A Study on the Secondary Rectification-Methods for the Three-Level Converter

Jin-Yong Bae* and Yong Kim†

Abstract - This paper proposes a coupled inductor-based rectifier of a Three-Level (TL) DC/DC converter and compares the rectification methods of a TL converter. The CICDR-TL (Coupled Inductor Current Doubler Rectifier Three-Level) converter achieves ZVS (Zero Voltage Switching) for the switches in a wide load range. CDR (Current Doubler Rectifier) and CICDR Three-Level converter have low voltage and current ripple. Advantages and disadvantages of topology compared to the rectifier of bridge, center-tap, CDR, and CICDR are discussed. Experimental estimation results are obtained on a 27V, 60A DC/DC TL converter prototype for the 1.8kW, 40kHz IGBT based experimental circuit.

Keywords: Three-Level Converter, CDR (Current Double Rectifier), CICDR (Coupled Inductor Current Double Rectifier)

1. Introduction

The TL (Three-Level) converter has attracted more and more attention in high voltage and high power conversion applications because its power switches withstand only half of the input voltage. In order to increase the efficiency and reduce the weight and volume, several soft-switching TL converters have been proposed in recent years. The ZVS (Zero-Voltage-Switching) PWM TL converter realizes ZVS for all switches by means of the leakage inductance of the transformer and the intrinsic capacitors of the switches. However, the outer switches will lose ZVS at light load, and the leakage inductance results in duty cycle loss. [1–6]

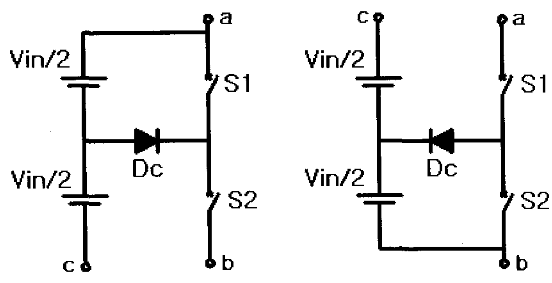
As an alternative rectification circuit, the CDR (Current Doubler Rectifier) has been proven to be promising for high current DC/DC converters. The applications for this kind of converter include high-input Voltage Regulator Modules, both load-end converters and front-end modules of Distributed Power Systems, and etc. Compared with the conventional bridge and center-tap rectifier, the CDR simplifies the structure of the isolation transformer, and reduces the secondary winding conduction loss by half. [6–7]

This paper proposes the CICDR-TL (Coupled Inductor Current Doubler Rectifier Three-Level) converter and investigates the comparison for rectification methods of the TL converter. Advantages and disadvantages of this topology compared to the conventional rectifier of bridge, center-tap, CDR, and CICDR are discussed. Good experimental results are obtained on a 27[V], 60[A] DC/DC TL converter prototype for the 1.8[kW], 40[kHz] IGBT based types.

2. The Previous Three-Level Converter

2.1 The Three-Level Switch cell

Fig. 1 shows the Three-Level switch cells. From the derivation of the TL converter, it can be known that in order to reduce the voltage stress of the switches, two switches in series are used to replace one switch, as well as the clamping diode and clamping voltage stress. The voltage of the clamping voltage source is equal to the voltage stress of the basic converter, which is split into two parts equally. [1]



(a) Anode (b) Cathode

Fig. 1. The Three-Level switch cells

2.2 The Three-Level Converter

Fig. 2 shows the Three-Level connection and the output

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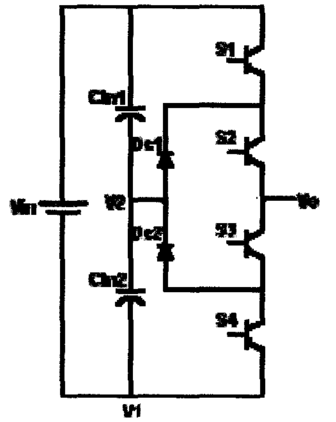
voltage in switch condition. This circuit consists of four switches, two diodes and two capacitors. Output voltage appears differently in each switch condition. [2, 3]

Fig. 3 shows the Three-Level converter circuit.

