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Single Phase Cascaded H5 Inverter with Leakage Current Elimination for Transformerless Photovoltaic System

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***Abstract*—Leakage current reduction is one of the important issues for the transformelress PV systems. In this paper, the transformerless single-phase cascaded H-bridge PV inverter is investigated. The common mode model for the cascaded H4 inverter is analyzed. And the reason why the conventional cascade H4 inverter fails to reduce the leakage current is clarified. In order to solve the problem, a new cascaded H5 inverter is proposed to solve the leakage current issue. Finally, the experimental results are presented to verify the effectiveness of the proposed topology with the leakage current reduction for the single-phase transformerless PV systems.**

I. INTRODUCTION

The transformerless photovoltaic (PV) inverters have the advantages of low cost, small size, light weight and high efficiency [1]−[3]. However, the leakage current will arise due to lack of galvanic isolation. The undesirable leakage current may lead to electromagnetic inferences, current harmonic distortion and safety concerns. Therefore, it is crucial to eliminate the leakage current in transformerless PV systems.

Many interesting single-phase topologies have been reported such as Heric, H5, H6, and so on. But they are limited to three-level inverters [4]−[8]. On the other hand, the multilevel inverters can decrease the voltage stress of dv/dt on switches and increase the output waveform quality [9]−[11]. However, few papers have been reported regarding eliminating the leakage current for the single-phase cascaded multilevel inverters. A significant contribution by Zhou and Li is the filter-based leakage current suppression solution for the single-phase cascaded multilevel PV inverter [12]. But the topology-based solution is rarely discussed in literature, and needs further investigation.

The main contribution of this paper is to present a new cascaded H5 inverter to achieve the leakage current reduction. The experimental results are presented to verify the effectiveness of the proposed topology with the leakage current reduction for the single-phase transformerless PV systems.

II. SINGLE-PHASE CASCADED H4 INVERTER

The schematic diagram of the single-phase cascaded H4 inverter is shown in Fig.1. Since each H-bridge unit requires an independent dc source, it is necessary to consider the stray capacitance of each PV panel to the ground. The common mode voltage (CMV) and differential-mode voltage (DMV) for the upper and lower H-bridge unit are defined as follows:

$$U_{cma} = (U_{AN} + U_{BN})/2 \tag{1}$$

$$U_{dma} = U_{AN} - U_{BN} \tag{2}$$

$$U_{cmb} = (U_{A'N'} + U_{B'N'})/2 \tag{3}$$

$$U_{dmb} = U_{A'N'} - U_{B'N'} \tag{4}$$

Fig. 2 shows the common-mode model for single-phase cascaded H4 PV system, where $C_{pva}=C_{pva1}//C_{pva2}$, $C_{pvb}=C_{pvb1}//C_{pvb2}$. Based on the common-mode model, the leakage current for the cascaded H4 inverter can be calculated as (5).

