Parallel Operation of Trans-Z-Source Network Full-Bridge DC-DC Converter for Wide Input Voltage Range

Hyeongmin Lee*, Heung-Geun Kim*, and Honnyong Cha*

Abstract – This paper presents a novel transformer isolated parallel connected full-bridge dc-dc converter using recently developed trans-Z-source network. Unlike the traditional voltage -fed or current-fed converters, the proposed converter can be open- and short-circuited without damaging switching devices. Therefore, the desired buck and boost function can be achieved and the converter reliability can be greatly improved. A 6 kW prototype dc-dc converter is built and tested to verify performances of the proposed converter.

Keywords : Buck-boost converter, dc-dc converter, parallel operation, interleaved PWM, trans-Z-source, Z-source

1. Introduction

In general, there are two full-bridge (FB) transformer isolated dc-dc converters: a voltage-fed (VF) FB converter and a current-fed (CF) FB converter. Fig. 1 and 2 show two traditional transformer isolated dc-dc power conversion circuits. The VF FB converter shown in Fig. 1 has always buck (step-down) function and the upper and lower switches consisting of a phase leg cannot be short-circuited [1-3]. Similarly, the CF FB converter shown in Fig. 2 has always boost (step-up) function and the upper and lower switches consisting of a phase leg cannot be open-circuited.

From the aforementioned reasons, the two traditional circuits shown in Fig. 1 and 2 can only produce output voltage smaller than or greater than input voltage. Furthermore, they cannot be either short- or open-circuited, thus the conventional VF and CF converters are very susceptible to EMI noise and hence system reliability of these converters is greatly impaired.

Parallel operation of power converter has been a general method of increasing power level easily in power electronics area. With the help of parallel operation, low current rating semiconductor devices can be used without over-sizing a converter module [4-7]. When multiple converters are connected in parallel, an interleaved PWM

