Three-Phase Transformer-less Hybrid-Bypass Inverter

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Abstract− This paper proposes a three phase transformer-less inverter to reduce the common mode voltage with hybrid AC/DC bypass circuit in the PV inversion system. The proposed inverter has the advantages of low conduction losses compared to the traditional three phase DC bypass inverter. The fluctuation range of the common mode voltage can be reduced to 1/3 of the traditional inverter. Thus, the leakage current will be significantly suppressed. Also, a variation topology of the proposed inverter is shown in this paper. The detailed comparison between the proposed inverter and the traditional three phase three level inverters reveals that the proposed inverter saves 3 switches compared to the NPC inverter and has less conduction losses compared to the DC bypass inverter.

I. INTRODUCTION

In the energy conversion field, especially the solar energy system, the bulky transformer has been used for isolating the leakage current between the AC and DC side. For the consideration of system volume and cost, transformer-less inverter is attracting more attention because of less cost and lower power losses. [1] One of the biggest trade-off for transformer-less topology is the common mode issue which may result in leakage current and safety problem. If the transformer is not installed in the photovoltaic (PV) inversion system, the high frequency voltage pulse can be generated by the switches and delivered to the parasitic capacitors among the inverter, PV panel, grid and ground. For the purpose of reducing the level of leakage current, one effective way is to stabilize the common mode voltage. [2] For this method of application, some typical single phase inversion structures have been studied, for example, H5, HERIC, and H6 topologies. [3-4] All the mentioned typical single phase inverters can fix the common mode voltage exactly half of DC bus voltage. However, in the field of three phase inversion system, same problem exists with even worse leakage current issues. But few studies focus on the three phase topology improvement to reduce the common mode current. [5-7]

This paper proposes a hybrid bypass three phase topology in order to decrease the leakage current in transformer-less PV system. Firstly, the overview of common mode issue in the single/three phase inverters is introduced to address the safety problem of leakage current. Then the structure of the proposed hybrid bypass topology is shown. The specific working modes of the proposed topology are illustrated and the common mode voltage reduction method is shown. Thirdly, the variation topology of the proposed inverter is also introduced. And this paper compares the proposed inverter with the traditional three phase NPC inverters and DC bypass inverter. The comparison reveals that the hybrid bypass topology has less device cost and lower conduction losses. Finally, the theoretical results are verified in a rigorous testing procedure.

II. COMMON-MODE CHARACTERISTIC OF THREE PHASE INVERTER

The typical topology of three phase two level inverter is given in Fig. 1. As is shown in Fig. 1, the three phase inverter has three phase legs each with two switches in the upper leg and lower leg, respectively. The switches in the upper and lower leg will be operating in high frequency (up to 10 kHz) and cannot be turned on simultaneously. That is to say the driving signals of upper switches and lower switches should be complementary. [8-9] And the six switches will generate eight working modes including six active modes and two null modes. According to the definition of the common mode (CM) voltage, the CM voltage can be defined as [10-12]:

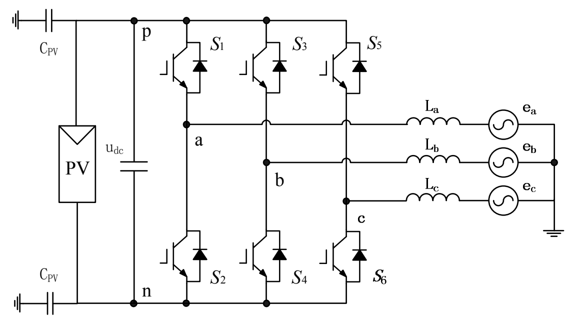


Fig. 1. The traditional three phase two level inverter.

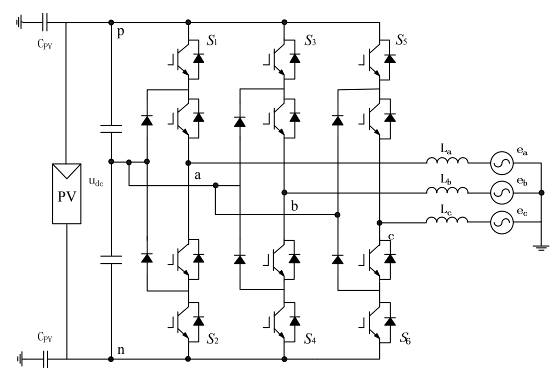


Fig. 2. The traditional three phase NPC three level inverter.

