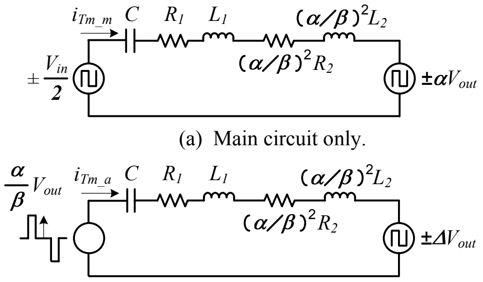


Fig. 6. Equivalent circuit of the proposed circuit.



(a) Main circuit only.

(b) Auxiliary circuit only.

Fig. 7. Control block diagram of the proposed circuit.

$i_{m(k)}$ and $i_{a(k)}$ are the initial currents of the leakage inductions, and $q_{m(k)}$ and $q_{a(k)}$ are the initial charges of resonance capacitor for the main and auxiliary sides, respectively. The optimization design of the proposed circuit can be obtained from this equation.

V. Experimental Result

At first, experimental results of the main circuit are presented to confirm the high efficiency can be achieved in the main circuit. Then, experimental results of the proposed circuit are presented at the second. Finally, the proposed circuit with connection in secondary side is compared with the connection in the primary side.

A. Experimental results of the main circuit

Fig. 8 shows the load characteristics of the main circuit (input voltage: 48V). The turn ratio of the transformer in the main circuit was 2:1. Therefore, the output voltage becomes 12V when the input voltage of the main circuit is 48V. However, the control method is an open-loop control, that is, the duty cycle is set to 50%. As a result, the maximum efficiency of 94.0% is obtained at load of

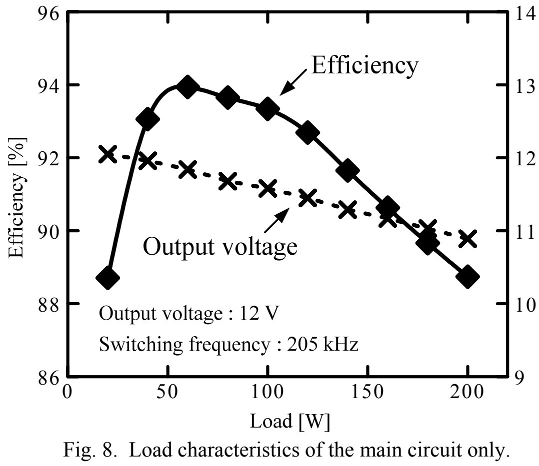


Fig. 8. Load characteristics of the main circuit only.

TABLE I
EXPERIMENTAL PARAMETERS OF SECONDARY SIDE COMPENSATION

Parameter	Value	Parameter	Value
Nominal input voltage	48 V	Wire turns Trans. 1	2 : 1
Input voltage fluctuation range	12 V (±25%)	Wire turns Trans. 2	2 : 1
Output voltage	12 V	Resonance Capacitance (C)	0.2 μF
Output power	60,100W		
Switching frequency	205 kHz	Resonance Inductance (L)	2.4 μH

60 W, as shown in Fig. 8. It is confirmed that the high efficiency is achieved in the main circuit. It should be noted that the synchronous rectification using MOSFET is applied to the secondary side in order to reduce the conduction losses of the rectifier.

B. Experimental results of the proposed circuit

Fig. 9 presents the efficiency of the proposed converter at a constant load (cf., Table 1) when the input voltage has fluctuation of ±25%. In order to confirm the validity of the concept, the proposed converter was tested. The maximum efficiency of 94.0% is obtained, as shown in Fig. 9, when the input voltage is very close to the nominal input voltage. The reason for low efficiency in the boost mode compared to the buck mode is that the current in the boost mode is increased by the circulation current between the auxiliary circuit and the rectifier. Consequently, the conduction loss is increased by the circulating current.

Fig. 10 shows the input current of the transformer and the terminal voltage of S_{m2}. In these modes, reference mode, boost and buck mode accordingly, the half-bridge converter maintain at zero current switching. A switching frequency of approximately 200 kHz was confirmed.

Fig. 11 shows the loss analysis of the proposed converter based on the simulated and experimental results. In order to clarify the power loss of the proposed circuit, the loss measurement and analysis for each of the part have been examined. When the input voltage is very close to the nominal input voltage, the maximum efficiency of the proposed circuit is obtained. The auxiliary FET loss increases in both boost and buck modes, and the loss in the main transformer and main FET are predominant. Therefore, in order to obtain higher efficiency, the selection of FETs in the auxiliary circuit is important. The low on-state resistance device should be chosen because the voltage rating of the FET can be reduced in comparison with the main circuit. Besides, the parameters design of the transformer based on the equivalent circuit analysis are required.

