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A NEW RESONANCE MODULATOR MULTILEVEL STEP DOWN DC TO DC CONVERTER WITH REDUCED AND BALANCED OUTPUT

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***Abstract*— Modular multilevel converters (MMCs) have become increasingly interesting in dc-dc applications, as there is a growing demand for dc-dc converters in high voltage applications. Power electronics transformers (PETs) are commonly used for high step-down ratio dc-dc power conversion, with high power rating and efficiency achieved. However, this arrangement requires a large number of high isolation voltage transformers and a complicated balancing control scheme. To provide a simple solution with inherent voltage balancing, this paper presents a new resonant MMC topology for dc-dc conversion. The proposed converter achieves high voltage step-down ratio depending on the number of sub-modules. The converter also exhibits simplicity and scalability with no necessary requirement of high voltage isolation transformers. By using phase-shift control, a much higher converter operating frequency is achieved compared to the switching frequency. Resonant conversion is achieved between the series inductor and sub-module capacitors. The operation principle and theoretical analysis are presented in this paper, which have been verified by experimental results based on a bench scale prototype.**

Keywords — Modular multilevel converters, dc-dc conversion, step-down ratio, phase-shift control, resonant converter

I. INTRODUCTION

Modular multilevel converters (MMCs) are used for dc-ac [1]–[5] , ac-dc [4], [6]–[8], ac-ac [9], [10] and dc-dc [11]–[13] conversion for medium and high voltage applications. These converters provide more than two levels which can be adjusted by changing the number of modular cells. Cells with a fault can also be bypassed while keeping the converters operating. High reliability and modularity are the main features of MMCs. However, all these MMCs require a complicated balancing control to maintain the voltage levels. Even though a requirement is placed on the tolerance of the cell capacitors, measuring capacitor voltages for balancing control is indispensable. Moreover, the operating frequency of the conventional control for MMCs is not higher than the switching frequency. High switching frequencies are used to reduce the sizes of passive components. Trade-offs between switch ratings and converter size should be made, but it is hard to find a good solution for high voltage, high step-down ratio and low power applications. Other new multilevel modular switched capacitor dc-dc converters designed for small power applications are proposed in [14]–[15]. These converters exhibit good efficiency and modularity, but are not suitable for high voltage applications. For high voltage applications, conventional diode clamped, flying capacitor or other types of converters are also not suitable as the circuit configuration becomes quite complicated with increased number of levels. These converters have poor modularity and reliability. The most promising solution may be converters known as power electronics transformers (PETs) [11], [12]. PETs are designed for high power applications. They require a large number of transformers with high voltage isolation. The isolation between primary side and secondary side has to withstand the entire high input voltage, even if the voltage across the primary side is only a small fraction of this. The secondary side terminals of the transformers are connected in parallel, and the balancing control between modules is necessary. PETs can be used for high voltage and high power applications with high efficiency, but the converter size will be increased dramatically with a high voltage step-down ratio. Therefore, other simple solutions may be promising for low power applications in medium voltage and high voltage applications. This paper presents a new form of modular multilevel converter for high voltage step-down unidirectional dc-dc conversion [13]. The proposed converter has inherent-balancing of each capacitor voltage. High step-down voltage conversion ratios can be achieved by using large numbers of sub-modules. With phase-shifted pulse-width modulation (PWM), higher operating frequency can also be achieved, which is equivalent to the product of the number of sub-modules and the switching frequency. Moreover, the converter operates with two resonant frequencies where zero-voltage-switching (ZVS) and/or zero-current-switching (ZCS) become possible. The proposed converters are more suitable for low power dc-dc applications as it has the feature of modularity, simplicity and flexibility. The Pulse Width Modulated (PWM) inverters can control their output voltage and frequency simultaneously and also they can reduce the harmonic components in load currents. These features have made them suitable in many industrial applications such as variable speed drives, uninterruptible power supplies, and other power conversion systems. The popular single-phase inverters adopt the full bridge type using approximate sinusoidal modulation technique as the power circuits. The output voltage of them has three values: zero, positive and negative of supply DC voltage levels. Therefore, the harmonic components of their output voltage are determined by the carrier frequency and switching functions [1]. Recently the multilevel inverter topology has drawn tremendous interest in the power industry since it can easily provide the high power required for high power applications for such uses as static VAR compensation, active power filters, and so that large motors can also be controlled by high power adjustable frequency drives. Multilevel inverters synthesize the AC voltage from several different levels of DC voltages. Each additional DC voltage level adds a step to the AC voltage waveform. These DC voltages may or may not be equal to one another [3]. From a technological point of view, appropriate DC voltage levels can be reached, allowing use of multilevel power inverter for the medium voltage for adjustable speed drives ASD [4]. Multilevel inverters can reach high voltage and reduce harmonics by their own structures without transformers [5]. There are three main types of multilevel inverters: diode-clamped, flying capacitor, and cascaded H-bridges [9]. If the DC supply voltage increased (adding more batteries in series to maintain the voltage or to decrease the current) for the larger power requirement, the inverter component must be able to withstand the maximum DC supply voltage. Apart from other multilevel inverters, is the capability of utilizing different DC voltages on the individual H-bridge cells. The cascaded topology has many inherent benefits with one particular advantage being its modular structure. In particular, the cascaded inverter has been reported for use in applications such as medium voltage industrial drives, electric vehicles and grid connection of photovoltaic cell generation systems. The proposed inverter can reduce the harmonic components using sinusoidal PWM technique [4] under the condition of identical DC sources with sinusoidal PWM technique. The comparison is also made for open-loop, closed-loop PI and Neural implementing sinusoidal PWM technique. The control scheme involves the generation of PWM pattern for the range of modulation index (m) between 0.1 to 1. The closed loop control of cascaded multilevel inverter is done by implementing conventional PI controller.