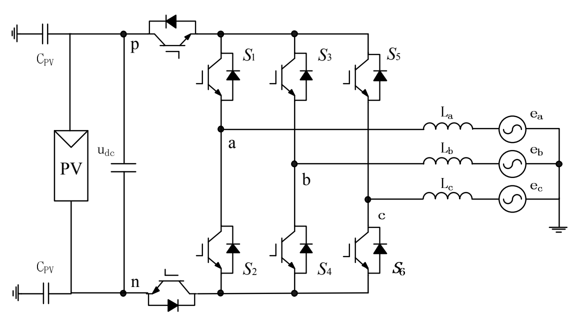


Fig. 3. The DC bypass three phase inverter.

TABLE I
COMMON MODE BEHAVIOR OF TRADITIONAL THREE PHASE INVERTER

Mode		u_{an}	u_{bn}	u_{cn}	u_{cm}
Active states	100	u_{dc}	0	0	$u_{dc}/3$
	010	0	u_{dc}	0	$u_{dc}/3$
	001	0	0	u_{dc}	$u_{dc}/3$
	110	u_{dc}	u_{dc}	0	$2u_{dc}/3$
	011	0	u_{dc}	u_{dc}	$2u_{dc}/3$
	101	u_{dc}	0	u_{dc}	$2u_{dc}/3$
Null states	111	u_{dc}	u_{dc}	u_{dc}	u_{dc}
	000	0	0	0	0

$$u_{cm} = \frac{u_{an}+u_{bn}+u_{cn}}{3} \quad (1)$$

Because the transformer-less topology has no isolation to separate the AC and DC side in the common mode paths, a leakage current excited by the common mode voltage will flow through the parasitic capacitors and other grounded components. To make a quantitative analysis of leakage current, the amplitude of common mode current is related to the parasitic capacitance and fluctuation of common mode voltage :

$$i_{cm} = C_{PV}\frac{du_{cm}}{dt} \quad (2)$$

It can be derived from equation (1) that all eight switching states can generate a common mode voltage. And the calculation of common mode voltage is based on the mean value of three phase output voltages. Table I gives the specific common mode voltages corresponding to each working state. It can be clearly observed that the ranges of common mode voltage are fluctuating among four levels, 0, $u_{dc}/3$, $2u_{dc}/3$ and u_{dc}. For example, if the switches, S_1, S_4 and S_6 are turned on, the switching state is (100). According to Table I and the common mode voltage equation in (1), the common mode voltage of (100) can be calculated as $(u_{dc}+0+0)/3=u_{dc}/3$. Similarly, all the eight working states has the common mode voltages which have been shown in the last column of Table I. From the column of u_{cm} in Table I, it can be summarized that the common mode voltage is ranging from 0 to u_{dc} which correspond to the two null states of (000) and (111), respectively.

The purpose of deriving the common mode voltage is to eliminate the leakage current. It can be seen from equation (2) that the leakage current will be largely reduced by stabilizing the common mode voltage. There exists some methods to decrease the fluctuation of common mode voltage by improving the modulation strategies in three phase NPC inverter. However, as is shown in Fig. 2, the NPC inverter costs six power diodes and twelve switches which is high-cost and more complicate than the topology in Fig. 1. On the other hand, more switches and diodes means more conducting losses and lower efficiency.

III. PROPOSED THREE-PHASE INVERTER WITH REDUCED COMMON MODE VOLTAGE

In this section, the proposed hybrid bypass three phase inverter is introduced with the working principle and function. Fig. 4 shows the proposed topology. In order to better elaborate the new inverter, the structure can be divided into two parts. The first part is the traditional three phase bridge legs including S_1-S_6. The second part is the hybrid bypass freewheeling circuit. It consists of DC bypass switch, S_7, and AC bypass switches, S_8, S_9, respectively. The subsections below analyze the working principle, expanded topologies, neutral point clamping application and comparison with other typical inverters specifically.

A. Working Principle

The proposed hybrid bypass inverter can generate three level output voltages. The main function of the extra hybrid bypass freewheeling circuit is to deliver the freewheeling current during the null switching states. Because the two null states have the maximum and minimum common mode voltages, the bypass circuit will replace the null state common mode voltages with smaller value. In the two level inverter of Fig. 1, the null states are generated by turning on the upper or lower three switches, illustrated as (111) and (000),

