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High Power Full-Bridge DC-DC Converter using a Center-Tapped Transformer and a Full-Wave Type Rectifier

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Abstract

This paper proposes a high power full-bridge DC-DC converter, using a center-tapped transformer and a full-wave type rectifier. The proposed converter realizes unipolar primary voltage switching, using the unipolar pulse-width modulation (*PWM*) *technique. Also, the proposed converter reduces the freewheeling conduction loss, using the unipolar PWM technique and a resonant circuit, composed of a clamp capacitor and resonant inductor in the primary, and thus achieves high efficiency. However, because the proposed converter uses only a full-bridge circuit, center-tapped transformer, and full-wave type rectifier, the structure of the proposed converter is simple. In this paper, the operational principle of the proposed converter is described in detail, and a design example of a proposed converter prototype is shown. Finally, experimental results of the prototype are shown, to verify the feasibility of the proposed converter.*

Keywords: Full-bridge DC-DC converter, Center-tapped transformer, Full-wave type rectifier, unipolar PWM technique, Resonant circuit

1. Introduction

Recently, according to the increase of power capacity of electric/electronic devices, many high power DC-DC power converters have been proposed [1-15]. Among these power converters, conventional ZVS (Zero Voltage Switching) unipolar PWM full-bridge converters are a popular topology for medium/high power applications, offering desirable features, such as ZVS operation, and high efficiency.

However, the conventional ZVS full-bridge DC-DC converter has a serious disadvantage: that of the narrow ZVS range of the lagging leg. During the lagging leg transition under light load operation, the primary current decreases, and finally changes its polarity; but the energy available for charging or discharging the switch output capacitor is insufficient, which unfortunately results in hard switching conditions. However,because this also increases the circulating current under normal load, itresults in increase of the total conduction loss of the converter and the voltage/current stress of each switch.

Therefore, many research results have been proposed, to extend the ZVS range down to a light load [3-6]. But there are some disadvantages: in [3] and [4], the effective duty ratio should be reduced, and in [5] and [6], excessive conduction losses occur,due to an increased auxiliary resonant current.Also, it causes problems, such as the thermal problem and increased cost. Because of these problems, ZVS full-bridge DC-DC converters were proposed that use two transformers. But, this proposal cannot solve the bulky system problem. Half-

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bridge DC-DC converters with other methods [7-11] are proposed, but their output power was not large.

In this paper, a high power DC-DC converter using a center-tapped transformer and full-wave type rectifier is presented. A clamp capacitor and resonant inductance are used as a resonant circuit for the soft-switching of the converter primary, with the unipolar PWM technique. The proposed converter reducesfreewheeling conduction loss with the unipolar PWM technique, and a simple resonant circuit, composed of a clamp capacitor and resonant inductor. The proposed converter utilizes the unipolar PWM technique like the conventional full-bridge DC-DC converter, so its modification from the conventional converter circuit is easy. Thus, the proposed converter achieves high efficiency. Also,because the proposed converter is composed of only a full-bridge circuit, center-tapped transformer, and full-wave type rectifier, the structure of the proposed converter becomes simple. In this paper, theoperational principle is explained in detail, and a design example of a prototype of the proposed converter is shown. Experimental results based on the prototype are shown, to confirm the validity of the proposed converter.