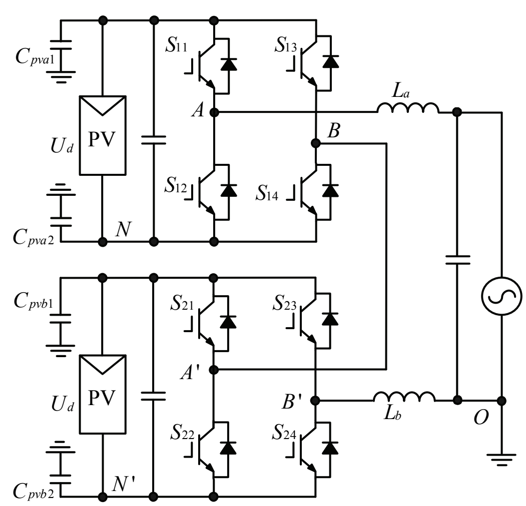


Fig. 1. Single-phase cascaded H4 inverter

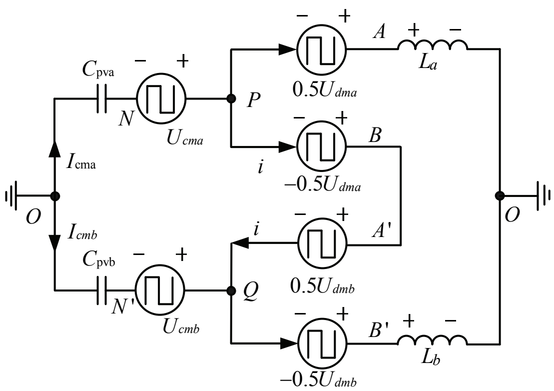


Fig. 2. Common-mode model of cascaded H4 inverter

The following equations can be derived from Fig. 2.

$$\begin{cases} -\dfrac{U_{PO}-U_{cma}}{Z_{cpva}} = i + \dfrac{U_{PO}+0.5U_{dma}}{Z_{La}} \\ -\dfrac{U_{QO}-U_{cmb}}{Z_{cpvb}} = -i + \dfrac{U_{QO}-0.5U_{dmb}}{Z_{Lb}} \\ U_{PQ} = 0.5U_{dma}+0.5U_{dmb} \\ I_{cma} = \dfrac{U_{OP}+U_{cma}}{Z_{cpva}} \\ I_{cmb} = \dfrac{U_{OQ}+U_{cmb}}{Z_{cpvb}} \end{cases} \tag{5}$$

where $Z_{cpva}=1/(sC_{pva})$, $Z_{cpvb}=1/(sC_{pvb})$.

$$\begin{cases} I_{cma} = \dfrac{AU_{cma}+BU_{dma}+CU_{cmb}+DU_{dmb}}{Z_{cpva}[(Z_{cpva}+Z_{cpvb})Z_{La}Z_{Lb}+(Z_{La}+Z_{Lb})Z_{cpva}Z_{cpvb}]} \\ I_{cmb} = \dfrac{A'U_{cma}+B'U_{dma}+C'U_{cmb}+D'U_{dmb}}{Z_{cpvb}[(Z_{cpva}+Z_{cpvb})Z_{La}Z_{Lb}+(Z_{La}+Z_{Lb})Z_{cpva}Z_{cpvb}]} \end{cases} \tag{6}$$

where $Z_{La}=sL_a$, $Z_{Lb}=sL_b$,

$A=Z_{cpva}\left(Z_{La}Z_{Lb}+Z_{cpvb}Z_{Lb}+Z_{cpvb}Z_{La}\right)$,

$B=-0.5Z_{cpva}\left(Z_{La}Z_{Lb}-Z_{cpvb}Z_{Lb}+Z_{cpvb}Z_{La}\right)$,

$C=-Z_{cpva}Z_{La}Z_{Lb}$, $D=-0.5Z_{cpva}Z_{La}(Z_{Lb}+Z_{cpvb})$,

$A'=-Z_{cpvb}Z_aZ_{Lb}$, $B'=Z_{cpvb}Z_{Lb}(0.5Z_a+Z_{cpva})$,

$C'=Z_{cpvb}(Z_aZ_{Lb}+Z_{cpva}Z_{Lb}+Z_{cpva}Z_{La})$,

$D'=0.5Z_{cpvb}(Z_aZ_{Lb}+Z_{cpva}Z_{Lb}-Z_{cpva}Z_{La})$

For (6), it can be concluded that the leakage current is dependent on many factors, e.g. the CMV and DMV of each H-bridge unit. Therefore, it is difficult to eliminate the leakage current of single-phase cascaded H4 inverter in an effective way.