In order to achieve ZVS operation for the inner switches S_2 and S_3, the proposed converter uses the stored energy in the leakage inductance of the transformer to charge and discharge the parasitic capacitances C_2 and C_3 when S_2 is turned off. For actual ZVS operation, the stored energy in L_{lk} has to satisfy the equality. [2–4]



switch condition				Output Voltage (Vo)
S1	S2	S3	S4	
1	1	0	0	V3 (=Vin)
0	1	1	0	V2 (=Vin/2)
0	0	1	1	V1 (=0)

Fig. 2. The Three-Level connection and the output voltage in switch condition

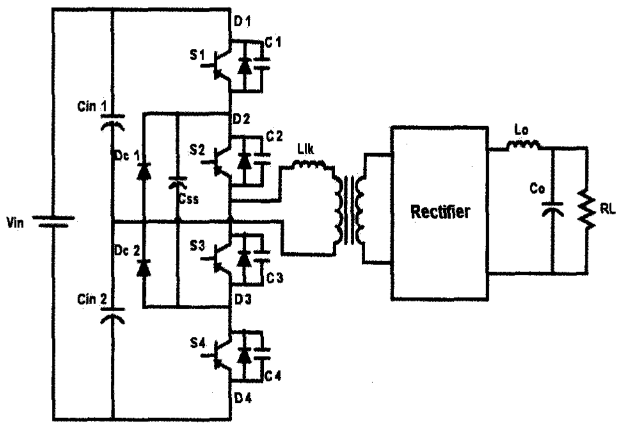


Fig. 3. The Three-Level converter circuit

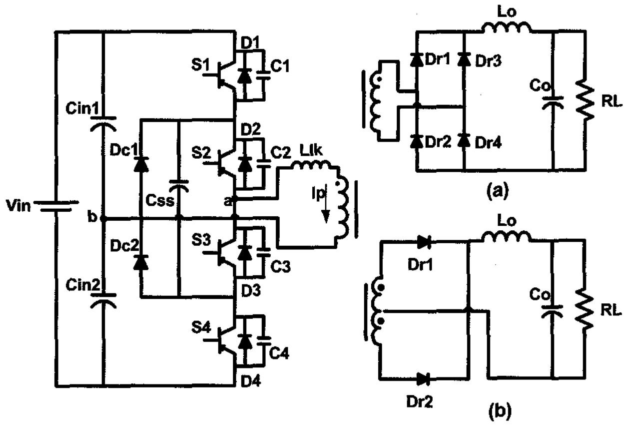
$$\frac{1}{2}L_{lk}I_{lk}^{2} > \frac{4}{3}C_{mos}\left(\frac{V_{in}}{2}\right)^{2} + \frac{1}{2}C_{tr}\left(\frac{V_{in}}{2}\right)^{2} \quad (1)$$

where the term $4/3C_{mos}$ is twice the typical non-linear parasitic capacitance of the switch and C_{tr} are the transformer winding capacitance.

In practice, it is recommended to lose the ZVS condition for S_2 and S_3 at certain load conditions. In this way, the critical primary current is needed so that ZVS operation can be obtained from (1) as in [2–4].

$$i_{crit} = \frac{V_{in}}{2}\sqrt{\frac{2}{L_{lk}}\left(\frac{4}{3}C_{mos}+\frac{1}{2}C_{tr}\right)} \quad (2)$$

Fig. 4 shows the Three-Level converter using conventional rectification.



(a) Bridge rectifier (b) Center-tap rectifier

Fig. 4. The Three-Level converter using conventional rectification

3. The Current Doubler Three-Level Converter

3.1 The CDR-TL Converter

Fig. 5 shows the CDR-TL converter circuit.

Fig. 6 shows theoretical waveform of the CDR-TL converter circuit.

A further improvement in the converter efficiency can be realized by utilizing the current doubler rectifier. In this case, only one diode drop exists in the current path. In addition, the transformer secondary winding is rated for one half the load current with no center-tapped connection required. Although two output filter inductors are rather small, they can be integrated on a single core.