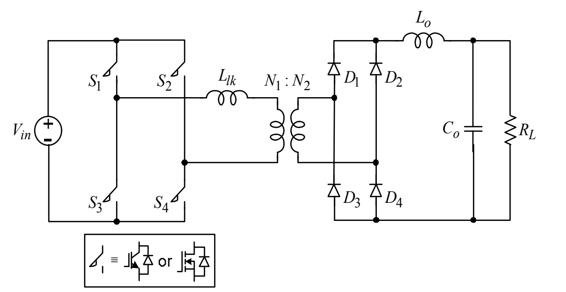

Fig. 1. Traditional V-fed FB DC-DC converter

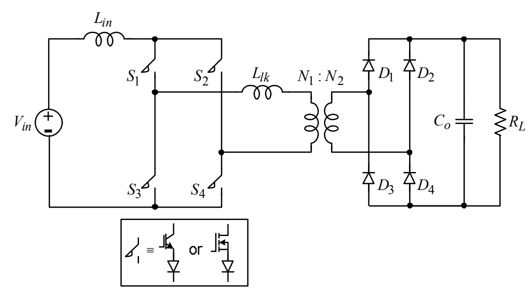

Fig. 2. Traditional C-fed DC-DC converter

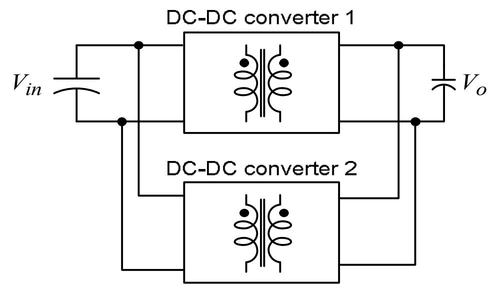

Fig. 3. Parallel operation of dc-dc converter

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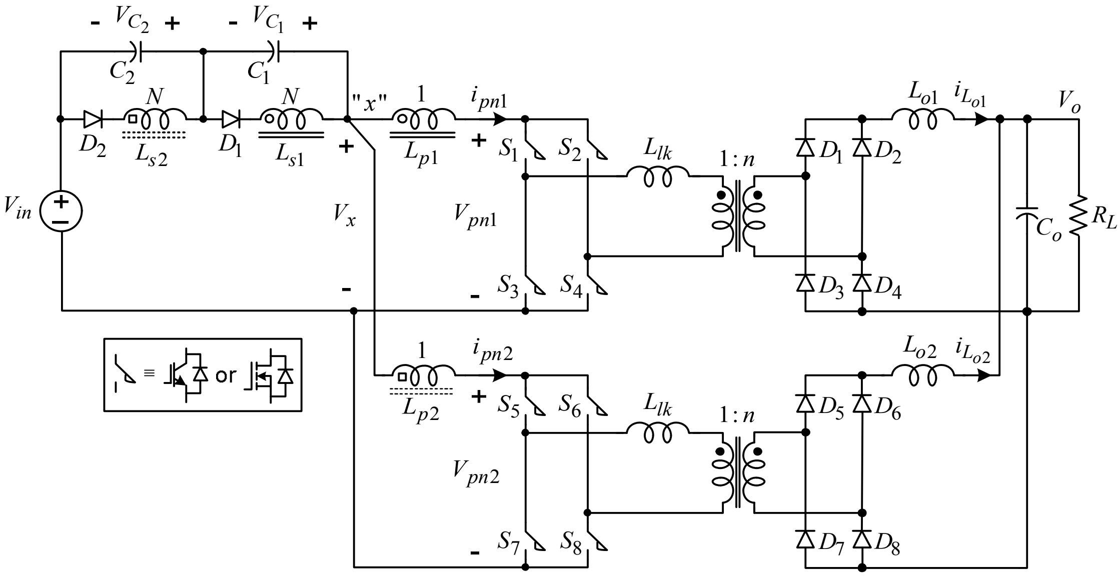
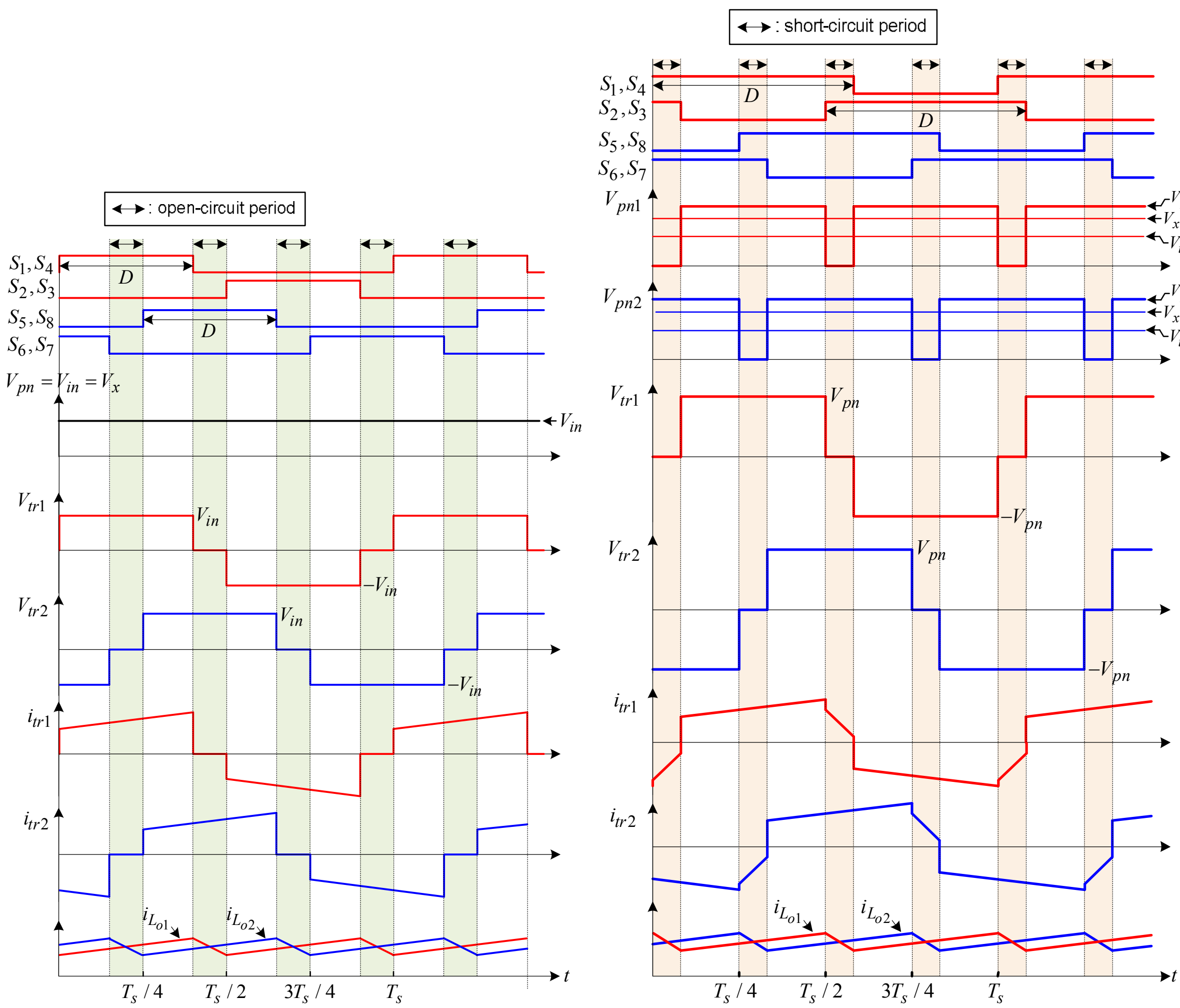


