This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2015.2487558, IEEE Transactions on Power Electronics

Novel Isolated Multi-level DC-DC Power Converter

Hurng-Liahng Jou, Member, IEEE, Jun-Jie Huang, Jinn-Chang Wu, Member, IEEE, Kuen-Der Wu

Abstract-- **An isolated multi-level DC-DC power converter is proposed in this paper. The proposed isolated multi-level DC-DC power converter consists of an isolated power converter, a series/parallel switching circuit and an output L-C filter. The isolated power converter is composed of a half-bridge inverter, a three-winding transformer and two full-bridge rectifiers. The half-bridge inverter is switched in constant duty to generate two output DC voltages through two secondary windings of the three-winding transformer and two full-bridge rectifiers, respectively. The series/parallel switching circuit is used to control the two output DC voltages of the isolated power converter connected in series or in parallel, to control the output voltage of isolated multi-level DC-DC power converter. To verify the performance of the proposed isolated multi-level DC-DC power converter, a prototype is developed and tested. The experimental results show that the proposed isolated multi-level DC-DC power converter has the expected performance.**

Index Terms—**isolated power converter, multi-level, series/ parallel switching circuit**

I. INTRODUCTION

The voltage jump in each switching operation affects the switching loss, switching harmonics and electromagnetic interference (EMI) of the power converter. A multi-level power converter reduces the voltage jump in each switching operation, which decreases the switching loss, switching harmonics and EMI [1, 2]. The output filter is also reduced to increase the power density for the power converter [3, 4].Multi-level power converters are widely used for AC-DC power conversion [5, 6], DC-AC power conversion [7-12] and DC-DC power conversion [13-15]. The applications for DC-DC power conversion can be divided into isolated and non-isolated [3]. This paper focuses on the isolated multi-level DC-DC power converter.

Several unidirectional isolated multi-level DC-DC converters have been published in recent years to reduce the capacity of passive devices and to improve the power efficiency [3, 14, 15]. Two unidirectional isolated multi-level DC-DC converters are shown in [3]. Two half-bridge DC-AC inverters are connected in series, and the output of each half-bridge DC-AC inverter is connected to the primary winding of an isolation transformer. The multiple voltage levels are formed by using different circuit configurations in the secondary windings of the isolation transformers. The ripple voltage in the secondary windings is reduced and the voltage stress on the isolation transformer's primary winding is also reduced by these topologies. A bidirectional resonant DC-DC converter is proposed in [14]. Two diode-clamp multi-level inverters are used at both sides of an isolation transformer to generate multi-level voltages at both sides of an isolation transformer. The power flow is bidirectional. In [15], a pulse-width modulation three-level converter with reduced filter size using two transformers is proposed. A flying-capacitor multi-level inverter is applied to the primary windings of an isolation transformer and generates a multi-level voltage to reduce filter size. Isolated multi-level DC-DC converters generate a multi-level ac voltage in the primary windings of a transformer [3, 14, 15] and the voltage variation that is caused by the switching of these isolated multi-level DC-DC converters is less than that of the conventional isolation DC-DC power converter. Therefore, the capacity of the L-C output filter can be reduced in isolated multi-level DC-DC converters. However, more than four power electronic switches are used, so both the power circuit and the control circuit are complicated.

In this paper, a new isolated multi-level DC-DC power converter is proposed. The proposed isolated multi-level DC-DC power converter is composed of an isolated power converter with a three-winding transformer, a series/parallel switching circuit and an output L-C filter. The isolated power converter is switched in constant duty to generate two output DC voltages. The multi-level voltage is generated in the secondary of the transformer by the series/parallel switching circuit, which controls the two output DC voltages of the isolated power converter connected in series or in parallel, by controlling only one power electronic. Therefore, the control circuit for the proposed isolated multi-level DC-DC power converter is simplified. The voltage variation at the input of the output L-C filter is reduced so the capacity of the output L-C filter can be reduced.