2. Operational Principles

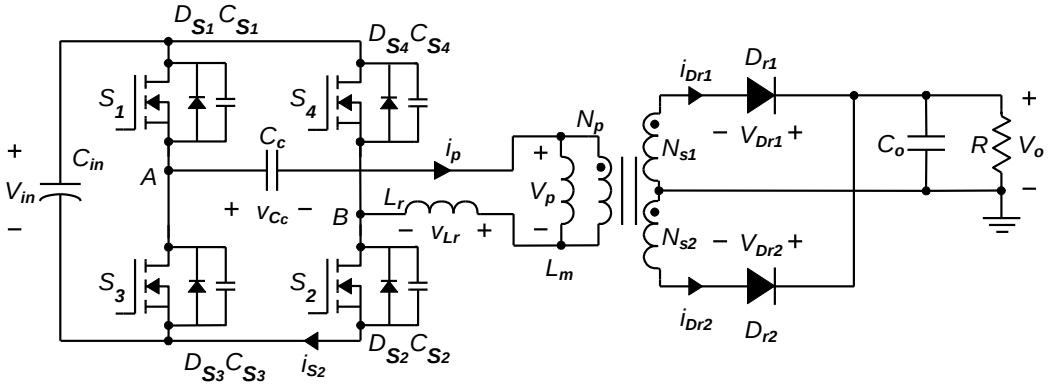


Figure 1. A circuit diagram of the proposed converter

Figure 1 shows a circuit diagram of the proposed full-bridge DC-DC converter. The proposed converter is composed of the primary, the center-tapped transformer, and the secondary. The primary part of the proposed converter is composed of a DC input source V_{in}, the main switches $S_1 \sim S_4$ of the full-bridge circuit, a clamp capacitor C_c, and a resonant inductor L_r. The secondary part of the proposed converter is composed of a full-wave type rectifier $D_{r1}$and D_{r2}, output filter capacitor C_o, and load R. The configuration of the proposed converter is basically similar to that of the conventional full bridge DC-DC converter, except for the center-tapped transformer, and resonant circuit, composed of a clamp capacitor and resonant inductor.

Figure 2 shows the key part waveforms of the proposed converter in steadystate. The proposed converter operatesbased onthe gate-source voltages $V_{GS1} \sim V_{GS4}$ of the main switches.The converter operation can be divided into six modes or three categories: ‘power delivery interval’, ‘freewheeling interval’, and ‘commutation interval’.

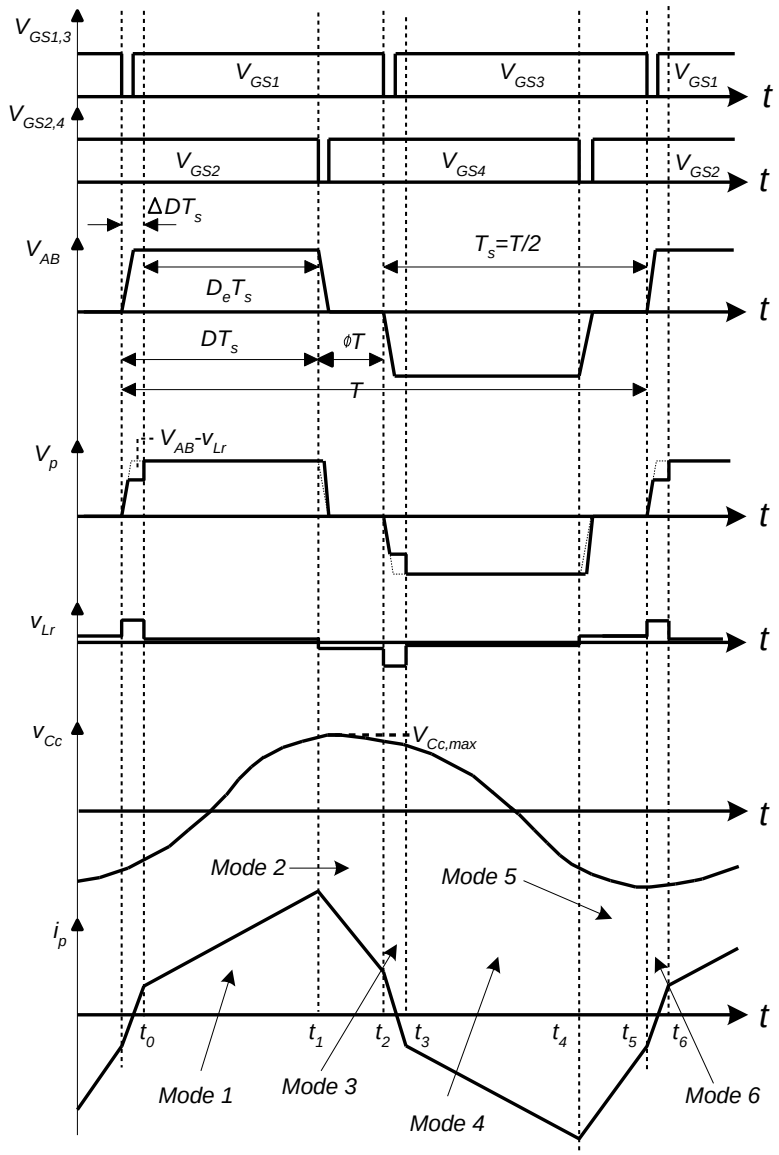
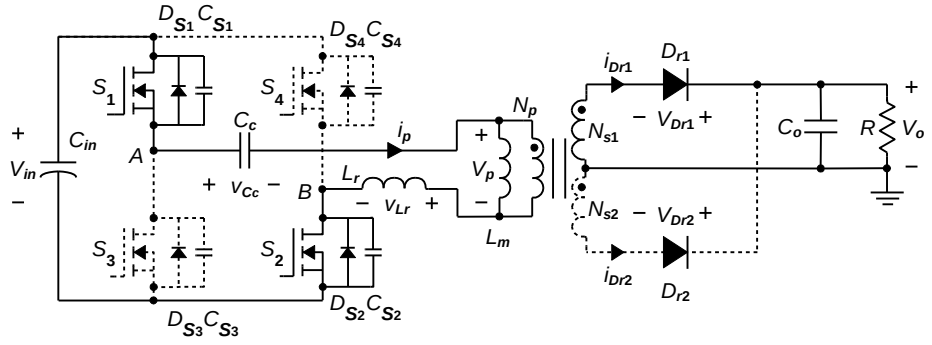