Fig. 4. General circuit configuration of the proposed Trans-Z-Source network parallel connected FB dc-dc converter



(a) Buck mode ($V_{in} > V_o$, $D < 0.5$) **(b)** Boost mode ($V_{in} < V_o$, $D > 0.5$)

Fig. 5. Operation mode of the proposed converter

method is widely used to decrease input and output current ripple. Thus, it can reduce the input and output capacitor volume and increase converter efficiency.

In this paper, a novel transformer isolated and parallel connected FB dc-dc converter is introduced. Fig. 3 shows the general configuration of parallel operation of dc-dc converters. In order to achieve the desired buck and boost function, the recently developed trans-Z-source network is used and connected in a special manner shown in section II [8-10]. With this structure, the proposed dc-dc converter has the following advantages over conventional converters.

- The proposed converter can be short- and open-circuited without damaging switching devices.
- The converter can operate in a very wide input voltage range because it has the buck and boost function.
- It can be applied to high power system with the help of parallel operation.

The system reliability is greatly improved by both parallel operation of the converter and the trans-Z-source network.

2. Principle Operation of Parallel Connected FB Trans-Z-Source Network DC-DC Converter

Fig. 4 shows overall circuit configuration of the proposed dc-dc converter. As shown in Fig. 4, two identical transformer isolated FB dc-dc converters are connected in parallel to increase power rating of the converter. The trans-Z-source network is inserted between the main input voltage and the switching devices.

In Fig. 4, (L_{p1}, L_{s1}) and (L_{p2}, L_{s2}) represent primary and secondary inductances of each coupled inductor in the trans-Z-source network. Primary windings of each coupled inductors (L_{p1}, L_{p2}) are connected between point "x" (see Fig. 4) and the switching devices of each dc-dc converter, whereas secondary windings of each coupled inductors (L_{s1}, L_{s2}) are connected in series with diodes (D_1, D_2) and they are connected in parallel with capacitors (C_1, C_2). With this configuration, the capacitor voltages (V_{C_1}, V_{C_2}) in the trans-Z-source network are added together and therefore V_x is expressed as follows

$$V_x = V_{in} + (V_{C_1} + V_{C_2}) \tag{1}$$

Therefore, the desired high voltage gain can be obtained even with small coupled inductor turns ratio (N).

Fig. 5 depicts theoretical waveforms of the proposed converter. As shown in Fig. 5, the two diagonal switches (S_1, S_4) and (S_2, S_3) or (S_5, S_8) and (S_6, S_7) are simultaneously on and off. Gate signals of the bottom converter ($S_5 - S_8$) are shifted by 90 degrees to the gate signals of top converter ($S_1 - S_4$) to achieve interleaved PWM switching.