II.HIGH STEP-DOWN RATIO

Phase-shifted PWM is then applied with a high duty-ratio such that an excitation is applied to the resonant components. The effective frequency of this excitation is much higher than the frequency of switching of an individual cell. This is arranged so that only one cell at a time is in "zero state" and thus the step-down ratio of the circuit becomes dependent on the number of cells N. To demonstrate the general operation principle, the converter in Fig.1 shows the circuit diagram, with the input filter removed to simplify the analysis. The dc input voltage is V_{dc}. The capacitor voltage and output voltage of j_{th} (j = 1; 2;:::; 5) cell are represented by v_{Cj} and v_j , respectively. The input current is composed of dc component and ac component. The dc current component returns to the converter input mainly through parallel inductor Ls, where an ac current component mainly flows to the rectifier. The sum of the parallel inductor current i_p and the rectifier input current it is equal to is. The output current i_o is rectified from it. The switching frequencies and duty-ratios of cells are equal, but the PWM signals from Cell 1 to Cell 5 are shifted by 0, 72, 144, 216 and 288, respectively. To analyze the circuit operation, the following assumptions are made:

1) The switches are lossless and the cells are identical with the same parameters.

2) The cut-off frequency of the input filter is much lower than the series current frequency in the converter.

The input ac current and dc current flow through the parallel branch and the series branch of the input filter, respectively.

3) The dc voltages of the cell capacitors are balanced at steady-state.

4) The rectifier diodes are synchronously switched on with the rectifier input voltage.

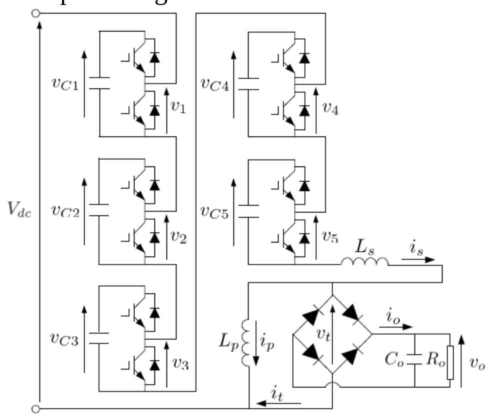

Fig. 1. A five-cell step-down series-parallel resonant converter.

