High Efficiency Isolated DC/DC Converter using Series Voltage Compensation

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Abstract

A new circuit topology is proposed 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. The proposed circuit regulates the voltage output by the series converter, which provides only the differential voltage between the input voltage and output voltage. Therefore, the circuit achieves high efficiency when the input voltage is close to the output voltage, because only the resonance converter operates. The validity of the proposed circuit was confirmed by experiment and loss analysis, with a maximum efficiency of 95.8%.

1. Introduction

Recently, the efficiency and size of power supplies for telecommunication applications and microprocessor boards have become very important issues. To achieve high efficiency and compact size, the power system is divided into several converters, such as a point-of-load converter, bus converter and front end converter. In this system, the power is distributed to the each device by a DC voltage line [1-3].

The DC bus converter, which regulates the constant DC voltage, is required at the input point of each device, because the DC bus voltage fluctuates due to the bus impedance. The DC bus converter is also used to obtain other DC voltage levels from the DC bus voltage. High efficiency DC/DC converters are required for the bus converters.

Resonant type half-bridge converters, which use the leakage inductance of transformers, are one of the most effective circuit topologies to obtain high efficiency. However, it is difficult to regulate the output voltage range for an input voltage fluctuation, because the switch 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 [4-5]. As a result, the converter loss increases, because all the power passes through two converters; the voltage control converter and a resonant-type converter.

This paper proposes a new topology for an isolated DC/DC converter with series voltage compensation. In the proposed circuit, the range of input voltage fluctuation is compensated by an auxiliary circuit that outputs only the differential voltage between the input and output side [6]. One of the advantages of the proposed circuit is that high efficiency can be achieved when the input voltage is close to the output 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, a decrease of the converter loss can be achieved.

Firstly, the approach used to obtain high efficiency with the proposed series compensation method is introduced in this paper. The circuit configuration that achieves the proposed method is described. Secondly, the operation mode is analyzed using a simple equivalent circuit of the proposed circuit. The stability of operation for the proposal circuit is clarified. In addition, the indicator for optimum design is clarified. Finally, experimental results and a loss analysis are presented in order to demonstrate the advantages of the proposed circuit.

2. Proposed Converter

2.1. Principle of series converter

Fig. 1 shows the configuration of a conventional DC/DC converter. The conventional circuit consists of a resonant half-bridge converter and a buck chopper. The fluctuation of the input voltage is constantly controlled by the buck chopper.

The voltage is then isolated by the resonant half-bridge converter.

This system has a two times power conversion from input to output. The total converter efficiency of the conventional circuit η_c is obtained from (1), using both the resonant type converter efficiency η_1 and the buck chopper efficiency η_2.

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

All power passes though both converters, despite the relation between the input and output voltage; therefore, the converter efficiency is decreased.

Fig. 2 shows the configuration of the proposed converter. In the proposed circuit, the resonant type half-bridge converter is used for the main circuit that channels most of the power. Zero current switching (ZCS) can be achieved by using the leakage inductance of the transformer and the resonance capacitor in the DC part, in order to achieve high efficiency.

The switching frequency of the main circuit is constrained by the resonance frequency. From the equivalent circuit of the transformer shown in Fig. 2, the resonant inductance of the proposed circuit L is obtained from (2), using the leakage inductance l_{xx}, mutual inductance M_{xx} and the number of wire turns N_{xx}.

$$L = l_{11} + \frac{M_1 (l_{12} + L_{R2})}{M_1 + (l_{12} + L_{T2})} \tag{2}$$

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

The resonant frequency of the proposed circuit f_o is obtained using (3)

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

On the other hand, a full-bridge converter is used for the auxiliary circuit that controls 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 differential voltage between the input voltage and the output voltage commands.

The proposed system consists of two power converters, which are connected in series to the output side. High efficiency is achieved in the proposed circuit as follows. The power P_{out} is obtained by adding the auxiliary converter power P_3 to the half-bridge converter power P_1. 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 $k=P_3/P_1$.

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

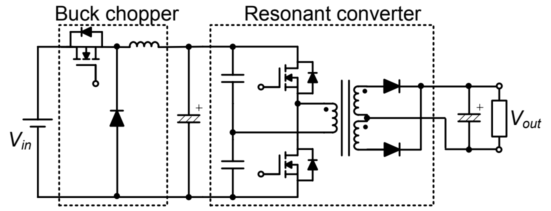


Fig. 1. Conventional circuit using a buck chopper and a resonant converter.