Depending on the duty cycle (D) of the converter, there are two operating mode in the proposed converter. In mode 1 called buck mode in this paper, D is smaller than 0.5 and in mode 2 called boost mode, D is greater than 0.5. In the buck mode, there is open-circuit (or dead time) interval in the gate signal because $D < 0.5$ and short-circuit (or shoot-through) interval in the gate signal in boost mode because $D > 0.5$. Therefore, the desired buck and boost function of the converter can be achieved by modulating D.

2.1 Buck mode operation ($V_{in} > V_o$, $D < 0.5$)

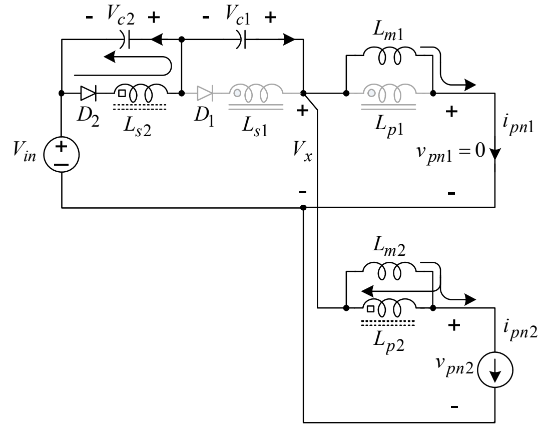
In this mode, there is no shoot-through interval and the diodes D_1, D_2 are always conducting. No energy is stored in the two coupled inductors and thus V_{C_1}, V_{C_2} is zero. Therefore V_{pn1}, V_{pn2} and V_x is equal to the input voltage, V_{in}. As a consequence, the converter operates as the conventional parallel connected FB dc-dc converters shown in Fig. 3. Voltage gain of the proposed converter in this mode is expressed as

$$\frac{V_o}{V_{in}} = nD' \tag{2}$$

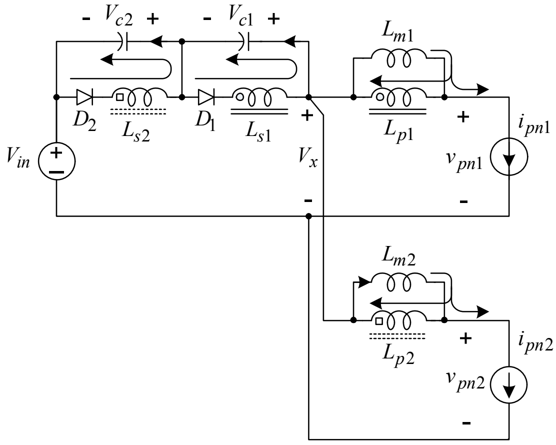
,where n represents transformer turns ratio of the converter and D' is the equivalent duty cycle of the converter and is defined as $D' = 2D$.

2.2 Boost mode operation ($V_{in} < V_o$, $D > 0.5$)

In the boost mode, there is a shoot-through interval in the gate signal and energy is stored in the two coupled inductors. Fig. 6 shows equivalent circuit and operation of the proposed converter in boost mode. The two coupled inductors are modeled as a magnetizing inductance, L_{m1}, L_{m2}, and an ideal transformer with a turns ratio of $1:N$ ($N_p : N_s$). Leakage inductance of the coupled inductor is assumed to be zero for the sake of simplicity. Fig. 6 (a) shows the operation when the top converter is in the shoot-through and the bottom converter in the non-shoot-through state, respectively.



(a) Boost mode 1



(b) Boost mode 2

Fig. 6. Operation of the proposed converter in boost mode

Fig. 6 (b) shows the operation when both the top and bottom converter is in the non-shoot-through state. More detailed mode analysis will be included in the final paper.

From the flux balance condition on the coupled inductors, the converter dc-link voltage V_{pn1} and V_{pn2} defined as V_{pn} in this paper is expressed as follows;

$$V_{pn} = \left(\frac{1}{1-D_{sh}}\right)V_x \qquad (3)$$

,where D_{sh} represents shoot-through duty ratio of the converter and D_{sh} is $(2D-1)$.