The resonant frequency in positive half cycle is

$$f_{rp} = \frac{1}{2\pi\sqrt{L_s C/(N-1)}}.$$

As $f_{rp} < f_{rn}$, f_{rp} and f_{rn} are defined as the first resonant frequency and the second resonant frequency, respectively. The resonant tank waveforms of the proposed converter when using an operating frequency between frp and frn are shown in Fig. 2. Here a low dc current plus ac current on the parallel inductor are assumed. Note that this converter is operating differently to the classic LLC resonant converters [22] as two resonant frequencies

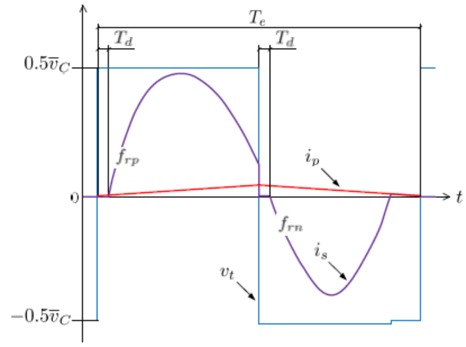

Fig. 2. Time domain waveforms of the resonant tank.

III. IMPLEMENTATION AND APPLICATIONS

To implement a converter prototype, Micro Controller can be used as the main controller for measuring feedback signals and generating phase-shifted PWM signals. As explained in the previous section, the proposed converter has an inherent-balancing ability. Therefore, the converter can operate in open-loop condition without using balancing control. However, active balancing control methods can still be used to ensure proper

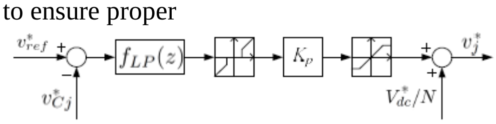

Fig. 3. Voltage controller of each cell.

operation under certain circumstances. The performances of the converter with and without balancing control will be compared in the next section.

A. Balancing Control

Fig. 8 shows the balancing controller of the proposed converter. In order to balance the capacitor dc voltages, measuring the capacitor voltage of each cell is required. The reference voltage v_ref for each cell is calculated from the averaged voltage of the capacitors, which is expressed as

$$v_{ref}^{*} = \frac{1}{N}\sum_{j=1}^{N} v_{Cj}^{*}.$$

As the cell capacitors are in resonant operation, each capacitor voltage contains a considerable ac component. First order low-pass filters are used to obtain the dc components of the capacitor voltages. As low-pass filters have to be implemented digitally, the transfer function of the filter can be written as

$$f_{LP}(z) = \frac{\alpha}{z-1+\alpha}$$

By comparing the reference voltage to the dc voltage of each cell, a proportional feedback control is used for regulation. A dead zone is created to allow a small tolerance of voltage imbalance. Saturation is used to limit the adjustable duty-ratio range. As the series current is positive at each switching instant (or in average), current measurement is not necessarily required for voltage balancing. The capacitor voltage can be charged by increasing the duty-ratio of each cell slightly.

B. Step-Down DC Transformer

The proposed converter has inherent-balancing ability and therefore can operate using open-loop control. Regardless of the voltage drop of semiconductors and tolerance of the cell components, the ideal output voltage is proportional to the input voltage when the switching frequency is fixed. This gives the possibility of using the proposed converter as a dc transformer. The ratio between the output voltage and the input voltage is roughly determined by the number of cells. By increasing the number of cells, higher step-down ratio can be achieved. However, as explained in the previous section, the current stress will be further increased as a function of N. To achieve higher step-down ratio, isolation transformers can be used to increase the step-down ratio without increasing the series ac current. The topology in Fig. 1 is recommended for higher step-down ratio dc-dc conversions.

C. Output Voltage Regulator

If the switching frequency is limited in a certain range for a practical application, the proposed converter may require a secondary dc-dc conversion stage to regulate the output voltage. This is a good solution for output voltage control. However, classic frequency controllers can be used for output voltage regulation without a secondary dc-dc converter. Frequency controllers have limitations in many applications, but as a simple solution they can achieve the requirement under some certain circumstances.