Figure 2. The key part waveforms of the proposed converter in steadystate

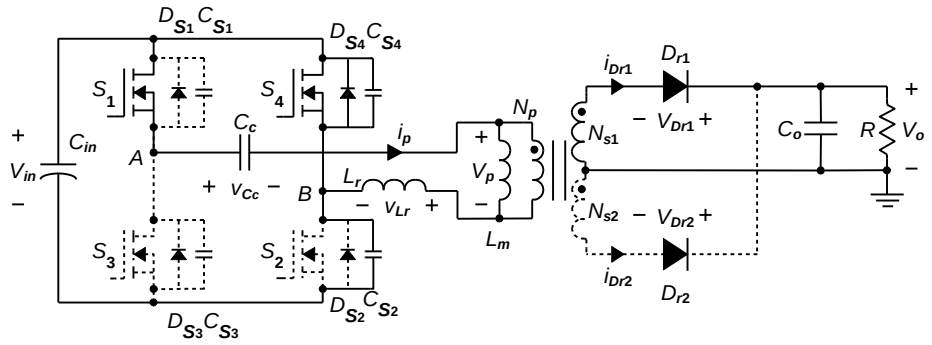
Figure 3 showsthe equivalent circuits of each mode of the proposed converter, where the bold lines denotepaths that conduct currents, andthe dotted lines denote paths that do not conduct current.

To illustrate the steady state operation, the following appropriate items are assumed:

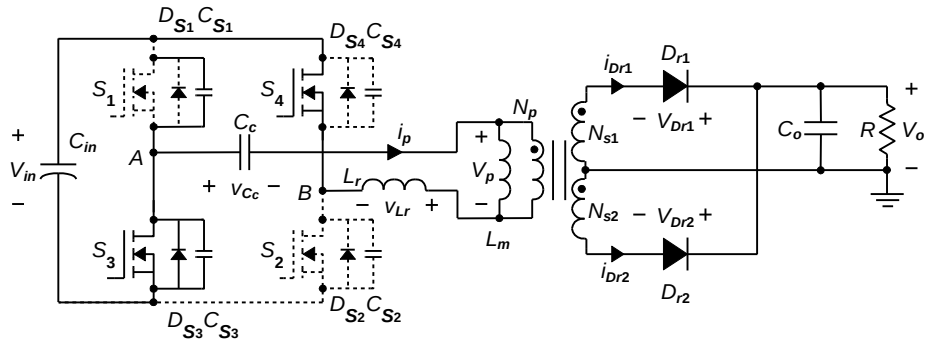
1) The power switches $S_1 \sim S_4$ are ideal, except for their anti-parallel diodes and parasitic capacitors.
2) The magnetizing inductance L_m is of very large value, and N_p and N_s ($N_s = N_{s1} = N_{s2}$) are the primary and the secondary turn numbers of the transformer, respectively.
3) The output voltage V_o is constant.