II. Circuit Configuration and Operating Principle

Figure 1 shows the proposed isolated multi-level DC-DC power converter. As can be seen in Fig.1,it is consisted of an isolated power converter, a series/parallel switching circuit and an output L-C filter. The isolated power converter is composed of a half-bridge inverter (C_1, C_2, S_1, S_2), a three-winding transformer (T_{r1}) and two full-bridge rectifiers (D_1~D_8, C_3, C_4).The duty cycle for the power electronic switches,$S_1$and S_2, of the half-bridge inverter is constant and

H. L. Jou is with the Department of Electrical Engineering, Nationl Kaohsiung University of Applied Sciences, Kaohsiung 807 ,Taiwan, R.O.C. (e-mail: hljou@mail.e.kuas.edu.tw)

J. J. Huang and K. D. Wu are with the Department of Electrical Engineering, Nationl Kaohsiung University of Applied Sciences, Kaohsiung 807 ,Taiwan, R.O.C.

J. C. Wu is with the Department of Microelectronics Engineering, National Kaohsiung Marine University, Kaohsiung, Taiwan, R.O.C. (e-mail: jinnwu@mail.nkmut.edu.tw).

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2015.2487558, IEEE Transactions on Power Electronics

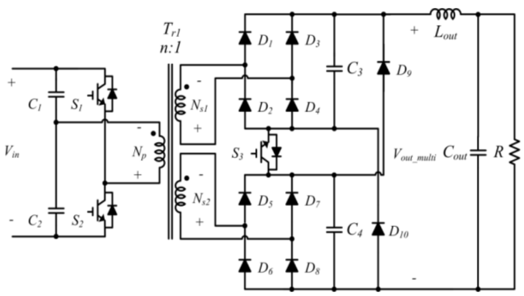


Fig. 1proposed isolated multi-level DC-DC power converter

equal to 0.5.The isolated power converter is switched in constant duty to generate two output DC voltages through two secondary windings of the three-winding transformer and two full-bridge rectifiers. The number of windings, N_{s1} and N_{s2}, are the same. Hence, the two output DC voltages of isolated power converter are almost the same. The series/parallel switching circuit contains a power electronic switch (S_3) and two diodes (D_9, D_{10}). The series/parallel switching circuit is used to connect the two output DC voltages from the isolated power converter connected in series or in parallel by controlling S_3. Therefore the voltage at the input of the output L-C filter is switched into two voltage levels. The voltage at the input of the output L-C filter is equal to the output DC voltage of the isolated power converter when the two output DC voltages are connected in parallel and two times that of the output DC voltage of the isolated power converter when the two output DC voltages are connected in series. Therefore, the voltage variation is reduced to reduce the capacity of the output L-C filter. The amount of power electronics is less than that for isolated multi-level DC-DC converters that generate a multi-level ac voltage in the primary windings of the transformer [3, 14, 15]. In addition, only the power electronic of the series/parallel switching should be controlled, and the control circuit is also simplified.

The switching frequency for the power electronic switch, S_3, is twice that for the power electronic switches, S_1 and S_2. The operation of the proposed isolated multi-level DC-DC power converter can be divided into four modes, depending on the switching operation of S_1 、 S_2 and S_3. The equivalent circuits are shown in Fig.2.

(1) Mode I

Figure 2(a) shows the equivalent circuit for mode I. In this mode, S_1 is turned on and S_2andS_3 are turned off. Figure 2(a) shows that the two output DC voltages from the two rectifiers are connected in parallel. The turn ratio between the primary winding and the secondary windings is:

$$n = \frac{N_p}{N_{S1}} = \frac{N_p}{N_{S2}} \quad (1)$$

Therefore, the voltage at the input of the output L-C filter can be written as:

$$V_{out\_multi} = \frac{V_{in}}{2n} \quad (2)$$

(2) Mode II

Figure 2(b) shows the equivalent circuit for mode II. In this mode, S_1 and S_3 are turned on and S_2 is turned off. As seen in Fig.2(b), the two output DC voltages from the two rectifiers are connected in series. The voltage at the input of the output L-C filter can be written as:

$$V_{out\_multi} = \frac{V_{in}}{n} \quad (3)$$

(3) Mode III

Figure 2(c) shows the equivalent circuit for mode III. In this mode, S_2 is turned on and S_1 and S_3 are turned off. It can be found in Fig.2(c) that the two output DC voltages from the two rectifiers are connected in parallel. The voltage at the input of the output L-C filter can be written as:

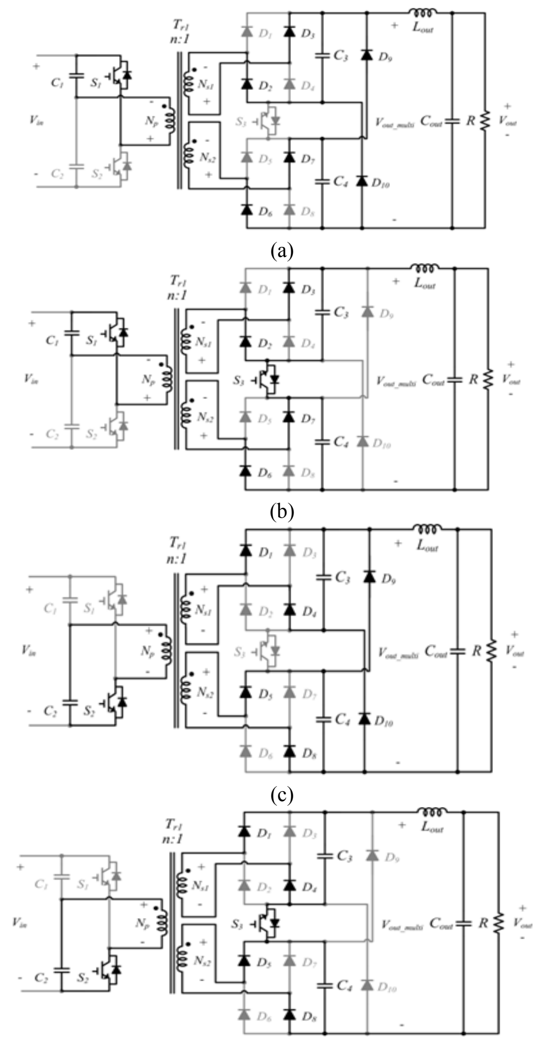
$$V_{out\_multi} = \frac{V_{in}}{2n} \quad (4)$$

(4) Mode IV

Figure 2(d) shows the equivalent circuit for mode IV. In this mode, $S_2$and S_3 are turned on, and S_1 is turned off. Figure 2(d) shows that the two output DC voltages from the two rectifiers are connected in series. The voltage at the input of the output L-C filter can be written as:

$$V_{out\_multi} = \frac{V_{in}}{n} \quad (5)$$

From this description, the relationships between the operating modes, the state of the power electronic switches and the voltage at the input of the output L-C filter for the



(a) (b) (c) (d)

Fig.2 equivalent circuits of the proposed isolated multi-level DC-DC power converter, (a) mode I, (b) mode II, (c) mode III, (4) mode IV.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2015.2487558, IEEE Transactions on Power Electronics

Table I relationships of operation modes, S_1, S_2, S_3 and V_{out_multi}

	S_1	S_2	S_3	V_{out_multi}
mode I	ON	OFF	OFF	$V_{in}/2n$
mode II	ON	OFF	ON	Vin/n
mode III	OFF	ON	OFF	$Vin/2n$
mode IV	OFF	ON	ON	Vin/n

proposed isolated multi-level DC-DC power converter can be summarized as shown in Table I. Since the two output DC voltages are connected in parallel and discharged during modes I and III, their voltages will be balanced automatically. In addition, the two output DC voltages are connected in series and discharged during modes II and IV such that their output currents are equal automatically. Hence, capacities of two secondary windings, N_{s1} and N_{s2} are almost equal. The leakage inductance of transformer will result in the commutation of rectifiers. C_3 and C_4 are applied to overcome the voltage variation induced by the commutation of rectifiers, and small capacity of film capacitors is used. As seen in Figs. 2(a) and (c), the voltage rating of S_3 is equal to the output DC voltage ($V_{in}/2n$) from the rectifier. It can be found in Figs. 2(b) and (d) that the current of S_3 is equal to the current of inductor L_{out}.