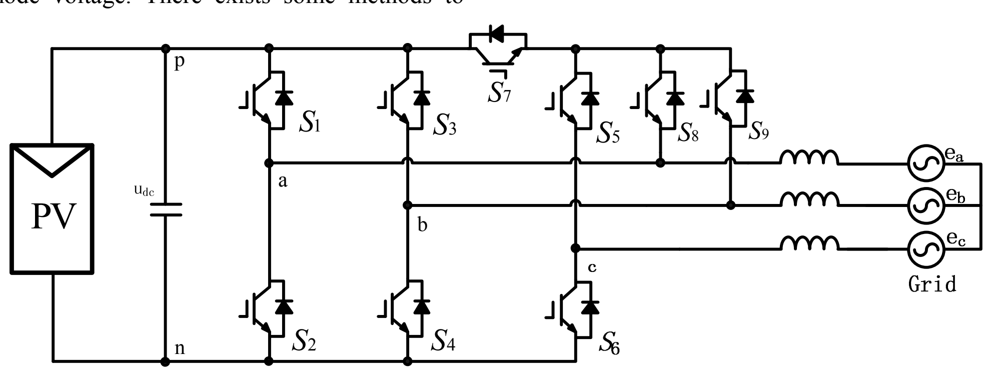


Fig. 4. Proposed hybrid bypass inverter.

TABLE II
COMMON MODE BEHAVIOR OF PROPOSED THREE PHASE INVERTER

Mode		u_{an}	u_{bn}	u_{cn}	u_{cm}
Active states	100	u_{dc}	0	0	$u_{dc}/3$
	010	0	u_{dc}	0	$u_{dc}/3$
	001	0	0	u_{dc}	$u_{dc}/3$
	110	u_{dc}	u_{dc}	0	$2u_{dc}/3$
	011	0	u_{dc}	u_{dc}	$2u_{dc}/3$
	101	u_{dc}	0	u_{dc}	$2u_{dc}/3$
Null states	***	$u_{dc}/2$	$u_{dc}/2$	$u_{dc}/2$	$u_{dc}/2$

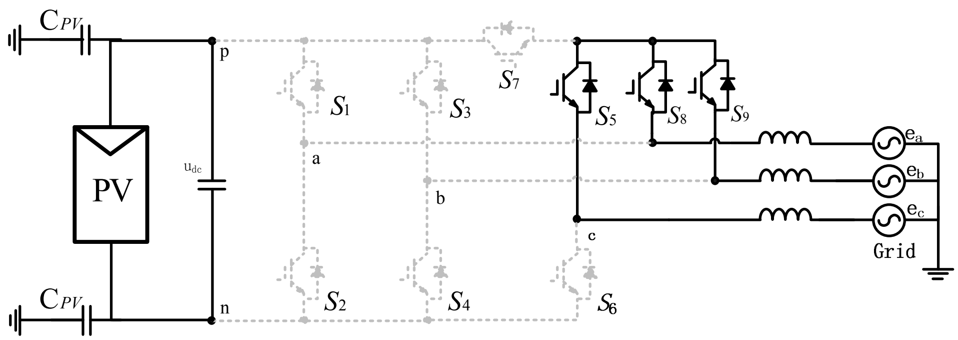


Fig. 5. The freewheeling mode of the proposed inverter.

respectively. In these two null states, the common mode voltage reach the peak and valley values which are u_{dc} and o. The common mode voltage oscillating ranges are significantly enlarged by these two values. In the hybrid bypass topology shown in Fig. 4, the null states of (111) and (000) are replaced by turning on the freewheeling switches, S_8 and S_9, and upper switch of phase leg c, S_5. With the hybrid bypass circuit, the common mode voltages of the null states, 0 and u_{dc}, are eliminated and replaced by the new freewheeling circuit. As is shown in Fig. 5, during the freewheeling modes of the proposed inverter, the three switches, S_5, S_8 and S_9, are turned on and the switches of phase leg a and b, S_6 and S_7, are turned off. In this situation, the voltage potentials between the three output points, a, b, c and the negative point of the PV panel are $u_{dc}/2$. Thus, the common mode voltage can be calculated as $(u_{dc}/2+ u_{dc}/2+ u_{dc}/2)/3= u_{dc}/2$.

If we make a comparison of the common mode voltages between the proposed topology and the traditional inverter in Fig. 1, Table II shows the detailed common mode voltage ranges after adding the hybrid bypass freewheeling circuit. The peak to peak value of the common mode voltage has been decreased from u_{dc} to $u_{dc}/3$. Thus, according to equation (2), the leakage current will be significantly attenuated.

B. The Expanded Topology

In this subsection, the variation topology of the proposed hybrid bypass inverter is introduced. As is shown in Fig. 6, the freewheeling circuit can be placed to connect the three phase output and the negative DC bus. This topology also has the function of attenuating the common mode voltage by 2/3. The modulation strategy of the topologies in Fig. 6 is similar to the proposed one in Fig. 4. During the freewheeling mode, the switches, S_6, S_8 and S_9 are turned on and other switches are turned off to isolate the DC source with the AC side. Thus, the common mode voltage can be kept as half of DC link. And the CMV ranges will be reduced by 66.7%.

