

Multilevel Inverter Based on Resonant Switched Capacitor Converter

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Abstract

Multilevel inverters are mainly used in high power and medium voltage applications to reduce the required voltage rating of the power semiconductor switching devices. On the other hands, these multilevel inverters are attractive for various applications regardless of the power ratings because they can essentially realize lower harmonics with lower switching frequency and lower electromagnetic interference (EMI). In this context, the multilevel inverters with larger number of levels suitable for circuit integration are actively investigated. Diode-clamped multilevel inverters are regarded as the promising solution. In the diode-clamped multilevel inverters whose number of the levels exceeds three, voltage balancing circuits for the DC capacitors to maintain the proper voltage are indispensable. The authors have been investigated the application of a circuit topology of the voltage balancing circuits so called Resonant Switched Capacitor Converters (RSCC). In the present paper, the utilization of the voltage boost function of RSCC to enhance the allowable range of the input voltage of the inverter is investigated. The voltage boost function is useful in the applications in which the DC source voltage is limited such as batteries and fuel cells. From the computer simulation and the experimental results, the usefulness and the operating characteristics of the voltage boost operation have been demonstrated.

1. Introduction

Multilevel power converters can essentially realize lower output harmonics and smaller step of the voltage change due to the switching operation. Thus, they can obtain high quality output waveforms without output LC filters and EMI filters. Consequently, the multilevel power converters can be one of the promising solutions to realize higher output power density converters.[1] As typical examples of the multilevel power converters, cascaded converter, diode-clamped converters, and flying capacitor converters shown in Figs.1 (a)-(c) are actively investigated.[2]-[8] Among them, 3-level diode-clamped inverters have already been put into practical use in medium voltage applications.[2] For the extreme reduction of the volume and the EMI in the

converters, a larger number of levels is required. In the case of the diode-clamped inverters with more than 3-level, the voltage balance of each DC capacitor cannot be maintained without additional balancing control, because the charge flowing from the individual capacitors are not equal in each cycle. Because the voltage deviation causes larger harmonics in the output voltage and over-voltage across the switching devices, voltage balancing circuits

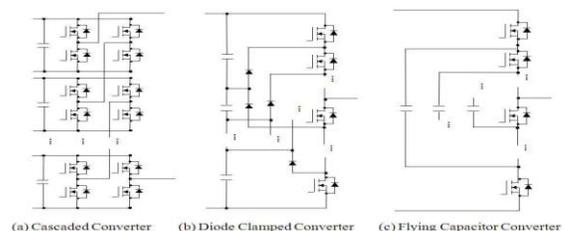


Fig. 1. Typical Circuit Topologies of Multilevel Inverters

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are indispensable for the DC capacitors in the diode-clamped multilevel inverters. [9]-[12] As a solution to realize the voltage balance, a method based on a resonant switched capacitor converter (hereafter, RSCC) has been proposed and its applicability has been confirmed.[11]-[15]

In this paper, a new possibility of the RSCC to enhance the operating range of the output voltage is focused on. As mentioned above, the RSCC can realize the voltage balance of the series connected DC capacitors in the diode clamped multilevel converters. Depending on the terminals of the series connected DC capacitors to which the DC power source is connected, voltage boost capability can be obtained. In the following, the basic operating principle is overviewed. And then, a new arrangement of the RSCC to realize the voltage boost capability is proposed. To confirm the proper operation and the usefulness of the proposed method, some simulated results and experimental results employing a prototype 5-level diode clamped multilevel inverter are included.

2. Voltage Balancing Circuit Based On RSCC

A. Basic Operating Principle

Fig.2 (a) shows the basic circuit configuration of a unit of the RSCC. The unit of RSCC consists of four switching devices, a resonant inductor L_r , and a resonant capacitor C_r . Each switching device is operated at a 50% duty factor and the resonant frequency determined by L_r and C_r as shown in Fig.2(b). Under the condition that the voltage V_{C1} of capacitor C_1 is larger than V_{C2} of capacitor C_2 , C_r is charged by C_1 when two switches S_1 and S_2 are in the on-state (State I). Then, C_2 is charged by C_r when two switches S_{1p} and S_{2p} are in the on-state (State II). In