C. Comparison between the connection on primary side and secondary side

Fig. 12 shows the comparison between of the series connection in the primary side and the secondary side. Table 2 shows the experimental parameters for the proposed circuit that is using series connection in the primary side. The same one as the proposed circuit using series connection on secondary side is used for the main circuit and the rectifier. However, the wire turns of the

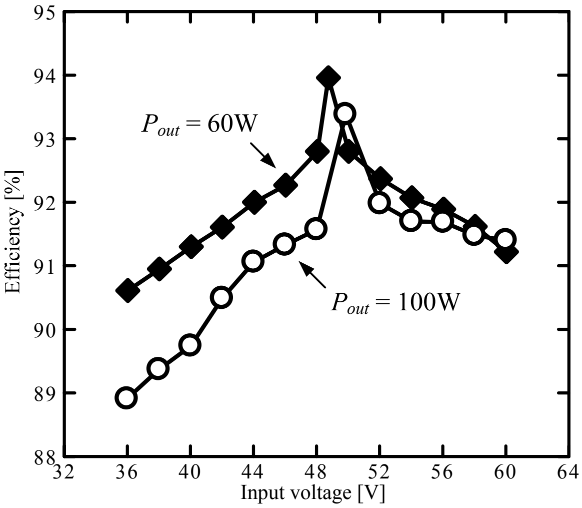


Fig. 9. Characteristics of the efficiency for the input voltage fluctuations.

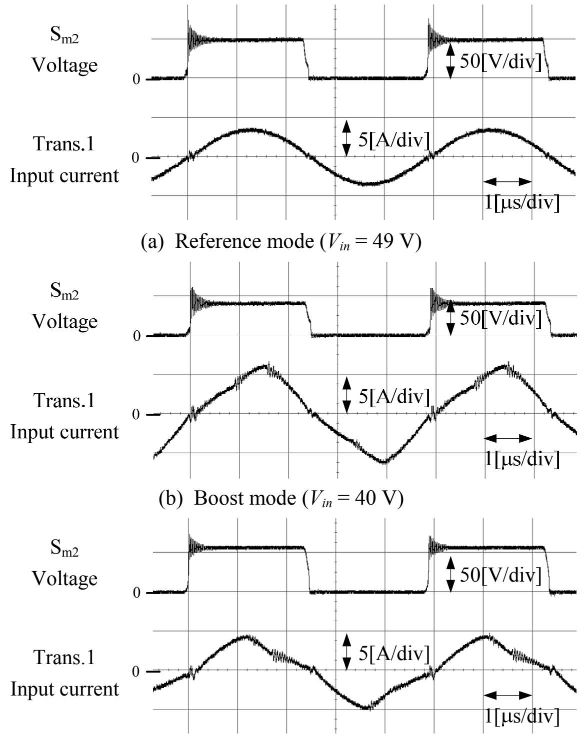


Fig. 10. Input current of the transformers and the terminal voltage of S_{m2} (Load: 60 W).

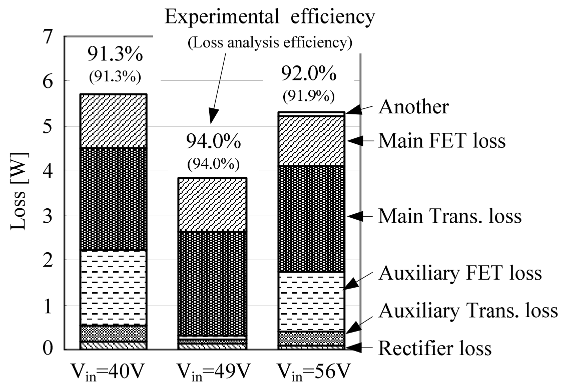


Fig. 11. Loss analysis at 60 W load.

transformer in the auxiliary circuit is 8:1, in order to equate the compensation circuit with the both circuit.

In both proposed circuit, the maximum efficiency of 94.0% is obtained, as shown in Fig. 12. When the input voltage is very closed to the nominal input voltage, the efficiency of the series connection in primary side is higher than the series connection in secondary side. During the operation of the boost mode and buck mode, the efficiency of the series connection in the primary side is decreased, because the switching loss in the auxiliary circuit is increased for high input voltage. In addition, the tendency of the efficiency is different since the power flow of each of the proposed circuit is different.

In the condition of the output voltage is lower than the input voltage, the efficiency of the connection on primary side is higher than the connection on secondary side has been confirmed.

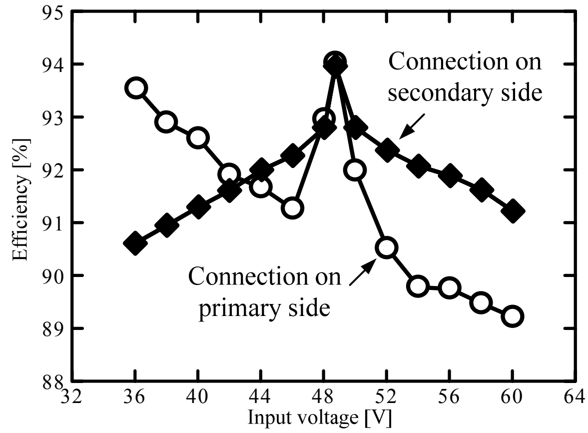
VI. Conclusions

A series type isolated DC/DC converter consisting of a resonant-type half-bridge converter and an auxiliary converter has been proposed. The concept of series compensation is that the output voltage is regulated by adding or subtracting the auxiliary converter voltage to the half-bridge converter voltage. The experimental results confirmed the highest efficiency of 94.0% is obtained when the input voltage was closed to the nominal input voltage. It was confirmed that voltage control can be regulated while maintaining a high efficiency. The connection in the secondary side is compared with the connection in the primary side and show that the connection in the primary side can obtain a higher efficiency.