III. Proposed Cascaded H5 Inverter

In order to solve the abovementioned problem, a new single-phase cascaded H5 inverter is proposed, as shown in Fig. 3. The common-mode model of cascaded H5 inverter is shown in Fig. 4, from which the following equation can be derived.

$$\begin{cases} I_{cma} = \dfrac{U_{cma}+U_{dm\_a}}{Z_{cpva}+Z_{Lab}} \\ I_{cmb} = \dfrac{U_{cmb}+U_{dm\_b}}{Z_{cpvb}+Z_{La'b'}} \end{cases} \tag{7}$$

Considering that the filter inductors are generally designed as the same value, the differential mode voltages $U_{dm\_a}=U_{dm\_b}=0$. So Eq. (7) can be rewritten as

$$\begin{cases} I_{cma} = \dfrac{U_{cma}}{Z_{cpva}+Z_{Lab}} \\ I_{cmb} = \dfrac{U_{cmb}}{Z_{cpvb}+Z_{La'b'}} \end{cases} \tag{8}$$

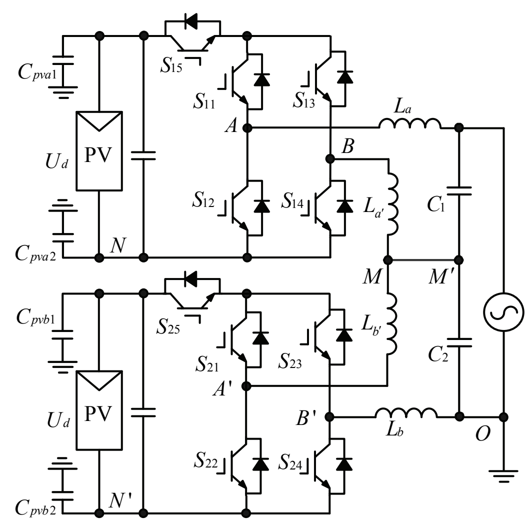


Fig. 3. Single-phase cascaded H5 inverter

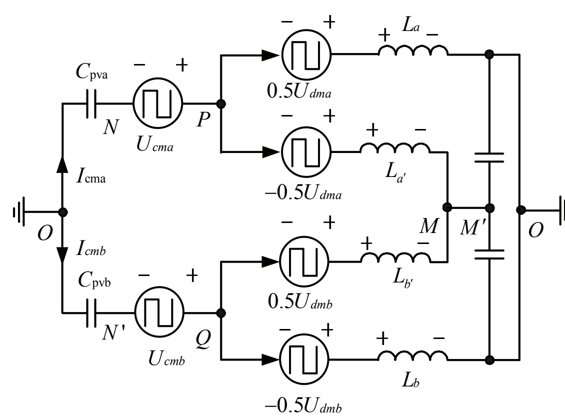


Fig. 4. Common-mode model of cascaded H5 inverter

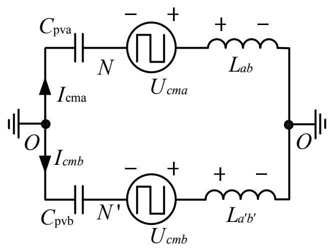


Fig. 5. Simplified common-mode model of cascaded H5 inverter

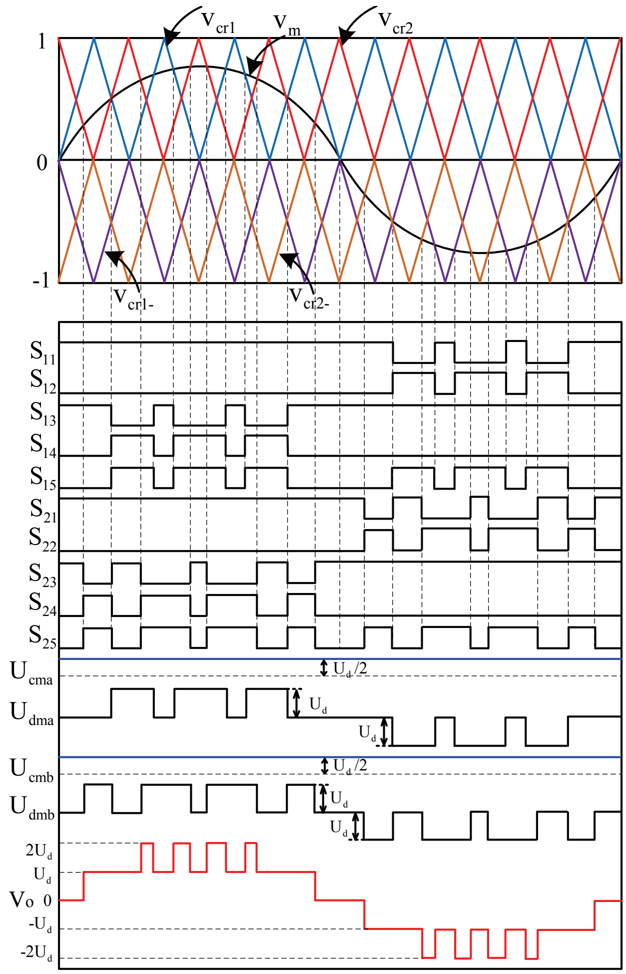


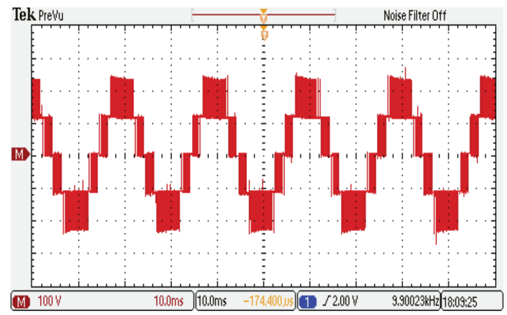
Fig. 6. Proposed modulation strategy