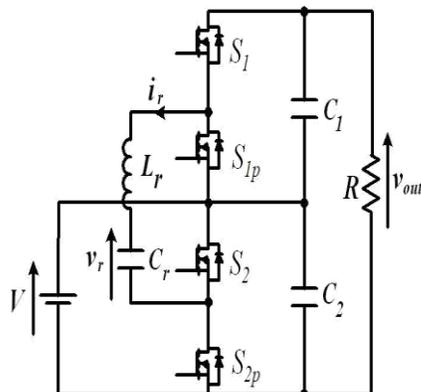
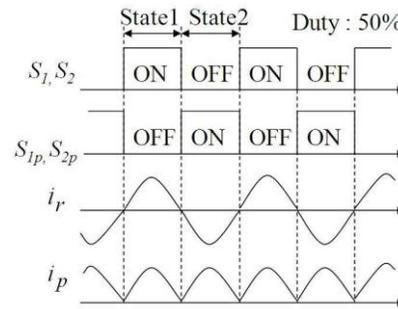


Fig: 2(a). Circuit Configuration.



(b) Operating Waveforms.

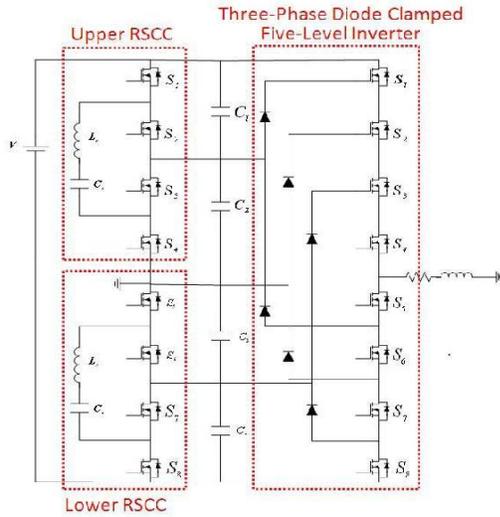
Fig: 2. Operating Principle of Resonant Switched Capacitor Converter

this way, the excessive charge in C_1 is transferred to C_2 by repeating the switching operation. In principle, V_{C1} and V_{C2} can be balanced without any feedback control by changing the amplitude and direction of i_r , automatically.

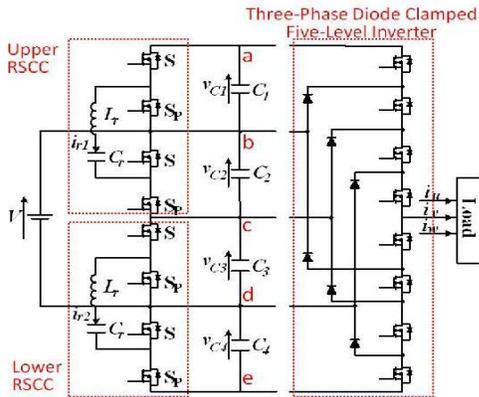
B. Application to Multilevel Inverters and Voltage Boost Function

Fig.3(a), (b) and (c) show examples of the arrangement of the RSCC to 5-level diode-clamped multilevel inverters with main circuit configuration per phase. An ordinal connection to 5-level diode clamped multilevel inverter is shown in Fig.3 (a). In this case, the voltage balance in the upper two capacitors C_1 and C_2 is achieved by the upper RSCC. On the other hands, the lower RSCC achieves the voltage balance in C_3 and C_4 . Due to the symmetrical operation of the diode clamped inverter, the total voltages of the upper half capacitors C_1, C_2 , and that of the lower half capacitors C_3, C_4 can be balanced essentially in the steady state. As the result, all the capacitor voltage can be balanced. In the case shown in Fig.3(a), each DC capacitor shares equally one fourth of the DC supply voltage V . In this case, the possible levels of the output phase voltage are $V, (3/4)V, (1/2)V, (1/4)V, 0$.

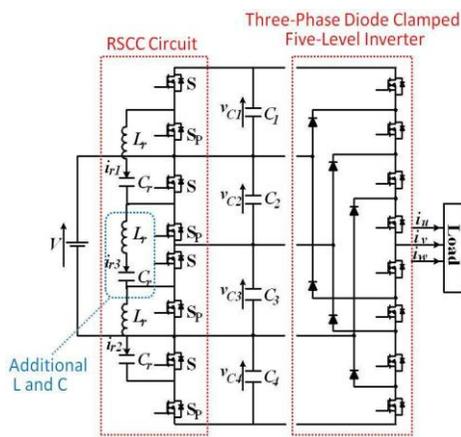
Fig.3(b) shows the proposed voltage boost connection of the RSCC. In this case, the DC voltage source V is connected to the intermediate terminals "b" and "d" of the DC circuit. In this case, C_2 and C_3 share a half of the DC voltage $(1/2)V$ equally due to the symmetrical operation of the diode-clamped inverter. By the function of the upper RSCC, the voltages of C_1 and C_2 are balanced. Consequently, the voltage of C_1 is also $(1/2)V$. The lower RSCC realizes the voltage balance between C_3 and C_4 . And then, all the voltages in C_1 - C_4 become $(1/2)V$. Consequently, the possible levels of the output phase voltage are $2V, (3/2)V, V, (1/2)V, 0$. In this way, the