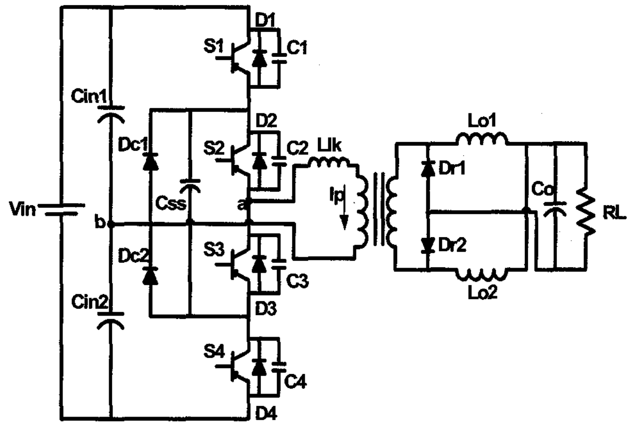


Fig. 5. The CDR-TL converter circuit

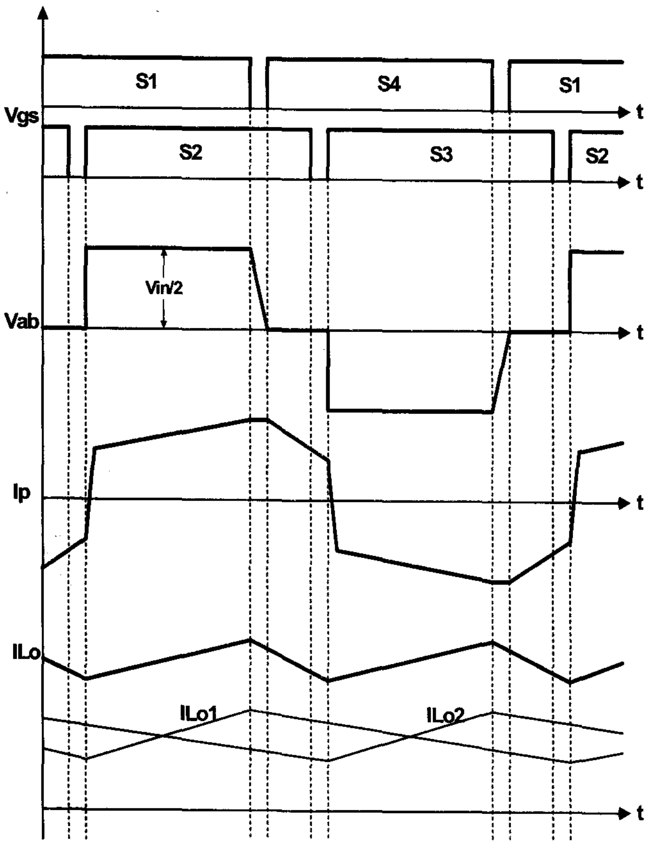


Fig. 6. Theoretical waveform of the CDR-TL converter circuit

3.2 The Proposed CICDR-TL Converter

Fig. 7 shows the proposed CICDR-TL converter circuit. Fig. 8 shows theoretical waveform of the CICDR-TL converter circuit.

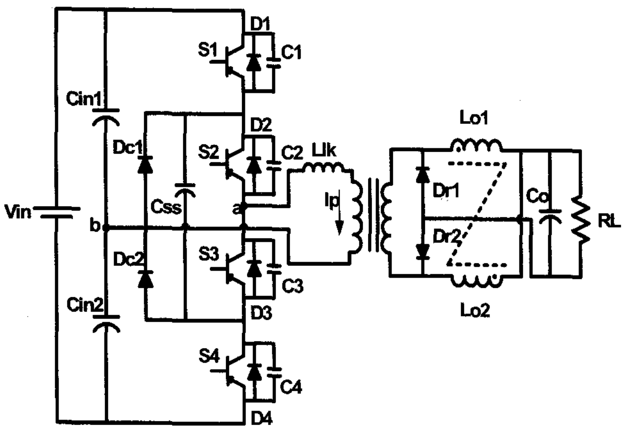


Fig. 7. The CICDR-TL converter circuit

Fig. 9 indicates the electrical schematic diagram and inductor winding arrangement for the coupled-inductor version of the current doubler.

Fig. 10 presents the coupled-inductor structure. The windings are placed on the outer legs of the double E-type core. Direction of the windings makes currents i_{Lo1} and i_{Lo2} produce fluxes, which are then added together in the center leg. Both windings have the same number of turns equal to N.

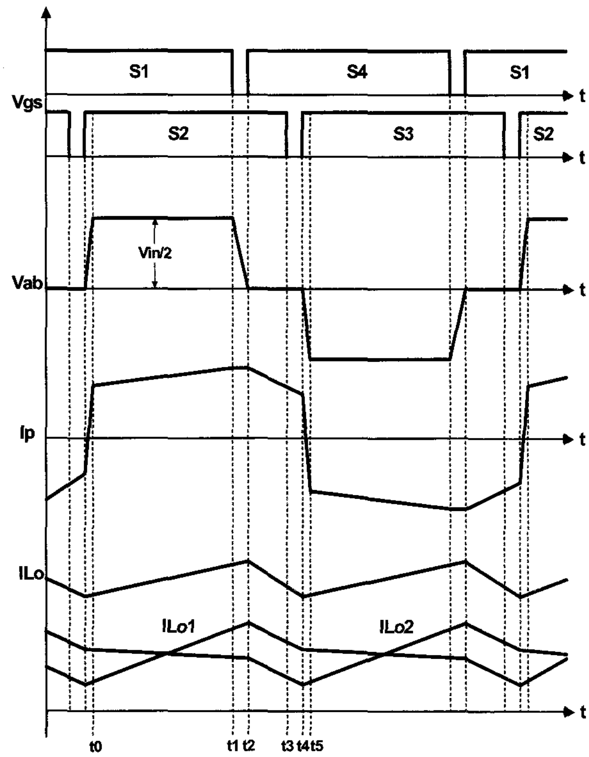
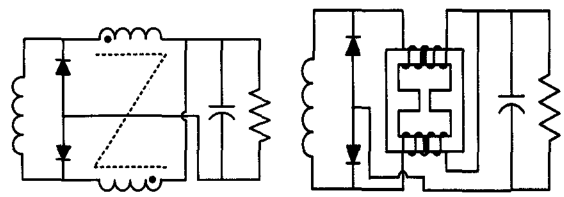