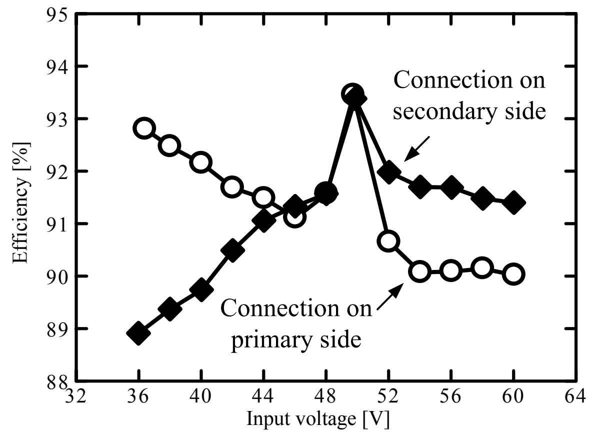
In future work, the optimal design approach will be clarified.

TABLE II
Experimental Parameters of Primary Side Compensation

Nominal input voltage	48 V	Wire turns Trans. 1	2 : 1
Input voltage fluctuation range	12 V (±25%)	Wire turns Trans. 2	8 : 1
Output voltage	12 V	Resonance Capacitance (C)	0.2 μF
Output power	60,100W		
Switching frequency	205 kHz	Resonance Inductance (L)	2.7 μH



(a) P_{out} = 60 W



(b) P_{out} = 100 W

Fig. 12. Comparison between the connection on primary side and secondary side.

References

[1] Ming Xu, F.C.Lee, "General concepts for high-efficiency high-frequency 48 V DC/DC converter", *PESC '03. 2003 IEEE 34th An-nual Volume 1, pp 156-162, 2003.*

[2] J.Biela, U.Badstuebner, J.W.Kolar, "Impact of Power Density Maximization on Efficiency of DC-DC Converter Systems", *IEEE Transaction on Power Electronics, Vol.24, No.1, pp288-300, 2009.*

[3] P.Alou, J.A.Cobos, J.Uceda, M.Rascon, E. de la Cruz, "Design of a low output voltage DC/DC converter for telecom application with a new scheme for self-driven synchronous rectification", *APEC '99, Vol.2 , pp 866-872, 1999.*

[4] H.Mao, S.Deng, J.Abu-Qahouq, I.Batarseh, "Active-Clamp Snubbers for Isolated Half-Bridge DC-DC Converters", *IEEE Transaction on Power Electronics, Vol.20, No.6, pp1294-1302, 2005.*

[5] K.Fathy, K.Morimoto, T.Doi, H.Ogiwara, H.W.Lee, M.Nakaoka, "A Diveided Voltage Half-Bridge High Frequency Soft-Switching PWM DC-DC Converter with High and Low Side DC Rail Active Edge Resonant Snubbers", *IPEMC 2006, vol. 2, pp. 1-5, 2006.*

[6] M.Takagi, K.Shimizu, T.Zaitsu, "Ultra High Efficiency of 95% for DC/DC Converter - Considering Theoretical Limitation of Efficiency", *IEEE APEC 2002, vol. 2, pp. 735-741, 2002.*

[7] P.Alou, J.Oliver, J.A.Cobos, O.Garcia, J.Uceda, "Buck+half bridge (d=50%) topology applied to very low voltage power converters", *APEC 2001, Sixteenth Annual IEEE Volume 2, pp 715-721, 2001.*

[8] G.Guidi, T.M.Undeland, Y.Hori, "An Interface Converter with Reduced VA Ratings for Battery-Supercapacitor Mixed Systems", *IEEE PCC 2007, pp 936-941, 2007.*

[9] B.Min, J.Lee, J.Kim, T.Kim, D.Yoo, E.Song, "A New Topology with High Efficiency throughout All Load Range for Photovoltaic PCS", *IEEE Transaction on Industrial Electronics, Vol.56, No.11, pp4427-4435, 2009.*

[10] J.Itoh, T.Fujii, "A new approach for high efficiency buck-boost DC/DC converters using series compensation", *PESC 2008.IEEE, pp 2109-2114, 2008.*

[11] S.Miyawaki, J.Itoh, K.Iwaya, "High Efficiency Isolated DC/DC Converter Using series Voltage Compensation", *PCIM Europe 2009 Conference, pp66-71, 2009.*