(a) Ordinal Connection



(b) Operating Waveforms.



(c) Modified Version of Proposed Voltage Boost Connection

Fig. 3. Variations of Circuit Configuration of 5-Level Multilevel Diode Clamped Inverters with RSCC.

voltage boost function can be obtained. This function is useful to enhance the operating range of the output voltage with the limited value of the DC supply voltage. Note that the voltage boost ratio is determined by the number of series connected capacitors and the connecting points of the DC voltage source.

Fig.3(c) shows the modified connection of Fig.3(b). In Fig.3 (b), the average values of the voltages of C_2 and C_3 are balanced in a fundamental period of the output frequency. But, these voltages fluctuate due to the instantaneous imbalance of the currents flowing out from C_2 and C_3 . Thus, an additional RSCC is effective to ensure the instantaneous voltage balance in C_2 and C_3 . The additional RSCC can be realized by adding only an inductor and a capacitor shown in Fig.3 (c) and no additional switching devices are needed.

3. Experimental Investigation

To confirm the effectiveness of the proposed voltage boost method, an experimental investigation employing a laboratory prototype of three phase 5-level diode clamped multilevel inverter have been carried out. In the experiment, the DC supply voltage is set to 50V and the resonant frequency of the RSCC is set to 50 kHz ($C_r=1\text{PF}$, $L_r=9.4\text{PH}$). The parameters of the experimental prototype are listed in Table 1. A three-phase RL load is connected to the output terminals of the experimental inverter.

A. Output waveforms and RSCC Current Waveforms

Fig.4 shows the experimental waveforms of the prototype. The upper part of Fig.4 shows the output phase voltage and current waveforms. In the output voltage waveform, 5-level output voltage 0, 25V, 50V, 75V, 100V can be seen. From this result, we can confirm the proper voltage boost operation of the proposed method. In addition, we can also see almost perfect sinusoidal output current. The lower part of Fig.4 shows the experimental waveforms of the envelopes of the inductor currents of the RSCC. The changes in the envelopes correspond to the fluctuation of the instantaneous power flowing out from the individual DC capacitors. The frequency of the fluctuation of power in the upper RSCC is three times the fundamental frequency. On the other hands, the fluctuating frequency of the power of the center RSCC is six times the output frequency. These results should be considered in the establishment of the design guidelines of the RSCC and DC capacitors.

B. Current in RSCC

Fig.5 shows the relationship between the output current and the current flowing through the RSCC for three different values of the capacitance of the DC capacitor. The current flowing through the RSCC is determined by the load current regardless of the capacitance. Fig.6 shows the relationship between the current in the RSCC and the load power factor at a constant output current. The RSCC current becomes large at the higher load power factor. From the results in Figs.5 and 6, we can see that the current of the RSCC corresponds to the required power in the load.

Table: 1. Parameters of Experimental Prototype.

Input Voltage	50V
Inductor of RSCC	1PH
Capacitor of RSCC	9.4PF
Resonant Frequency of RSCC	50kHz
On Resistance of Main MOSFET's	0.04:
Forward Voltage Drop of Diodes	1V
Equivalent Series Resistance of RSCC	0.03:
DC Link Capacitor	1mF, 560PF,220PF

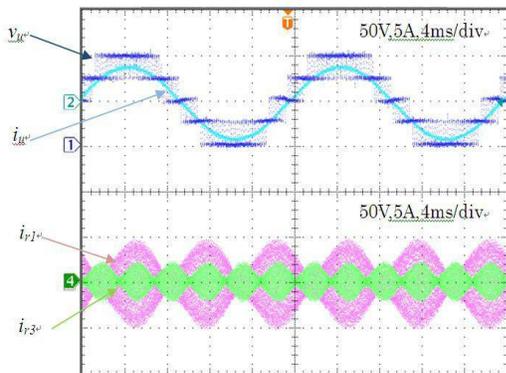


Fig: 4. Experimental Waveforms of 5-Level Diode Clamped Multilevel Inverter with RSCC Shown in Fig.3(c).