Fig. 8. Theoretical waveform of the CICDR-TL converter circuit



(a) (b)

(a) Electrical schematic diagram

(b) Coupled-inductor realization

Fig. 9. The proposed CICDR

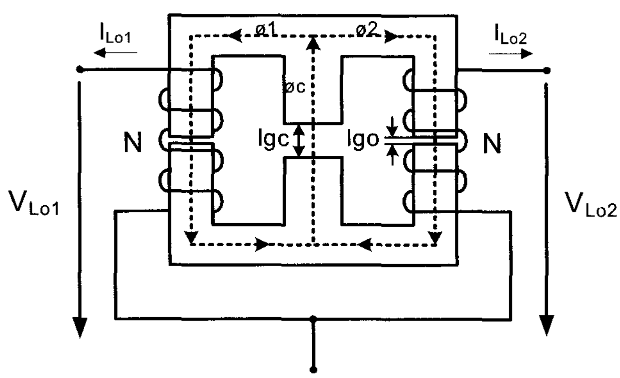


Fig. 10. Realization of the coupled-inductor

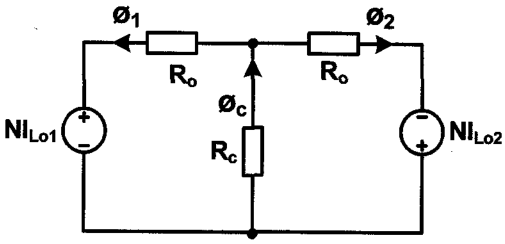


Fig. 11. Reluctance model of the coupled-inductor

Fig. 11 shows that the core has air-gap l_{gc} in the center leg and two equal air-gaps l_{go} in the two outer legs. It is a simplified reluctance model of such magnetic structure.

The model of Fig. 11 can be easily described by the following equations.

$$\phi_1 = \frac{R_C + R_O}{R_O(R_O+2R_C)} N i_{Lo1} - \frac{R_C}{R_O(R_O+2R_C)} N i_{Lo2} \tag{3}$$

$$\phi_2 = -\frac{R_C}{R_O(R_O+2R_C)} N i_{Lo1} + \frac{R_C + R_O}{R_O(R_O+2R_C)} N i_{Lo2} \tag{4}$$

where,

R_c : the reluctance of gap l_{gc}

R_O : the reluctance of gap l_{go}

Multiplying Eq. (3) and (4) by N are differentiated with respect to time, giving

$$v_{Lo1} = N\frac{d\phi_1}{dt} = L_o\frac{di_{Lo1}}{dt} - M\frac{di_{Lo2}}{dt} \tag{5}$$

$$v_{Lo2} = N\frac{d\phi_2}{dt} = -M\frac{di_{Lo1}}{dt} + L_o\frac{di_{Lo2}}{dt} \tag{6}$$

where,

$$L_o = N^2 \cdot \frac{R_c + R_o}{R_o(R_o + 2R_c)}, \quad M = N^2 \cdot \frac{R_c}{R_o(R_o + 2R_c)}$$

Manipulating Eqs. (5) and (6) can obtain

$$v_{Lo1} = (L_o - M)\frac{di_{Lo1}}{dt} - M\left(\frac{di_{Lo2}}{dt} - \frac{di_{Lo1}}{dt}\right) \tag{7}$$

$$v_{Lo2} = -M\left(\frac{di_{Lo1}}{dt} - \frac{di_{Lo2}}{dt}\right) + (L_o - M)\frac{di_{Lo2}}{dt} \tag{8}$$

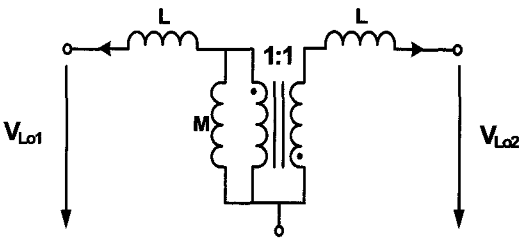


Fig. 12. Electrical model of the coupled-inductor

Eqs. (7) and (8) can be represented in the circuit model form indicated in Fig. 12. The model is composed of the inductance M and the inductance L, which are equal.