If the two coupled inductors are identical both in inductance value and turns ratio, then the capacitor voltage V_{C_1} and V_{C_2} must be same and defined as V_C in this paper. Therefore, V_C is $(V_x - V_{in})/2$. By using the aforementioned relationship and (3), V_x, V_{pn} and V_C can be expressed as

$$V_x = \left(\frac{1-D_{sh}}{1-(1+2N)D_{sh}}\right)V_{in} \qquad (4)$$

$$V_{pn} = \left(\frac{1}{1-(1+2N)D_{sh}}\right)V_{in} \qquad (5)$$

$$V_C = \left(\frac{ND_{sh}}{1-(1+2N)D_{sh}}\right)V_{in} \qquad (6)$$

, where N is turns ratio of the coupled inductor.

Therefore, voltage gain of the proposed converter in boost mode is expressed as follows;

$$V_o = \frac{n(1-D_{sh})}{1-(1+2N)D_{sh}}V_{in} \qquad (7)$$

Since $D_{sh} = 2D-1$, (7) can be rewritten as

$$V_o = \frac{n(1-D)}{1+N-(1+2N)D}V_{in} \qquad (8)$$

Fig. 7 shows the plot of voltage gain of the proposed converter when D varies. As expected, desired buck-boost function can be achieved by changing D.

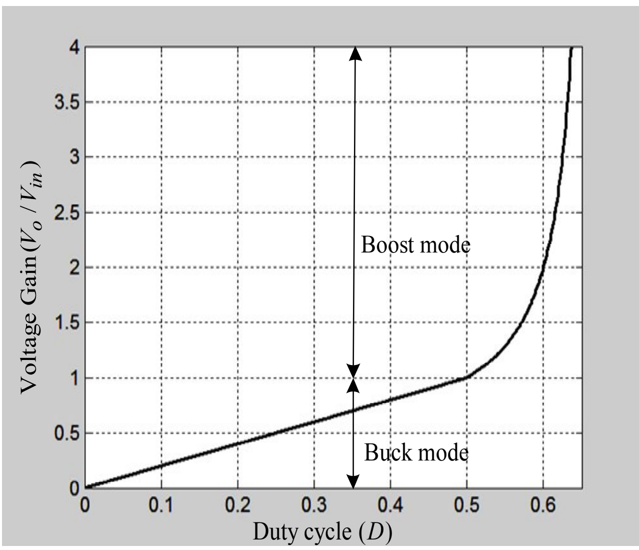


Fig. 7. Voltage gain of the proposed converter

Table 1. Electrical specification of the proposed dc-dc converter

Output Power		6 kW
Input voltage range		200~600 Vdc
Output voltage		400Vdc
Coupled inductor in trans-Z-source network	L_{p1}, L_{s1}	$210\mu H$
	L_{p2}, L_{s2}	$210\mu H$
Z-source capacitor (C_1, C_2)		$100\mu F$
Transformer turns ratio (n)		1:1
Transformer leakage inductance (L_{lk})		$3\mu H$
IGBT		BSM75GB120DLC
Diode		RHRG75120
Output filter inductor (L_{o1}, L_{o2})		$1mH$
Output filter capacitor (C_o)		$2mF$
Switching frequency		$25kHz$