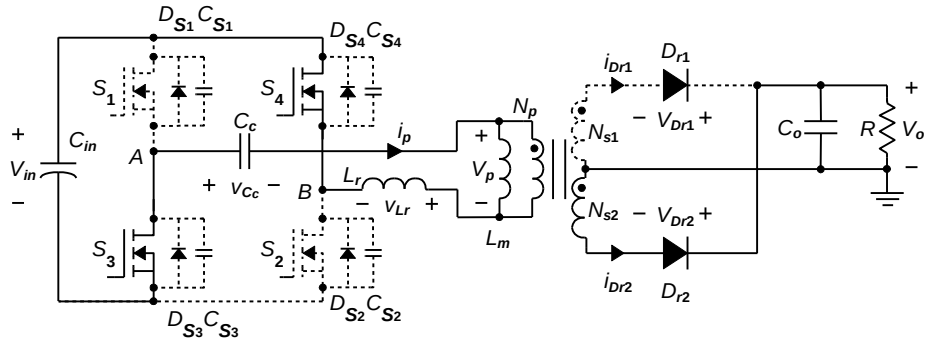
(a) Mode 1



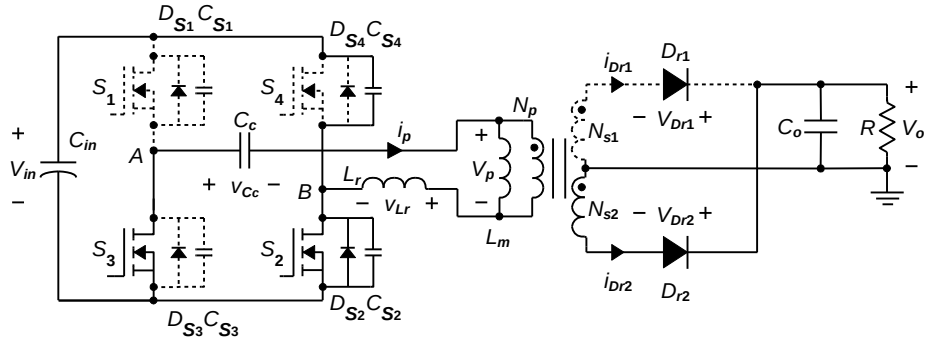
(b) Mode 2



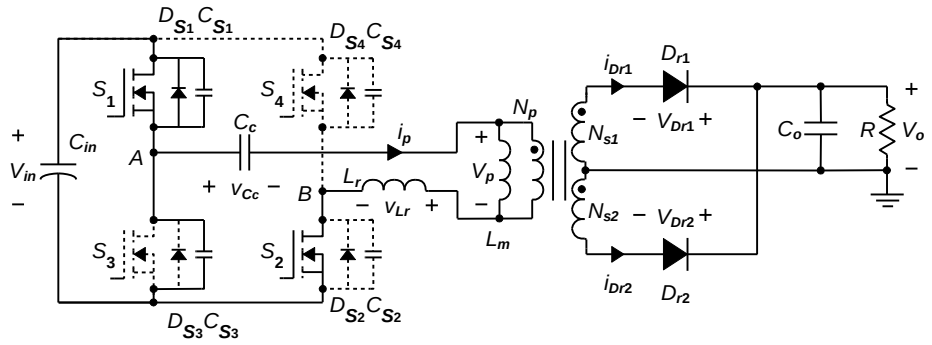
(c) Mode 3



(d) Mode 4



(e) Mode 5



(f) Mode 6

Figure 3. The equivalent circuits of each mode of the proposed converter

Mode 1(t_0~t_1): In this mode, the power is delivered from the primary to the secondary. This is the power delivery interval. The secondary diodes D_{r1} and D_{r2} are turned on and off, respectively. At this time, the primary current i_p increases almost linearly, as follows:

$$i_p = \frac{V_{in} - \frac{N_p \cdot V_o}{N_{s1}} - v_{Cc}}{L_r}(t - t_0) + i_p(t_0) \tag{1}$$