$$L = L_{o1} - M = L_{o2} - M \tag{9}$$

From Eq. (9)

$$L = \frac{N^2}{R_o + 2R_c}, \quad M = \frac{R_c}{R_o}L \tag{10}$$

In addition to L and M in the further analysis the coupling coefficient k defined as

$$L = \frac{N^2}{R_o + 2R_c}, \quad M = \frac{R_c}{R_o}L \tag{11}$$

will be used. Inserting Eq. (10) in Eq. (11) the coupling coefficient k can be expressed by the parameters of the reluctance model

$$k = \frac{1}{1 + \frac{R_o}{R_c}} \tag{12}$$

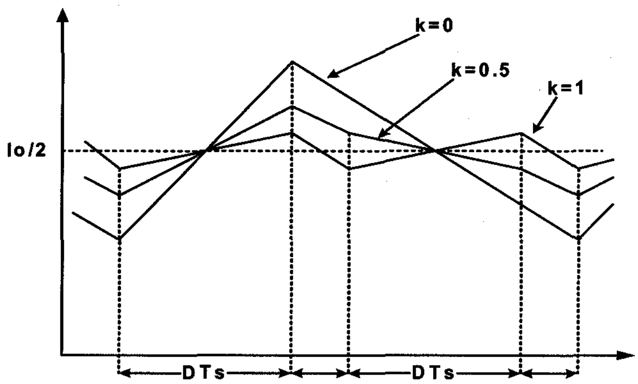


Fig. 13. Inductor current waveform for various coupling coefficient values k

Fig. 13 shows the inductor current waveform for various coupling coefficient values k. It can be noted that when k approaches 1, both current i_{Lo1} and i_{Lo2} became to equal half of i_o.

4. The Experimental Result

The prototype of the TL DC/DC converter has been implemented. Advantages and disadvantages of topology compared to the rectifier of bridge, center-tap, CDR, and CICDR are discussed.

Table 1 shows specifications and parameters concerning the prototype.

Table 1. The specifications and parameters used in the converter

Input Voltage	DC 430 ~ 560 V
Output Voltage	DC 27 V
Rated Power	1.8
Main Transformer	EC40. TDK 10 : 8 L_{LK} = 18uH
Flying Capacitor	470 uF
Main Switch	FM2G50US60, FAIRCHILD IGBT, 600V/ 50A
Freewheeling Diode	DEXI 2X61. IXYS
Rectification Diode	KSF30A40B. NI
Output Inductor	111.27 uH
Output Capacitor	6600 uF
Switching Frequency	40 ㎑

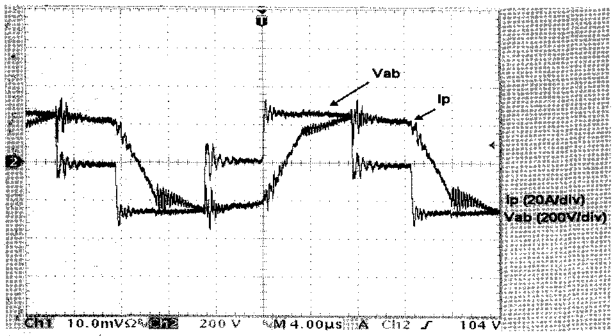


Fig. 14. Voltage and Current waveforms of the Bridge-TL Transformer (100% load)

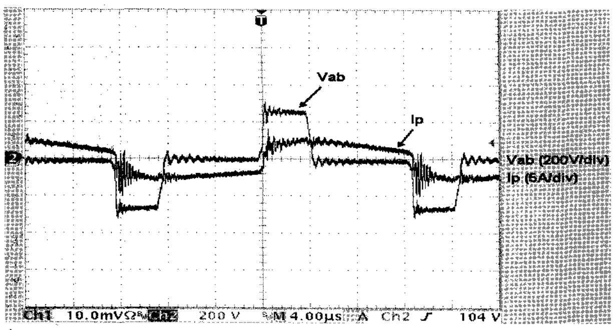


Fig. 15. Voltage and Current waveforms of the Bridge-TL Transformer (10% load)

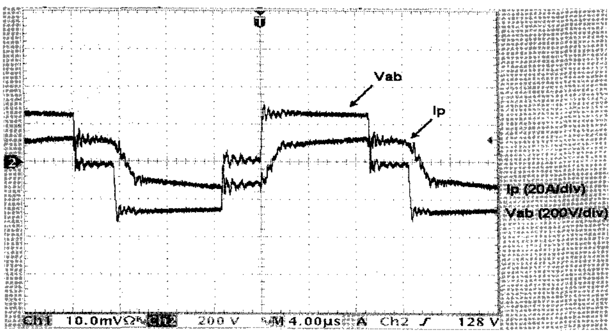


Fig. 16. Voltage and Current waveforms of the Center-tap-TL Transformer (100% load)