IV. RESULTS

An experimental prototype was constructed based on the proposed circuit in Fig. 3 with five chopper cells. The dc supply was rated at 500 V. Between the dc supply and the converter stack, an input LC filter was connected to suppress the ac current going to the dc supply. The filter inductance and capacitance were selected respectively. Note that big tolerance of capacitance applies during manufacturing process. As a result, real values of the cell capacitors are different from each other. The switching frequency for

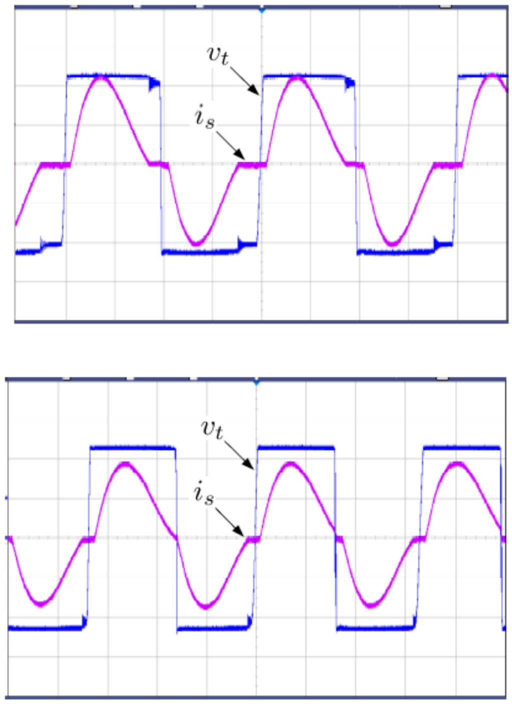

Fig.9.a Experimental waveforms under open-loop condition

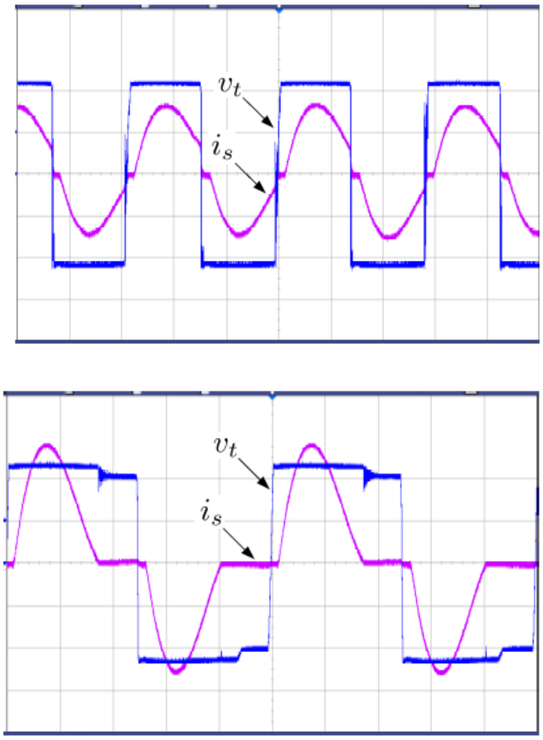

Fig.9.b.Experimental waveforms under closed-loop condition

Fig. 9a&b shows the open-loop and closed controlled experimental waveforms of the rectifier input voltage and series current. When the equivalent operation frequency is smaller than both frp and frn, the series current resonates quickly and the rectifier input current becomes zero before both the ends of positive half cycle and negative half cycle. The converter is fully operating in DCM

V. CONCLUSION

As high step-down ratio dc-dc converters becomes increasingly interesting, there is a strong demanding on novel dc-dc converter topologies. This paper has presented a family of new transformerless MMC dc-dc converters. The dc capacitors of the cells are used also for resonant operation. The equivalent operating frequency can be increased as a function of the number of chopper cells and the voltage step-down ratio is also dependent on the number of the cells. The proposed converter has a simple configuration and inherent-balancing capability. Two resonant operating frequencies exist in the converter. The converter can operate under open-loop control as a dc transformer. It exhibits a good linearity with different switching frequencies. When closed-loop controller is used for the converter, the capacitors are balanced and the output voltage is regulated within a smaller tolerance range of the rated value. Compared to the other topologies such as PETs, the proposed converter may exhibit more losses as a high ac current is flowing through the cells. However, the proposed converter can eliminate the use of transformers and even cell voltage sensors. Hence, the proposed converter has the feature of reliability, scalability and simplicity which may be suitable for developing high voltage and low power applications.

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