From (8), it can be concluded that the leakage current can be eliminated if the common mode voltage of each cascaded unit is constant. Fig. 6 shows the proposed modulation strategy for the cascaded H5 inverter. It can be observed that the proposed method can achieve both the constant common mode voltage and five-level output voltage. That is, the high quality output waveforms with the leakage current reduction can be achieved.

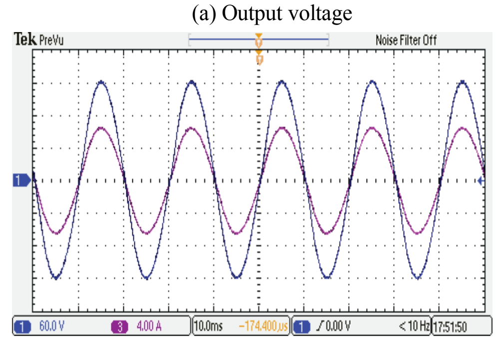
IV. EXPERIMENTAL RESULTS

The experimental prototype of the proposed cascaded H5 topology is controlled with TMS320F28335 DSP and XC3S400 FPGA. The experimental parameters are listed as follows. The dc link voltage of each cascaded unit is 120V, switching frequency is 10 kHz. The filter inductor is 5mH. The output filter capacitor is 9.4μF. The parasitic capacitance is 150nF.

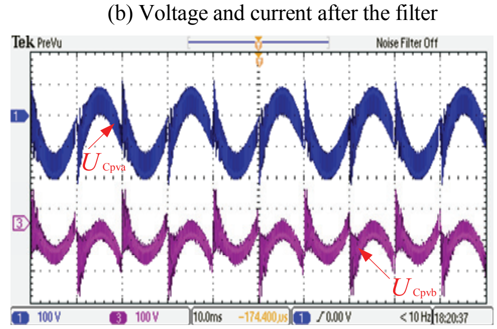
The experimental results are shown in Fig. 6 and Fig. 7, from which, it can be observed that the both cascaded H4 and H5 topology can achieve five-level output waveforms. However, for the cascaded H4 topology, the voltage across the stray capacitor is polluted with the high frequency components, which result in very high leakage currents.