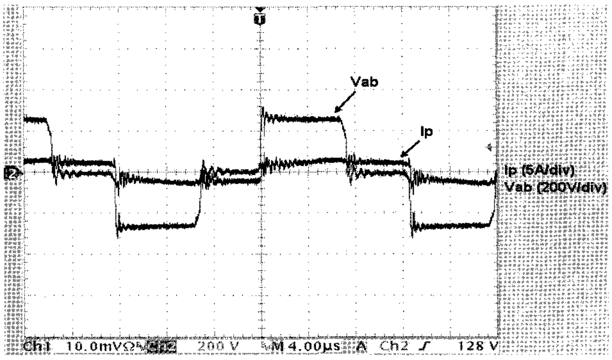


Fig. 17. Voltage and Current waveforms of the Center-tap-TL Transformer (10% load)

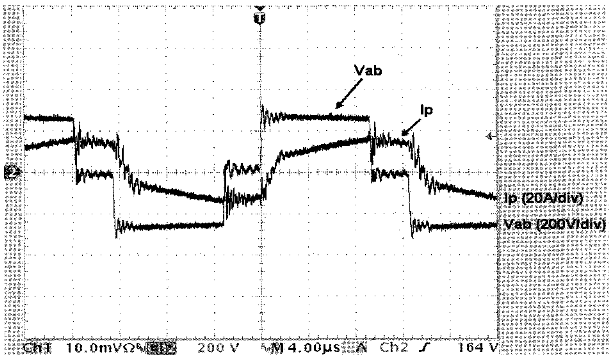


Fig. 18. Voltage and Current waveforms of the CDR-TL Transformer (100% load)

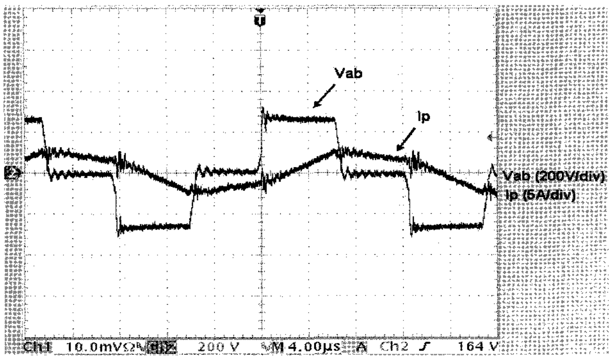


Fig. 19. Voltage and Current waveforms of the CDR-TL Transformer (10% load)

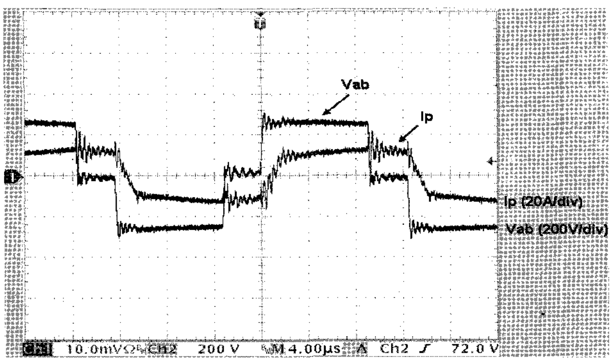


Fig. 20. Voltage and Current waveforms of the CICDR-TL Transformer (100% load)

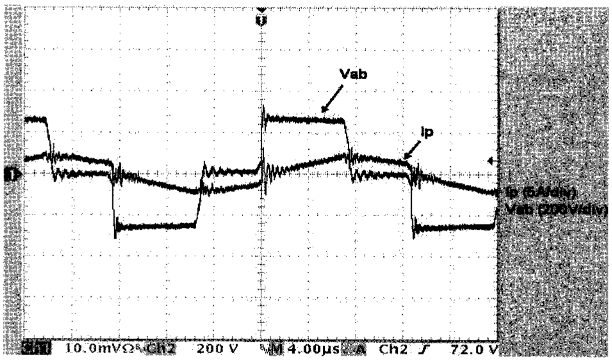


Fig. 21. Voltage and Current waveforms of the CICDR-TL Transformer (10% load)

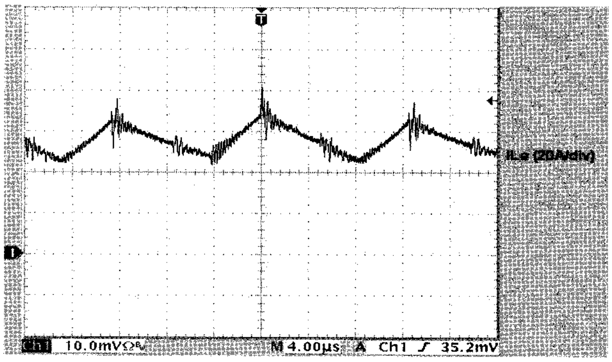


Fig. 22. Current waveform of the Bridge-TL Output inductor (100% load)