Figure 3 shows the time sequence for the proposed isolated multi-level DC-DC power converter. The switching frequencies of S_1 and S_2 are f_s and the switching frequency of S_3 is $2f_s$. The duty cycles of S_1 and S_2 are equal to 50%. The duty cycle of S_3, shown in Fig.3(e), is used to control the output voltage to supply the load. The output voltage from the isolated multi-level DC-DC power converter is the average of voltage, V_{out_multi}, which can be derived as:

$$V_{out} = (1 + \mathrm{D})\frac{V_{in}}{2n} \tag{6}$$

where D is the duty cycle of S_3. As can be seen in Fig. 3, the voltage at the input of the output L-C filter is between V_{in}/n and $V_{in}/2n$. The current variation of inductor L_{out} under the continuous conduction mode (CCM) can be derived as:

$$\Delta I_{Lout} = \frac{\mathrm{D}(1-\mathrm{D})\mathrm{V_{out}}}{2(1+\mathrm{D})\mathrm{L}_{out}f_s} \tag{7}$$

where L_{out} is the inductance of output L-C filter and f_s is the switching frequency. For the conventional isolated power converter, the voltage at the input of the output L-C filter is between 0 and V_{in}/n, and the current variation of filter inductor under CCM can be derived as:

$$\Delta I_c = \frac{(1-\mathrm{D_c})\mathrm{V_{out}}}{2\mathrm{L_f}f_s} \tag{8}$$

where L_f is the inductance of output L-C filter, and D_c is the duty cycle of half-bridge inverter for the conventional isolated DC-DC power converter. It should be noted that D for the proposed isolated multi-level DC-DC power converter is not equal to D_c for the conventional isolated power converter. In the condition of the same input and output voltages, the relation between D and D_c can be derived as:

$$\mathrm{D}_c = (1 + \mathrm{D})/2 \tag{9}$$

If the output voltage is constant and L_{out} is equal to L_f, the relation for the current variations, ΔI_{Lout} and ΔI_c, under the same input voltage can be represented as:

$$\frac{\Delta I_{Lout}}{\Delta I_c} = \frac{2\mathrm{D}}{(1+\mathrm{D})} \tag{10}$$

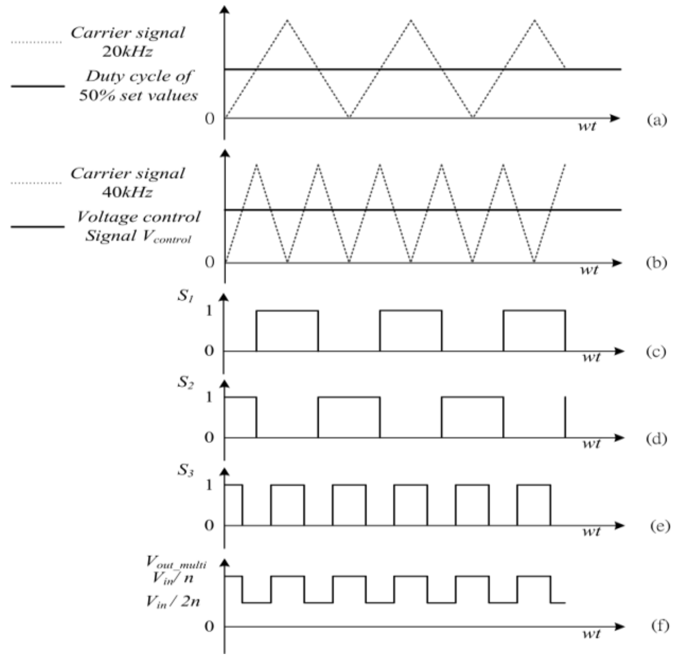


Fig. 3 time sequence of the proposed isolated multi-level DC-DC power converter, (a) carrier and control signals of S_1 and S_2, (b) carrier and control signals of S_3, (c) driver signal of S_1, (d) driver signal of S_2, (e) driver signal of S_3, (f) waveform of V_{out_multi}

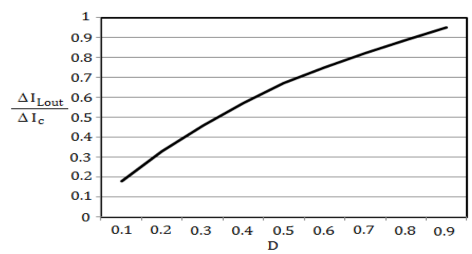


Fig. 4 curve of $\Delta I_{Lout}/\Delta I_c$.