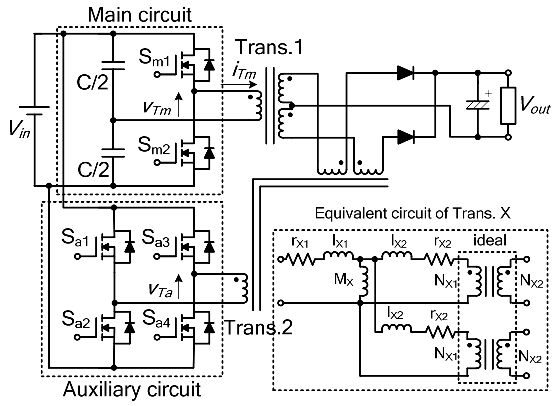


Fig. 2. Proposed circuit using series compensation.

Therefore, the total efficiency η_p of the proposed circuit is higher than the conventional circuit when the relation of efficiency for each circuit is given by (5).

$$\eta_p = \frac{\eta_1 + k\eta_3}{1+k} > \eta_1 \eta_2 \tag{5}$$

It should be noted that the proposed circuit uses many switching devices. However, the current rating of the auxiliary circuit is much lower than that of the main circuit.

2.2. Control Strategy

In the proposed circuit, the main circuit is controlled under optimum conditions by the resonant converter. In order to obtain maximum efficiency, the resonant converter functions at a 50% duty cycle, which is synchronous to the resonance frequency f_o. Therefore, the main circuit can achieve ZCS at any time.

Fig. 3 shows the operation mode and the waveforms in secondary side of the transformer when in boost mode. The switching timing of the auxiliary circuit is synchronous with the main circuit. The auxiliary circuit outputs three voltage levels; $+V_{dc}$,$-V_{dc}$ and zero voltage. When the input voltage is decreased (boost mode), the auxiliary circuit outputs a positive phase voltage to the main circuit without preventing the resonance operation of the main converter. Similarly, when the input voltage is increased (buck mode), the auxiliary circuit outputs a negative phase voltage.

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

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

Fig. 4 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 required 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. Note that the proposed converter has buck, boost or reference voltage modes, so that the auxiliary circuit does not operate when the input voltage is almost the same as the output voltage.

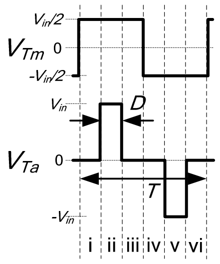
3. Operation mode analysis

3.1. Simple equivalent circuit

Fig. 5 shows the equivalent circuit of the proposed circuit under boost operation. In AC signal analysis, the switching operation of the main circuit and the rectifier part on the output side is expressed as a square wave, which has the amplitude of the input and output voltage, and the frequency of the switching frequency. The capacitors of the half-bridge converter can be represented as one resonance capacitor and ideal transformers with a turn ratio of 2:1. Moreover, the full-bridge converter in the auxiliary circuit is represented as two switches. When S_{add} is turned on, the additional voltage mode is engaged. When S_{short} is turned on, the zero voltage mode is engaged. These switches function with mutual and complementary synchronization of the switching frequency. Note that the excitation inductance of the transformer is disregarded, because it is much larger than the leakage inductance.

3.2. Derivation of the circuit equation

Fig. 6(a) and (b) show the simplified equivalent circuit separated into the main circuit side and auxiliary circuit side, respectively, 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 per-



State	Fig. 3			Fig. 6	
	S_{m1}	S_{a1}	S_{a3}	S_{add}	S_{short}
i	ON	OFF	OFF	OFF	ON
ii	ON	OFF	ON	ON	OFF
iii	ON	ON	ON	OFF	ON
iv	OFF	ON	ON	OFF	ON
v	OFF	ON	OFF	ON	OFF
vi	OFF	OFF	OFF	OFF	ON

$S_{m2} = \overline{S_{m1}}$, $S_{a2} = \overline{S_{a1}}$, $S_{a4} = \overline{S_{a3}}$

Fig. 3. Correspondence of the switching pattern and operation mode (boost operation).