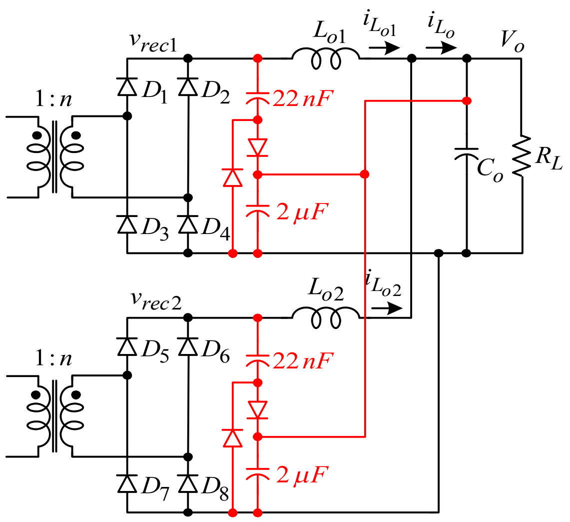


Fig. 8. Secondary side lossless snubber circuit

3. Experimental Waveforms

Based on the above analysis, a 6 kW prototype dc-dc converter is built and tested. Table I shows the electrical specifications of the proposed dc-dc converter and list of components used. As shown in Table 1, the proposed converter has very wide input voltage range. In the experiment, a lossless snubber circuit as shown in Fig. 8 is employed in the secondary side rectifier diodes to suppress the voltage overshoot across rectifier diodes caused by both the rectifier diode reverse recovery current and the oscillation between transformer leakage inductance (L_{lk}) and junction capacitance of rectifier diodes (C_j) [11-14].

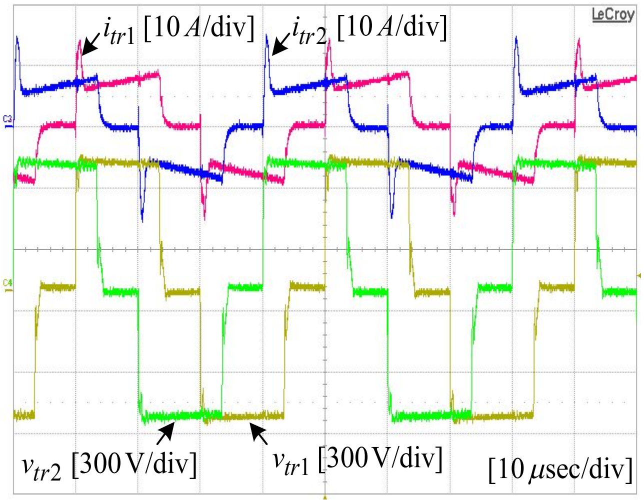


Fig. 9. Experimental waveform at buck mode when $V_{in} = 600V$, $V_o = 400V$ and $P_o = 6kW$

Fig. 9 shows the transformer voltage and current waveforms of the dc-dc converter at the buck mode when $V_{in} = 600V$, $V_o = 400V$ and $P_o = 6kW$. Fig. 10 shows the same waveforms at boost mode when $V_{in} = 200V$, $V_o = 280V$ and $P_o = 3kW$. As shown in Fig. 9 and 10, the two top and bottom FB dc-dc converters are phase shifted by 90 degrees and switched at 25 kHz. Therefore, the equivalent phase shift angle and switching frequency in both the trans-Z-source network and the secondary diode rectifier becomes 180 degrees phase shifted and thus switched at 50 kHz equivalently.

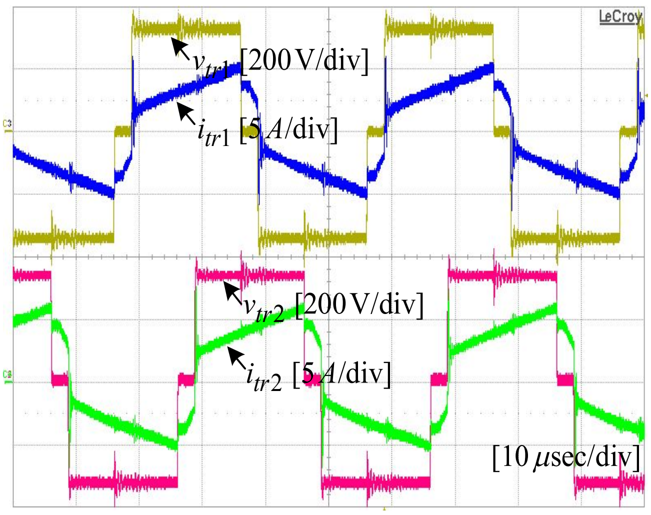


Fig. 10. Experimental waveform at boost mode when $V_{in} = 200V$, $V_o = 280V$ and $P_o = 3kW$