Figure 4 shows the curve of $\Delta I_{Lout}/\Delta I_c$. As can be seen, $\Delta I_{Lout}/\Delta I_c$ is proportion to D. It can be found that the current variation of filter inductor for the proposed isolated multi-level DC-DC power converter is smaller than that for the conventional isolated power converter under the same output L-C filter. As compared with the conventional isolated power converter, the proposed isolated multi-level DC-DC power converter increases the complexity of power circuit but reduces the inductance of the output L-C filter under the same current variation. The reducing amount of inductance of the output L-C filter for the proposed isolated multi-level DC-DC power converter is dependent on D.

III. Control Block Diagram

Figure 5 shows the control block diagram for the proposed isolated multi-level DC-DC power converter. The control block is divided into two parts. The duty cycles of the power electronic switches, S_1 and S_2, operateat 50%. A setting value is sent to be compared with a carrier signal, to generate a square signal with a duty cycle of 50%, which is the driver signal for S_1. Because the operation of S_1 and S_2 is complementary, the driver signal for S_1 is sent to an inverter to generate the driver signal for S_2. The output voltage, V_{out}, is detected by a voltage detector and the detected output

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2015.2487558, IEEE Transactions on Power Electronics

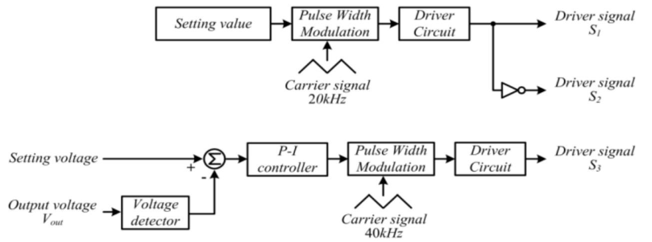


Fig.5 control block diagram of the proposed isolated multi-level DC-DC power converter.

voltage and a setting voltage are sent to a subtractor. The subtracted result is sent to a P-I controller. The output from the P-I controller is sent to be compared with a carrier signal to generate the driver signal for S_3.

IV. Experimental Results

To verify the performance of the proposed isolated multi-level DC-DC power converter, a prototype was produced and tested. Table II shows the major parameters for the hardware of the prototype.

Figure 6 shows the experimental results for the gate signals of the power electronic devices, S_1, S_2 and S_3. It is seen that the gate signals for the power electronic devices, S_1 and S_2, are out of phase, and the frequency of the gate signal for S_3 is twice that of the gate signal for S_1 and S_2.

Figures 7 and 8 show the experimental results for the proposed multi-level DC-DC converter. Figures 7(a) and 7(b) show the voltage across the transformer's primary winding and secondary winding. Figures 7(c) and 7(d) show the voltage, V_{out_multi}, and the current in the filter inductor. It is seen that the voltage, V_{out_multi}, switches between two levels (215V and 430V). Compared with a conventional isolated DC-DC power converter wherein the voltage is switched between two levels (0 and 430V), the switching harmonic for the proposed multi-level DC-DC converter is reduced so the capacity of output L-C filter can be reduced. Figure 8 shows the voltages and currents for the input side and the output side for the isolated multi-level DC-DC power converter. As seen in Figs. 8(a) and 8(b), the input voltage is 400V and the input current is 5.09A. Figures 8(c) and 8(d) show that the output voltage is 380V and the filter inductor current is

Table II major parameters of the prototype

V_{in}	$400V$
V_{out}	$380V$
P_{out}	$2kW$
switching frequency of $S_1$and S_2	$20kHz$
switching frequency of S_3	$40kHz$
C_1andC_2	$2200\mu F$
C_3 andC_4	$20\mu F$
N_p:N_{s1}:N_{s2}	24:26:26
magnetizing inductance of transformer	$4.5mH$
leakage inductance of transformer	$0.5\mu H$
L_{out}	$88\mu H$
C_{out}	$2200\mu F$

Fig. 6 experimental results for the gate signals of power electronic devices, (a) gate signal of S_1, (b) gate signal of S_2, (c) gate signal of S_3