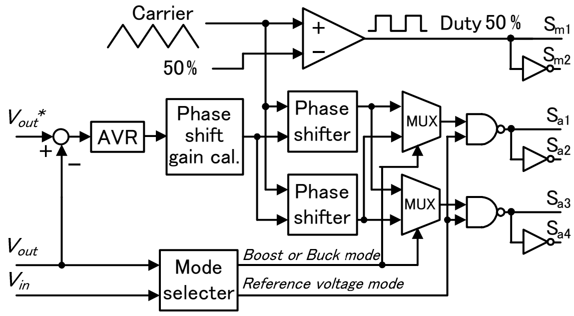


Fig. 4. Control block diagram.

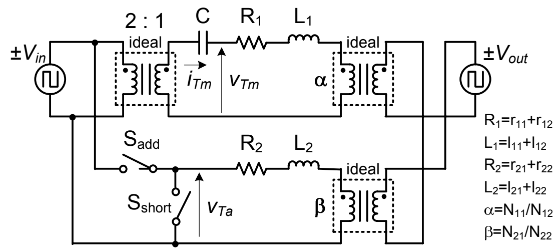
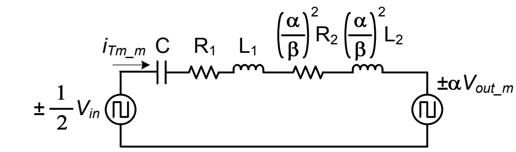
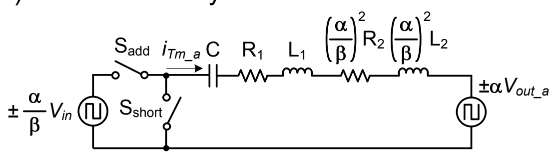


Fig. 5. Equivalent circuit of the proposed converter (boost operation).



(a) Main circuit only.



(b) Auxiliary circuit only.

Fig. 6. Simplified equivalent circuits for each circuit according to the superposition principle.

spective 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 (7),

$$i_{Tm} = i_{Tm\_m} + i_{Tm\_a} \quad (7)$$

where i_{Tm_m} is the input current on the main circuit side shown in Fig. 6(a) and i_{Tm_a} is the input current on the auxiliary circuit side shown in Fig. 6(b).

Consequently, the circuit equation of the entire circuit can be obtained by deriving each equation for each circuit equation in Fig. 6. The input currents i_{Tm_m} and i_{Tm_a} are obtained from (8) and (9).

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

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

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

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

$i_{m(k)}$ 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.

Thus, the current vibrates at angular frequency ω, and exhibits the phenomenon known as series resonance.

4. Design method

4.1. Basic principle and circuit specifications

Fig. 7 shows the design flowchart for the proposed circuit. Optimization of the design is achieved by following the design flow. Firstly, the design specifications, which consist of the volume of the circuit, the minimum power of the stable operation area P_{min}, the fluctuation range of the input voltage V_{fluc}, the input and output voltage V_{in}-V_{out}, and the rated power P_{max}, are determined by application. The resonance frequency is determined by the switching frequency. The resonance impedance is then designed based on the specifications. Specifically, the minimum value of the resonance inductance L is limited by the minimum power of the stable operation area P_{min}. After L is determined, C can be obtained by (3) according to the resonance frequency. Note that the resonance impedance is adjusted so that the maximum voltage of C is not larger than the minimum input voltage.

4.2. Determination of resonant inductance

In order to obtain high efficiency, stable operation is required. The boundary condition for stable operation depends only on the operation of the auxiliary circuit (Fig. 6(b)). Instability is caused by discontinuance of the resonance current in the light load area. In this state, the peak value of the transformer current increases significantly compared to that in continuous mode, because the same output power is obtained as that using a narrow current pass period. This is the same problem encountered for the continuous or discontinuous current mode of a boost reactor in a chopper circuit. Therefore, the continuous mode has to be maintained until the minimum power P_{min} is achieved. The lower limit of the light load in which continuous mode is maintained is dependent on the resonance impedance.