(Upper: Output Voltage and Current, Lower: Currents of RSCC)

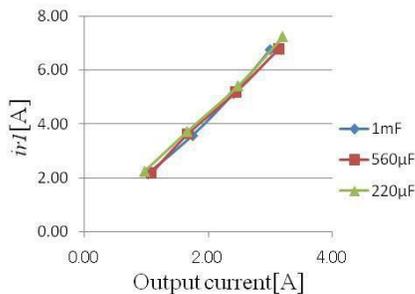


Fig: 5. Experimental Result of Relationship between Resonant Current and Output Current for Different Values of DC Link Capacitor.

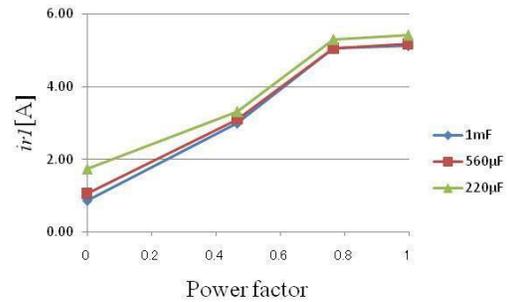


Fig: 6. Experimental Result of Relationship between Resonant Current and Load Power Factor for Different Values of DC Link Capacitor

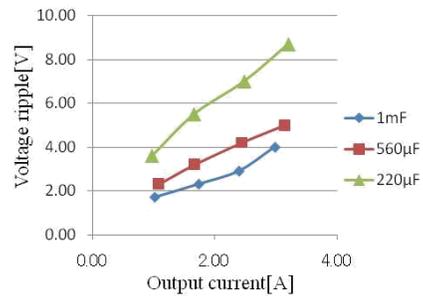


Fig: 7. Experimental Result of Relationship between Ripple Voltage of DC Capacitor and Output Current for Different Values of Capacitance.

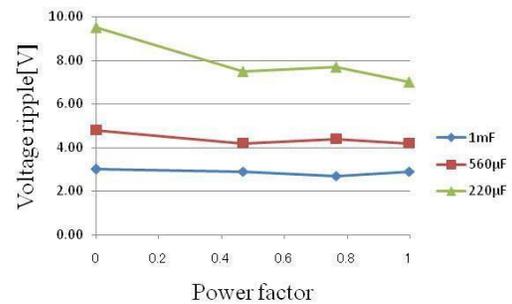


Fig: 8. Experimental Result of Relationship between Ripple Voltage of DC Capacitor and Load Power Factor for Different Values of Capacitance.

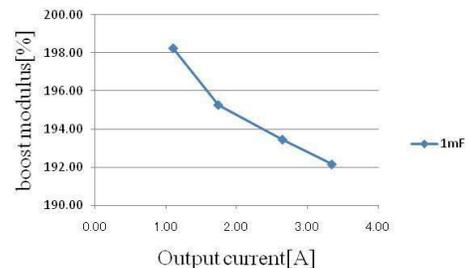


Fig: 9. Experimental Result of Relationship between Voltage Boost Ratio and Output Current.

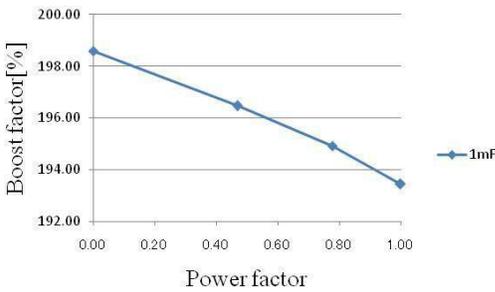


Fig. 10. Experimental Result of Relationship between Voltage Boost Ratio and Load Power Factor

C. Ripple Voltage of DC Capacitor

Fig.7 shows the relationship between the ripple voltage of the DC capacitor and the load current for three different capacitances of the DC capacitor. When the output current is large, the ripple voltage becomes large. In addition, the smaller capacitance results in the larger ripple voltage. Fig.8 shows the relationship between the ripple voltage of the DC capacitor and the load power factor. Again, we can see that the smaller capacitance results in the larger ripple voltage. But, the dependence of the ripple voltage on the load power factor is not significant in this experiment.