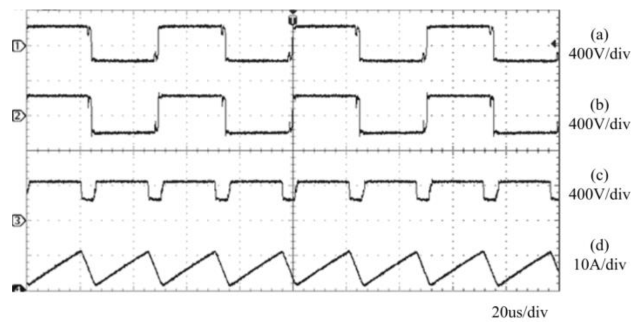


Fig.7 experimental resultsof the proposed multi-level DC-DC converter before the output filter, (a)voltage of transformer's primary winding V_p, (b) voltage of transformer's secondary winding V_{S1}, (c)output voltage V_{out_multi}, (d) output current I_{out}

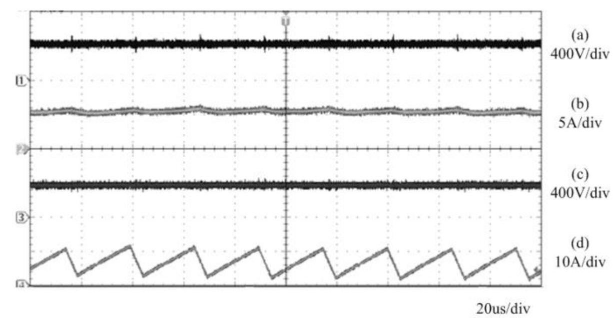


Fig. 8 experimental results for the proposed multi-level DC-DC converter, (a) input voltage V_{in}, (b) input current I_{in}, (c)output voltage V_{out}, (d) filter inductor current I_{Lout}

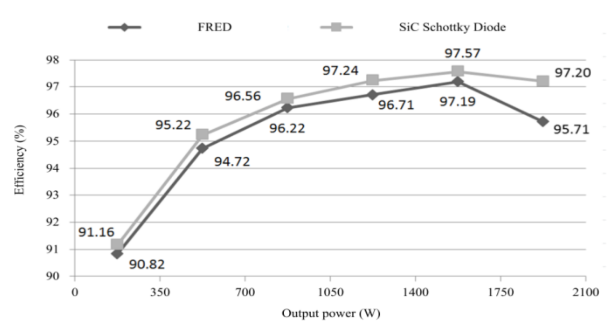


Fig. 9 efficiency curves of the proposed multi-level DC-DC converter

5.21A.The proposed isolated multi-level DC-DC converter outputs 2kW DC power. Figure 9 shows the respective efficiency curves for the proposed multi-level DC-DC converter where Silicon Carbide (SiC) Schottky diodes and Fast Recovery Epitaxial diodes (FRED) are used for diodes (D_1-D_{10}). Figure9 shows that the highest efficiency is 97.57%

when SiC Schottky diodes are used and 97.19% when FREDs are used.

V. Conclusion

The galvanic isolation for AC-DC power conversion interface can be achieved by using low frequency transformer in the utility side or integrating a high frequency transformer in the isolated DC-DC power converter. The isolated DC-DC power converter has advantages of smaller size and lower cost. The applications of isolated DC-DC power converter has been widely used in DC micro grids, high voltage direct current (HVDC) power distribution systems for data centers and electric vehicles (EV). This paper proposes an isolated multi-level DC-DC power converter. In the proposed isolated multi-level DC-DC power converter, the two-winding transformer of a conventional isolated power converter is replaced by a three-winding transformer, to generate two output DC voltages. A series/parallel switching circuit is used to control the two output DC voltages from the isolated power converter connected in series or in parallel to control the output voltage. The voltage variation at the input of the output L-C filter is reduced so the capacity of output L-C filter can be reduced. Since only the power electronic device of series/parallel switching circuit should be controlled, the control circuit of proposed isolated multi-level DC-DC power converter is simplified. In addition, only three power electronic devices are used in the proposed isolated multi-level DC-DC power converter. The experimental results show that the proposed isolated multi-level DC-DC power converter outputs a stable DC voltage to supply a load and the voltage variation at the input of the output L-C filter is reduced.