Fig. 8 shows the resonant current waveforms for the separate auxiliary circuit with the boundary condition shown in Fig. 6(b). The boundary condition indicates the edge state between the continuous and discontinuous current. At the boundary condition (i), the current value i_{Tm_a} until t_1 is zero. Next, i_{Tm_a} in section (ii) can be obtained from (10) using a linear approximation according to the inductance L and its voltage. Note that the capacitor voltage is equal to the output voltage.

$$i_{Tm\_a(ii)} = \frac{\alpha}{\beta}\cdot\frac{V_{in}}{L}\cdot D \quad (10)$$

i_{Tm_a} becomes the maximum at t_2, and decreases in section (iii). The output voltage period (output pulse width D in the auxiliary circuit) is limited according to (11).

$$2D_o > \frac{T}{2} - D \quad (11)$$

where D_o is the zero voltage period of the auxiliary circuit for a half cycle.

When the linear approximation is used, the current waveform can be approximated to a triangular shape. Therefore, the current mean value I_0 for the half cycle is obtained by (12).

$$I_0 = \frac{1}{T/2}\left\{\frac{1}{2}\cdot\frac{\alpha}{\beta}\frac{V_{in}}{L}D(D+D_0)\right\} \quad (12)$$

On the other hand, the current mean value I_0 is obtained from the output power with (13), using the load resistance R_L and the output voltage V_{out_a}.

$$I_0 = \frac{V_{out\_a}}{\alpha R_L} \quad (13)$$

Thus, the range of L for stable operation is obtained by (14), using (11) to (13).

$$L \geq \frac{\alpha^2 V_{in} R_L D}{4\beta V_{out\_a}}\left(1+\frac{D}{T/2}\right) \quad (14)$$

Consequently, the minimum value of L is limited by the output pulse width D and the load condition.

4.3. Design example

The table in Fig. 7 shows the specifications for the circuit.

The value of the minimum resonance inductance is obtained by (14) using the specifications given in Fig. 7. When P_{out} = 75 W, approximately 2.5 μH is necessary for the resonance inductance. The inductance is inserted in series to the primary side of the transformer in the main circuit, because the leakage inductance of the main transformer is insufficient. Moreover, C is determined by (3) to be 0.19 μF.

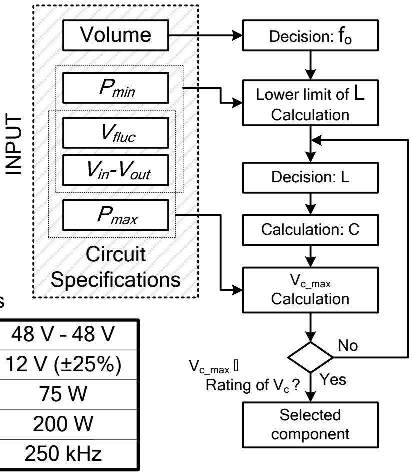
The maximum value of the resonance current I_{max} is then obtained from (15), using the maximum power P_{max}.

$$I_{max} = 2\cdot\frac{V_{in}}{V_{out}^2/P_{max}}\cdot\frac{\pi}{2} = 13\text{A} \quad (15)$$

Therefore, the maximum value of the resonance capacitor voltage V_{c_max} can be obtained from (16).

$$V_{c\_max} = \frac{I_{max}}{\omega C} = 45\text{V} \quad (16)$$

V_{c_max} is lower than the input voltage. Consequently, each element in the proposed circuit is selected.



V_{in} - V_{out}	48 V - 48 V
V_{fluc}	12 V (±25%)
P_{min}	75 W
P_{max}	200 W
f_o	250 kHz

Fig. 7. Design procedure flowchart.

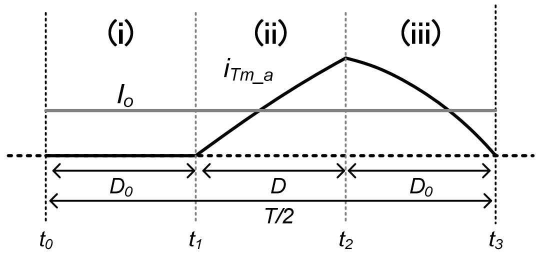


Fig. 8. Resonant current waveforms for the separate auxiliary circuit with the boundary condition shown in Fig. 6(b).