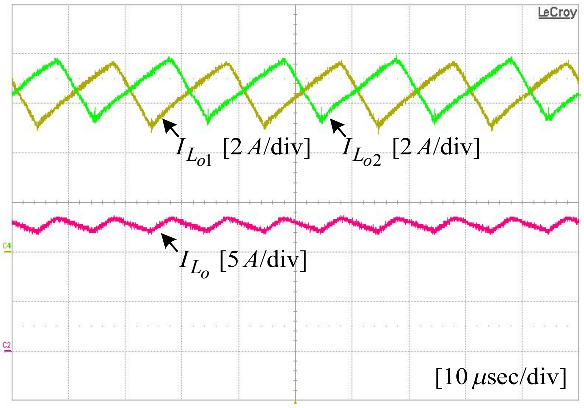


Fig. 11. Inductor and output current waveform when $V_{in} = 600V$, $V_o = 400V$ and $P_o = 6kW$

Fig. 11 shows the output inductor current ($I_{L_{o1}}, I_{L_{o2}}$) and output current (I_{L_o}) waveforms, respectively. Due to interleaving effect, the output current ripple is reduced significantly. Fig. 12 shows the voltage across secondary rectifier diode (v_{rec1}, v_{rec2}) using the lossless snubber circuit shown in Fig. 8. As expected, the diode voltage is well clamp. Fig. 13 shows the photo of the 6 kW proposed converter.

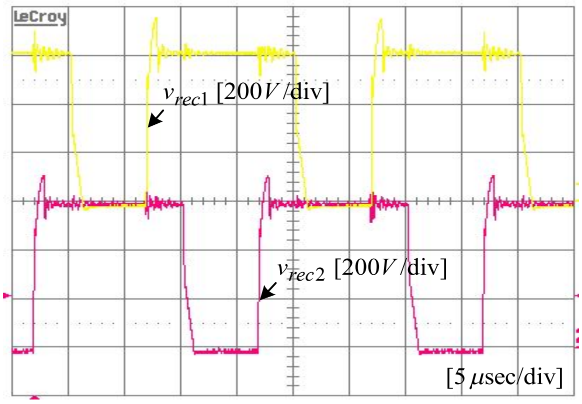


Fig. 12. Rectifier diode voltage when $V_{in} = 600V$, $V_o = 400V$ and $P_o = 6kW$

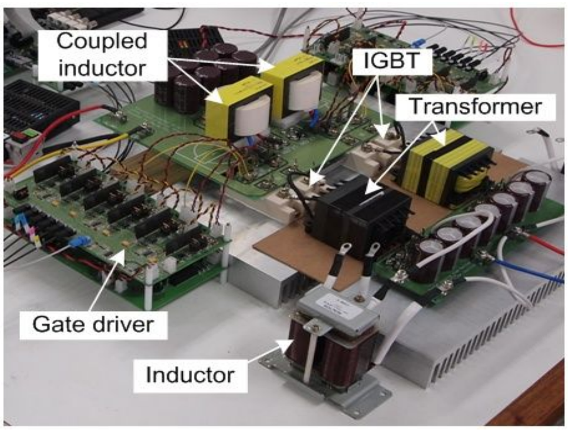


Fig. 13. 6 kW prototype photo

4. Conclusions

In this paper, parallel operation of the FB dc-dc converter using the recently developed trans-Z-source network is introduced. With this configuration, the proposed converter has the following features.

- It has both buck and boost functions. Output voltage can be greater or smaller than input voltage. Thus it is a very desirable circuit topology when the input voltage range of the converter is wide.
- It can be short- and open-circuited without damaging switching devices. Therefore, it is very resistant to EMI noise and therefore its robustness and reliability are significantly improved.
- The proposed converter has all the advantages of paralleling power converters such as modularity, ease of maintenance, (n+1) redundancy, high reliability, etc.

A 6 kW prototype consisting of two parallel FB dc-dc converters has been built and successfully tested to verify operation principle of the proposed converter. By using the buck and boost function of the proposed converter, the proposed converter can be a good candidate in such systems as requiring wide input voltage variation.

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