Reference

1. K. Filsoof,and P.W.Lehn,“Design and control of a bidirectional triangular modular multilevel DC-DC converter”, IEEE 14th Workshop on Control and Modeling for Power Electronics (COMPEL),pp. 1-7, 23-26 June, 2013.
2. Z. Pan, F. Zhang, and F.Z.Peng,“Power losses and efficiency analysis of multilevel dc-dc converters”, The 20thAnnual IEEE Applied Power Electronics Conference and Exposition, Vol. 3, pp. 1393-1398, 6-10 Mar, 2005.
3. L.D'Errico, A. Lidozzi, G. Lo.Calzo, A.Romanelli, and L.Solero,“Multi-level configurations for three-phase AC-DC 48V power supply”, IEEE International Symposium on Industrial Electronics (ISIE), pp. 945-950, 4-7 July, 2010.
4. F. Zhang, F.Z.Peng, and Zhaoming Qian, “Study of Multilevel Converter In DC-DC Applications”, The 35th Annual IEEE Power Electronics Specialists Conference, Vol. 2, pp.1702-1706, June, 2004.
5. J. Lee, U.Choi, K.Lee, “Comparison of Tolerance Controls for Open-Switch Fault in a Grid-Connected T-Type Rectifier”, IEEE Trans. Power Electronics, Vol. 30, No.10, pp. 5810-5820, 2015.
6. Z. Zheng, Z. Gao,C. Gu,L. Xu,K. Wang, Y. Li, “Stability and Voltage Balance Control of a Modular Converter With Multiwinding High-Frequency Transformer”, IEEE Trans. Power Electronics, Vol. 29, No.8, pp. 4183-4194, 2014.
7. J. C. Wu, C. W. Chou, “A Solar Power Generation System with a Seven-Level Inverter”, IEEE Trans. Power Electronics, Vol. 29, No.7, pp.3454-3462, 2014.
8. X. She, A. Q. Huang, T. Zhao, and G. Wang, “Coupling effect reduction of a voltage-balancing controller in single-phase cascaded multilevel converters,” IEEE Trans. Power Electronics, vol. 27, no. 8, pp. 3530–3543, 2012.
9. J. Mei, B. Xiao, K. Shen, and L. M. Jian Yong Zheng, “Modular multilevel inverter with new modulation method and its application to photovoltaic grid-connected generator,” IEEE Trans. Power Electronics, vol. 28, no. 11, pp. 5063–5073, 2013.
10. I. Abdalla, J. Corda, and L. Zhang, “Multilevel DC-link inverter and control algorithm to overcome the PV partial shading,” IEEE Trans. Power Electronics, vol. 28, no. 1, pp. 11–18, Jan. 2013.
11. K. Hasegawa and H. Akagi, “Low-modulation-index operation of a fivelevel diode-clamped pwm inverter with a dc-voltage-balancing circuit for a motor drive,” IEEE Trans. Power Electronics, vol. 27, no. 8, pp. 3495–3505, 2012.
12. A. Edpuganti, and A. K. Rathore, "Optimal Low Switching Frequency Pulse width Modulation of Nine-Level Cascade Inverter," IEEE Trans. Power Electronics, vol. 30, no. 1, pp. 482-495, 2015.
13. F. H. Khan, L. M. Tolbert, “Bi-directional power management and fault tolerant feature in a 5-kW multilevel dc-dc converter with modular architecture”, IET Power Electronics, vol. 2, no. 5, pp. 595-604, 2009.
14. Y. Cai, C. Wang, F. Zhao, R. Dong, “Design of a high-frequency isolated DTHB CLLC bidirectional resonant DC-DC converter,” IEEE Conference onTransportation Electrification Asia-Pacific, pp. 1-5, 2014.
15. D.-Y.Kim, J.-K. Kim, G.-W.Moon, "A Three-Level Converter With Reduced Filter Size Using Two Transformers and Flying Capacitors," IEEE Trans. Power Electronics, vol. 28, no. 1, pp. 46-53, 2013.