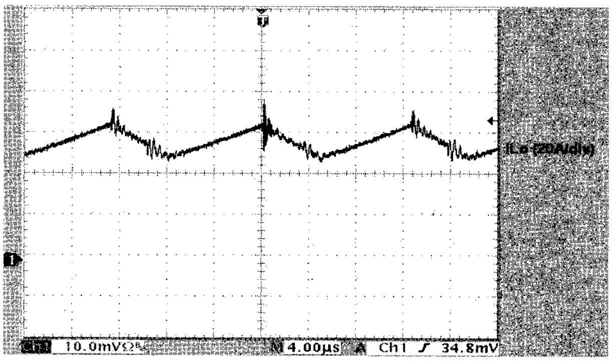


Fig. 23. Current waveform of the Center-tap-TL Output inductor (100% load)

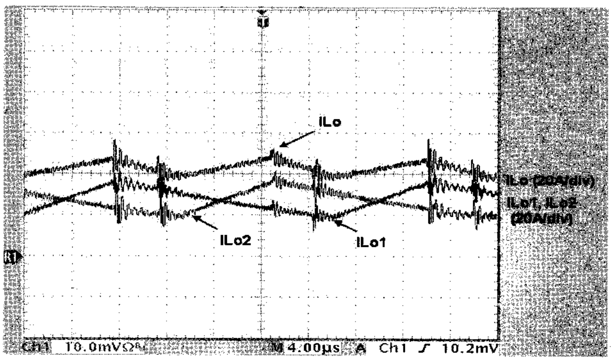


Fig. 24. Current waveforms of the CDR-TL Output inductor (100% load)

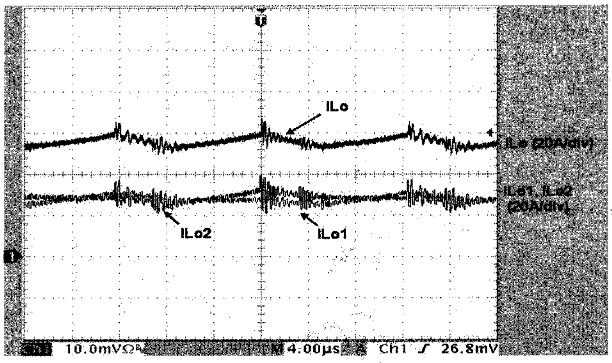


Fig. 25. Current waveforms of the CICDR-TL Output inductor (100% load)

Figs. 14～21 show voltage and current waveforms of the bridge, center-tap, CDR, and CICDR-TL converter. The bridge TL converter has a lot of freewheeling loss in light load.

Figs. 22～25 demonstrate current waveforms of the bridge, center-tap, CDR, and CICDR-TL converter in 500[V].

Figs. 27～30 indicate rectification method efficiency according to variable input voltage.

The center-tap and CICDR-TL converter has good efficiency for high input voltage and large output current.

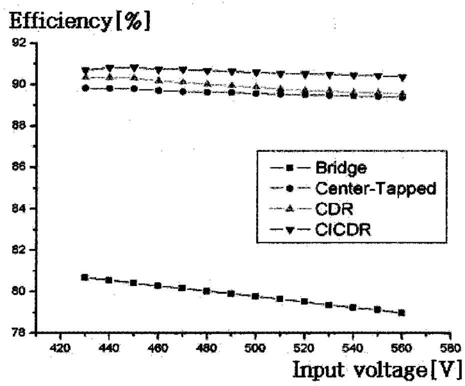


Fig. 27. Rectification method efficiency according to variable input voltage (100% load)

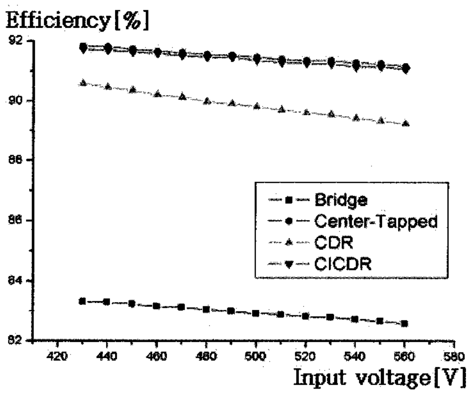


Fig. 28. Rectification method efficiency according to variable input voltage (50% load)

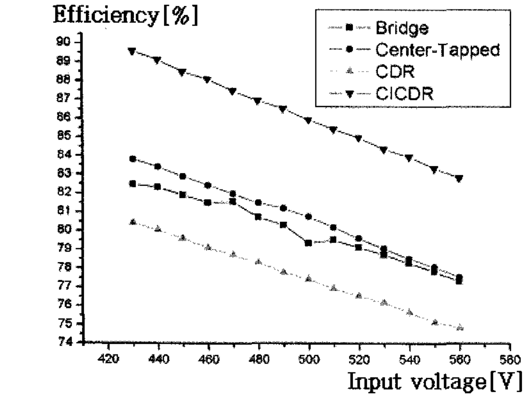


Fig. 29. Rectification method efficiency according to variable input voltage (10% load)