Then, the resonant inductor voltage v_{Lr} and the clamp capacitor voltage $v_{Cc}$are expressed, respectively, as follows:

$$v_{Lr} = L_r \frac{di_p}{dt} \tag{2}$$

$$v_{Cc} = \frac{1}{C_c}\int i_p dt \tag{3}$$

The slope of the primary current i_p is changed more rapidly by the clamp capacitor voltage v_{Cc}, compared with the conventional full-bridge DC-DC converter.

Mode 2(t_1~t_2): Mode 2 begins when the switch S_2 is turned off at time $t = t_1$. This mode is the freewheeling interval. The primary current i_p charges and discharges the parasitic

capacitors C_{S2} and $C_{S4}$of the switches $S_2$and S_4, respectively. At this time, the primary current $i_p$can be expressed as follows:

$$i_p = -\frac{\frac{N_p \cdot V_o}{N_{s1}} + v_{Cc}}{L_r}(t - t_1) + i_p(t_1) \quad (4)$$

The anti-parallel diode D_{S4} of switch S_4 conducts, and thus the ZVS of $S_4$is achieved.

Mode 3($t_2 \sim t_3$): Mode 3 begins when the switch S_1 is turned off at time $t = t_2$,. During mode 3, the direction of primary current i_p is changed, which is different from modes 1 and 2. The primary current i_p is expressed by the following equation:

$$i_p = -\frac{V_{in} + v_{Cc}}{L_r}(t - t_2) + i_p(t_2) \quad (5)$$

At time $t = t_3$, the commutation between secondary diode D_{r1} and $D_{r2}$is completed, and this mode ends.

Since from mode 4, the mode operations are symmetric in the current conducting paths and components, as shown in Figures 2 and 3, the explanation of the next three modes, modes 4~6, can conveniently be omitted.

3. Design Examples

In order to verifythe performance of the proposed converter, a prototype of the proposed converteris designed and implemented, based on the following Table 1:

Table 1. Design specifications of theprototype converter

Item	Symbol	Value
Input DC voltage	V_{in}	380V
Output DC voltage	V_o	24V
Max output power	$P_{o,\max}$	960W
Switching frequency	f	100kHz
Effectiveduty ratio	D_e	0.5

Based on the structure and operation of the proposed converter, the main center-tapped transformer turn ratio N (=N_s/N_p) is calculated by the following equation:

$$V_o = D_e \cdot N \cdot V_{in} \quad (6)$$

where, D_e is the effective duty ratio of the converter primary voltage applied to the bridge points A-B. Thus, based on the design specifications of Table 1, the turn ratio is set as $N \approx 0.13$.

At modes 1 and 3, the clamp capacitance C_c is calculated by its maximum voltage $V_{Cc,\max}$at mode 3, and the maximum voltage $V_{Cc,\max}$is calculated by the ripple voltage of the clamp capacitor from equation (3), as follows:

$$V_{Cc,\max} = \frac{1}{2}\Delta v_{Cc} = \frac{1}{2} \cdot \frac{NI_o}{2} \cdot \frac{1}{C_c} \cdot \frac{T}{2} = \frac{NI_oT}{8C_c} \quad (7)$$

where,I_o is the load current at maximum output power $P_{o,\max}$.From equation (7), the clamp capacitanceC_c is given by the following equation:

$$C_c = \frac{NI_oT}{8V_{Cc,\max}} \quad (8)$$

In order that the slope of the primary current$i_p$becomes positive, the following relation should be satisfied:

$$V_{in} - \frac{V_o}{N} > v_{Cc} \approx V_{Cc,\max} \quad (9)$$

Therefore, the clamp capacitance C_c can be calculated using equations (8) and(9), as follows:

$$C_c > \frac{NI_oT}{8V_{Cc,max}} \approx 0.325\mu\text{F} \quad (10)$$

From equation (9), the maximum value $V_{Cc,\max}$of the clamp capacitor voltage should be less than $V_{in} - \frac{V_o}{N}$. Here, the design margin of the maximum value $V_{Cc,\max}$ is considered, whichis set to about 10% of thevoltage $V_{in} - \frac{V_o}{N}$. Therefore, the clamp capacitance C_c was selected as an approximated value ofC_c=0.33μF. Thus,by equation (7), the maximumclamp capacitor voltage$V_{Cc,\max}$is modified to $V_{Cc,\max} \fallingdotseq 20\text{V}$.

In order to achieve the ZVS of the primary full-bridge circuit,normally the lagging-leg switchesS_2 and S_4 must operate as the ZVS at the turn-off condition. This means that the following relation should be satisfied:

$$\frac{1}{2}L_rI_{p,pk}^2 > 2 \cdot \frac{2}{3}C_SV_{in}^2 \quad (11)$$

where, theleft side $(1/2)L_rI_{p,pk}^2$ is the energy stored in L_r at mode 1,and the right side $2 \cdot (2/3)C_SV_{in}^2$is the double margin value of the energy comingout from the resonant inductor L_r, whichthe parasitic capacitors of the lagging-leg switches S_2 and S_4 should charge or discharge.So the peak value $I_{p,pk}$ of the primary current $i_p$can beapproximately calculated by the following equation:

$$I_{p,pk} \approx \frac{V_{in}-\frac{V_o}{N}-v_{Cc}}{L_r} D_e T_s \quad (12)$$

where,$D_e T_s$ is the effective on-duty time, which can be approximated as the time of mode 1.Therefore, the resonant inductance L_r can be calculated using equations (11) and(12), as follows:

$$L_r < \frac{(\left(V_{in}-\frac{V_o}{N}-v_{Cc}\right)D_e T_s)^2}{2\cdot\frac{2}{3}C_s V_{in}^2} \approx 887\mu\text{H} \quad (13)$$

where,the parasitic capacitance C_s of the MOSFET switches is selected as C_s =2200pF, according to the specification of the MOSFET used, FQA24N50. Thus, the resonant inductance L_r is selectedas $L_r = 100\mu$H.

4. Experimental Results

To verify the effectiveness of the proposed converter, a prototype of the proposed converter is implemented, with the specifications of Table 1 in Section 3.

Figure 4 shows the experimental waveforms of the gate-source driving voltages of the upper MOSFET switches $S_1$and S_2 , and the bridge voltage V_{AB} of the primary full-bridge MOSFET circuit. From this, it can be known that the control and driving circuit operations of the proposed converter are good, and the full-bridge circuit is well operated by the operations of the control and driving circuits.

Figure 5 shows the experimental waveforms of the primary voltages and currents of the primary full-bridge circuit, which let us know that the full-bridge circuit is well designed and operated, because the experimental waveforms coincide with the theoretical waveforms of Figure 2.

Figure 6 shows the experimental waveforms of the secondary output voltage, and current of the proposed converter. This shows that the proposed converter operates well and stably, as a high power DC-DC converter.