D. Voltage Boost Ratio

Fig.9 shows the experimental result of the relationship between the voltage boost ratio and the load current in the modified circuit shown in Fig.3(c). The voltage boost ratio is defined as a ratio of the maximum output phase voltage with respect to the DC source voltage. When the load current increases, the voltage boost ratio decreases slightly. Fig.10 shows the relationship between the voltage boost ratio and the load power factor. When the load power factor is high, the voltage boost ratio decreases slightly. From the results of Figs.9 and 10, the voltage boost ratio decreases when the active power increases. When the active power increases, the current of the RSCC increases. In this condition, the voltage drop in the MOSFET's and the equivalent resistance of the resonant components of the RSCC increases. Thus, the DC capacitor voltage decreases and then the voltage boost ratio is reduced. In the circuit connection shown in Fig.3(c), the theoretical value of the voltage boost ratio is 2. Thus, the difference between the actual and theoretical values of the voltage boost ratio is about 4% in Figs.9 and 10. From these results, we can conclude that the proposed voltage boost function can achieve a practical voltage regulation.

4. Extension To Larger Number Of Levels

The proposed voltage boost function of the RSCC can be applied regardless of the number of the output levels. Fig.11 shows a circuit configuration of a 9-level inverter in which the DC voltage source is connected to the center terminals A-A'. In this case, the voltage boost ratio is 4. When, the DC voltage source is connected to B-B' and C-C', the voltage boost ratio is 2 and 1.33, respectively.

Fig.12 shows an example of the results of computer simulation for the circuit shown in Fig.11 using simulation software PSIM. The upper and lower traces show the output phase voltage and current waveforms. We can confirm the successful 9-level operation and a perfect sinusoidal output current waveform. Fig.13 shows the currents of the three RSCC's in the upper half in Fig.11. To realize a higher voltage boost ratio, a large supply current is needed to derive the required power from the DC power source. Especially, the current in the center RSCC is the largest. From these results, the reduction of the equivalent resistance of the RSCC is required when the voltage boost ratio is high.

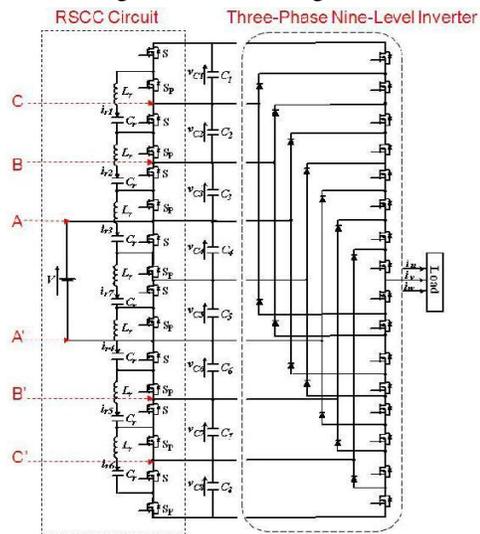


Fig. 11. An Example of Extension of RSCC to 9-Level Inverters

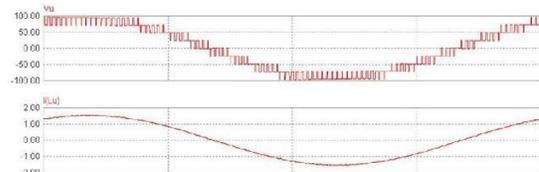


Fig. 12. Simulated Output Waveforms of an Extension of RSCC to 9-Level Converters. (Upper: Output Voltage, Lower: Output Current).

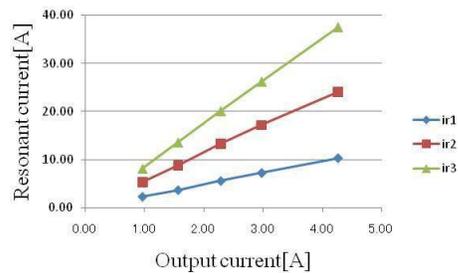


Fig. 13. Simulated Result of Relationship between Resonant Current and Output Current in Circuit Configuration shown in Fig.11.

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5. Conclusions

In this paper, the diode-clamped multilevel inverters with DC voltage balancing circuit based on RSCC with voltage boost function are proposed. The basic effectiveness of the proposed method has been experimentally confirmed. In addition, various characteristics useful for the selection of the circuit parameters are obtained. Furthermore, the extension of the proposed method to the multilevel inverters with large number of output levels has been demonstrated by computer simulation.