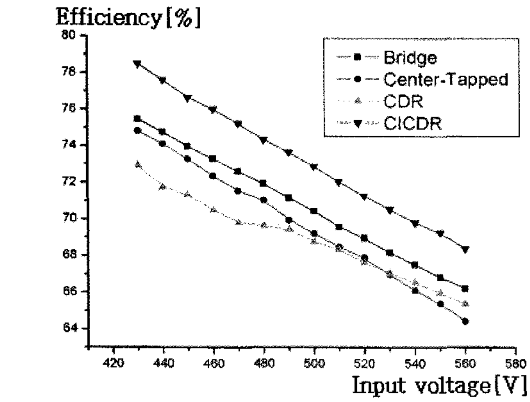
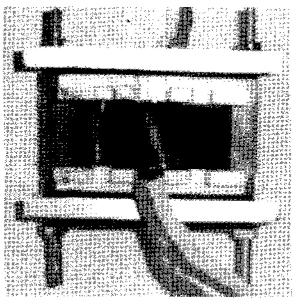
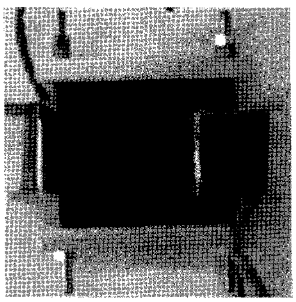


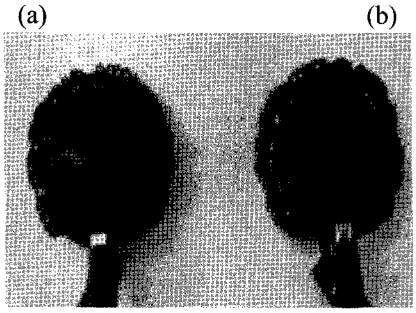
Fig. 30. Rectification method efficiency according to variable input voltage (5% load)



(a)



(b)



(c)

(a) Filter of the Bridge and Center-tap rectifier
(b) Filter of the CICDR
(c) Filter of the CDR

Fig. 31. Manufactured Filters

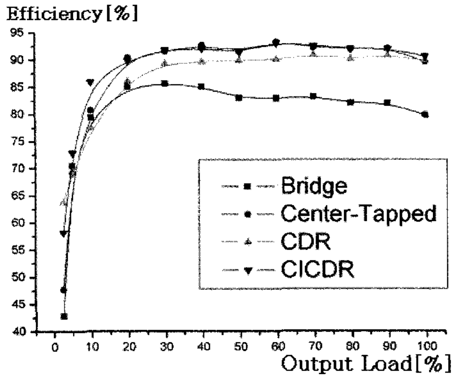


Fig. 32. Compared Efficiency

Table 2. The characteristics of Three-Level converter according to rectification methods

Rectification Method	Efficiency	Maximum Efficiency	Output Ripple
Bridge-TL Converter	79.76% (Rated load 1.8kW) 46.36% (2.5% load 45W)	85.57% (30% load 540W)	Voltage : 3.2V Current : 0.24A
Center Tap -TL Converter	89.56% (Rated load 1.8kW) 47.7% (2.5% load 45W)	93.29% (60% load 1.1kW)	Voltage : 2.4V Current : 0.16A
CDR-TL Converter	89.87% (Rated load 1.8kW) 63.71% (2.5% load 45W)	90.79% (70% load 1.3kW)	Voltage : 2V Current : 0.8A
CICDR-TL Converter	90.58% (Rated load 1.8kW) 58.23% (2.5% load 45W)	93.05% (60% load 1.1kW)	Voltage : 1.1V Current : 0.12A

Fig. 31 shows the manufactured filters of each rectifier.

Fig 32 shows comparison of efficiency for each rectifier TL converter in 500[V].

Table 2 shows the characteristics of the Three-Level converter according to rectification method.

In Table 2, the efficiency is improved by center-tap, CICDR-TL converter. Furthermore, the ripple is improved by CDR, CICDR-TL converter.

The CICDR-TL converter has a great advantage of efficiency and ripple improvement for high power application.

5. Conclusion

This paper proposed a coupled inductor-based rectifier of Three-Level converter and studied the comparison of the rectification methods of such a converter

The CICDR-TL converter topology has good efficiency and small output ripple for high input voltage and large output current. Also the two inductor filter components can be integrated in a single magnetic core which simplifies their design and construction.

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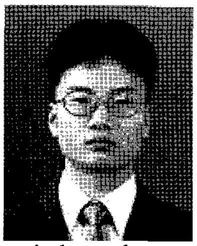

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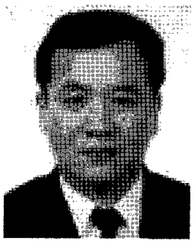

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