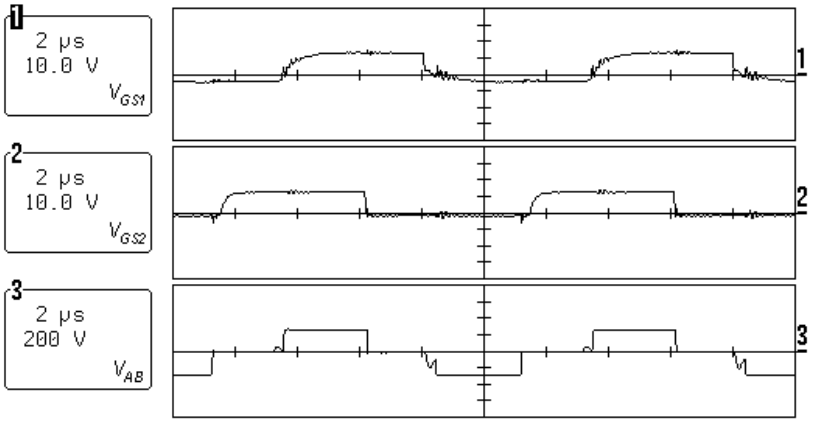


Figure 4. Experimental waveforms of the gate-source driving voltages of the upper switches, and the bridge voltage of the primary full-bridge circuit

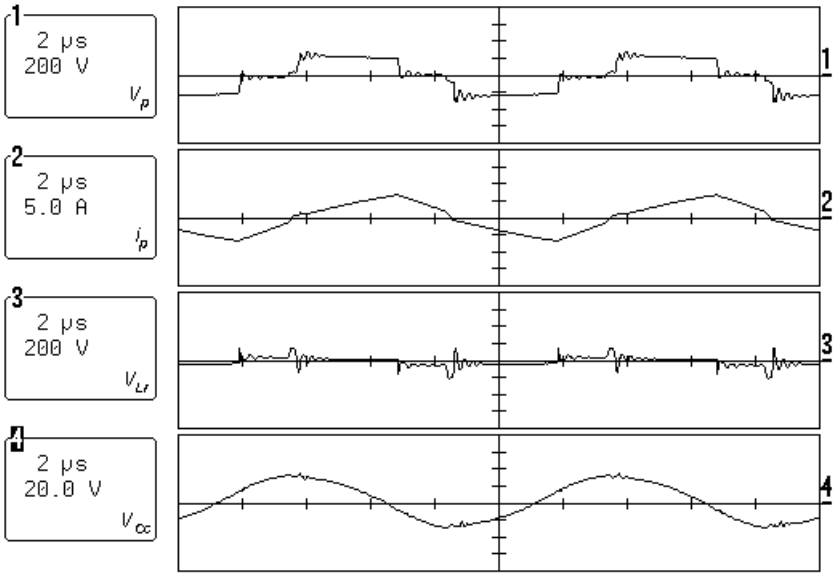


Figure 5. Experimental waveforms of the primary voltages, and current of the full-bridge circuit

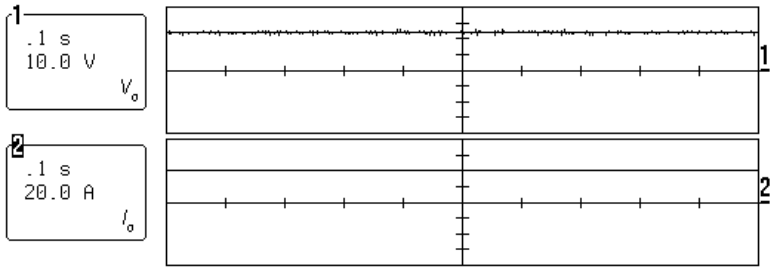


Figure 6. Experimental waveforms of the secondary output voltage, and current of the proposed converter

5. Conclusion

In this paper, a high power DC-DC converter is proposed, using a center-tapped transformer and full-wave type rectifier. A simple resonant circuit, composed of a clamp capacitor and resonant inductor, is used for soft-switching of the converter primary, with the unipolar PWM technique. The proposed converter reduces freewheeling conduction loss,using the unipolar PWM technique, and a simple resonant circuit. Thus, the proposed converter achieves high efficiency. However, the proposed converter utilizes the unipolar PWM technique, like the conventional full-bridge DC-DC converter. Because the proposed converter is composed of a full-bridge circuit, center-tapped transformer, and full-wave type rectifier, the structure of the proposed converter is simple. In this paper, the operational principle is explained in detail,according to each operation mode; and a design example of a prototype of the proposed converter is shown. Experimental results based on the implemented

prototype are shown, to confirm the validity of the proposed converter. The proposed converter shows good performance as a high power DC-DC converter.

Acknowledgements

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