5. Experimental results

Fig. 9 presents the efficiency of the proposed converter at constant load (load: 100 W, output voltage: 48 V) when the input voltage has fluctuation of ±25%. To confirm the validity of the concept, the proposed converter was tested. A maximum efficiency of 95.8% was obtained, as shown in Fig. 9, when the input voltage was very close to the output voltage to maximize efficiency. The reason for the lower efficiency of the buck mode compared to that of the boost mode is that the current is increased due to the circulation current between the auxiliary and main circuits, and the switching loss is increased due to an increase in the input voltage.

Fig. 10 shows the input current of the transformer and the terminal voltage of S_{m2}. In both boost and buck modes, the half-bridge converter can maintain zero current switching. A switching frequency of approximately 250 kHz was confirmed.

Fig. 11 shows the loss analysis based on the simulated and experimental results. The simulated efficiency is in good agreement with that determined experimentally. Therefore, the converter loss can be discussed with respect to the loss analysis simulation. As a result, the switching loss in the auxiliary circuit increases in both boost and buck modes, and the loss in the transformer and the rectification diode are predominant.

6. Conclusion

A series-type isolated DC/DC converter consisting of a resonant-type half-bridge converter and an auxiliary converter was proposed. The concept for series compensation is to obtain the output voltage by adding or subtracting the auxiliary converter voltage to the half-bridge converter voltage. The operational mode of the proposed circuit was analyzed using a simple equivalent circuit, and the optimal design approach was clarified.

The experimental results demonstrated a maximum efficiency of 95.8% when the input voltage was close to the output voltage. It was confirmed that voltage control can be regulated while maintaining high efficiency.

In future work, the circuit topology will be optimized to reduce the switch count in the auxiliary circuit.

7. Literature

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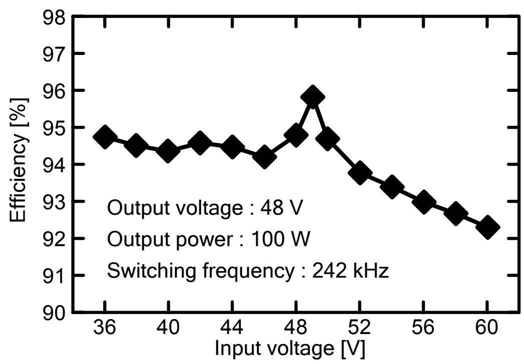
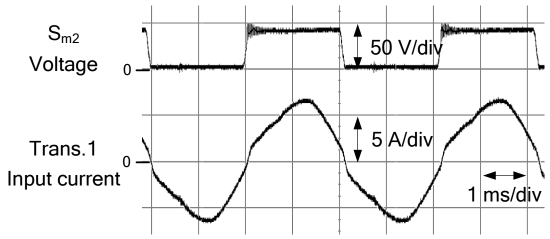
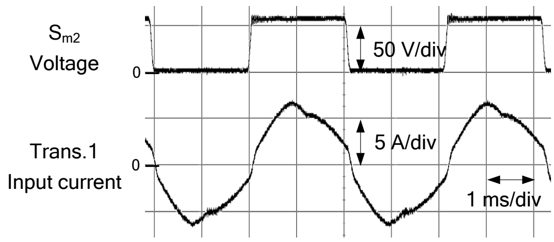


Fig. 9. Efficiency of the proposed circuit (experimental result).



(a) Boost mode (V_{in} = 40 V)



(b) Buck mode (V_{in} = 56 V)

Fig. 10. Waveforms of the input current of the transformer and the terminal voltage S_{m2}.

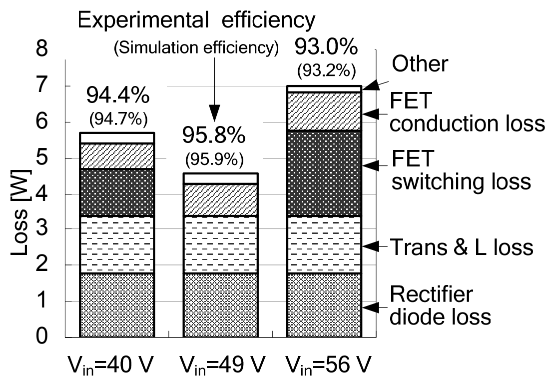


Fig. 11. Loss analysis at 100 W load based on loss simulation.