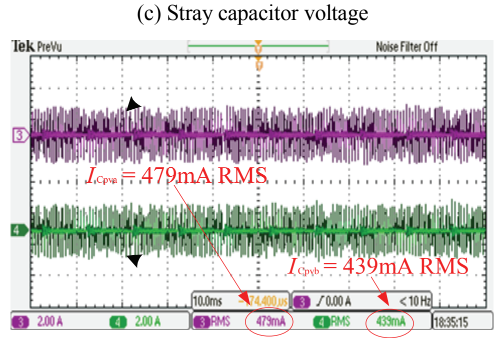
(a) Output voltage



(b) Voltage and current after the filter

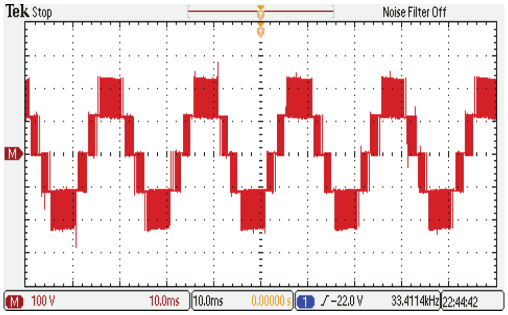


(c) Stray capacitor voltage

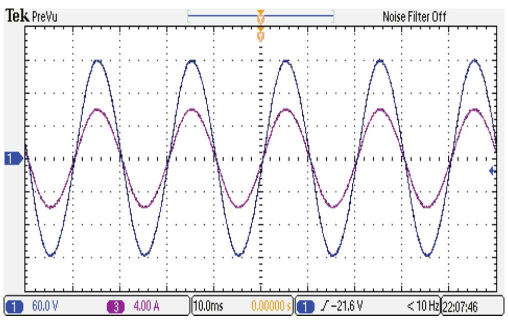


(d) Leakage current

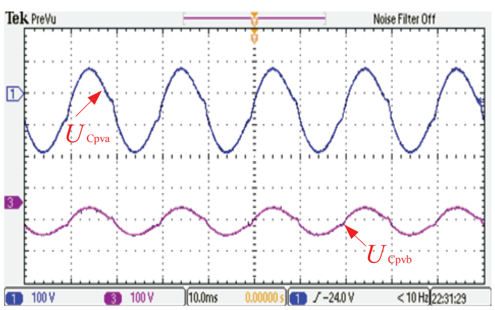
Fig. 7. Experimental results of cascaded H4 topology



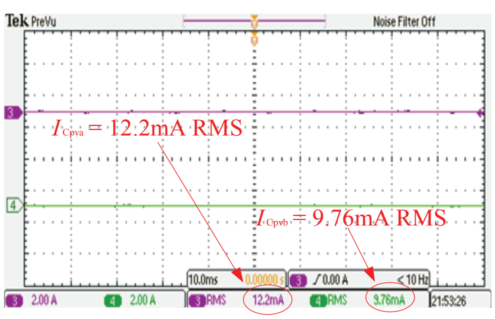
(a) Output voltage



(b) Voltage and current after the filter



(c) Stray capacitor voltage



(d) Leakage current

Fig. 8. Experimental results of proposed topology

As shown in Fig. 8, for the cascaded H5 topology, the voltage across the stray capacitor is free of any high frequency components. Consequently, the high frequency leakage current is significantly reduced, which is well below 300mA, as specified in VDE 0126-1-1.

V. Conclusions

This paper has presented the theoretical analysis and experimental verification of the leakage current suppression capability of single-phase cascaded H-bridge topologies for the transformerless PV systems. The experimental results indicate that the conventional single-phase cascaded H-bridge topology fail to reduce the leakage current. On the other hand, the proposed topology and new modulation strategy can ensure that the stray capacitor voltage is free of any high-frequency components, and the leakage current can be effectively reduced. Therefore, it is attractive for single-phase transformerless PV systems.

Acknowledgment

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