C. The Neutral Point Clamping (NPC) Improvement

During the high frequency operation of the inverter, each

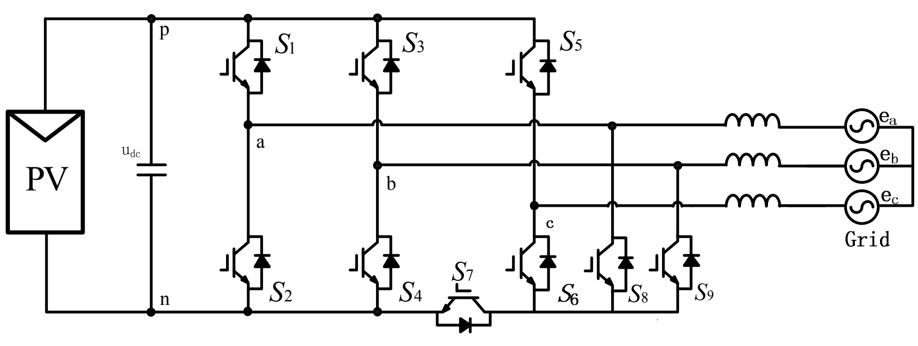
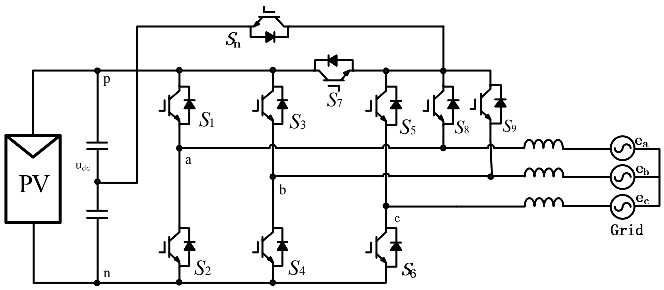
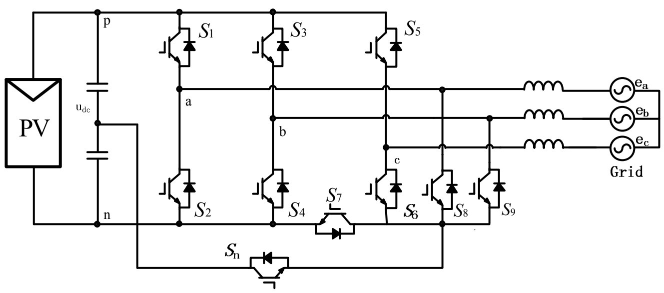


Fig. 6. The expanded topology of the proposed inverter.



(a)



(b)

Fig. 7. The NPC improvement topologies of the proposed inverters in (a) Fig. 4 and (b) Fig. 6.

switch has an equivalent junction capacitor which will be charged and discharged in every switching transition cycle. The period of charging and discharging will influence the stability of common mode voltage. In this subsection, a neutral point clamping switch is added between the middle of the DC capacitors and the freewheeling circuit of the proposed hybrid bypass inverter as is shown in Fig. 6(a) and 6(b). During the energy transferring modes, the clamping switch, S_n, is turned off. In the freewheeling modes, S_n is turned on to clamp the potential of the hybrid bypass freewheeling path strictly constant as half of the DC link. For controlling principle, the PWM signals of the clamping switch are synchronous as the freewheeling switches, S_8 and S_9.

D. The Comparison with Traditional Topologies

As is known, the traditional three phase NPC topology and DC bypass inverter can be applied in the photovoltaic inversion system. Some methods have been proposed to reduce the common mode voltage based on the modulation strategies rather than on the improvement of circuit structures. This subsection gives a brief comparison among the proposed topologies and the traditional NPC inverters, DC bypass inverter. [4][10-12]

Firstly, in the aspect of device cost, the proposed topology in Fig. 4 only uses nine switches which costs three switches fewer than the traditional NPC inverter. Secondly, in terms of the conduction losses, the proposed topologies only conduct one switch in phase leg a and b and two switches in phase leg c only if upper switch is ON during the energy transferring mode. However, the NPC topology in Fig. 2 conducts two switches per phase leg which is twice higher than the proposed inverters. Also the DC bypass inverter also conducts two switches in the three phase legs which will cause more conduction losses than the proposed inverter. So, the proposed topologies have the advantages in device cost and conduction losses compared to the typical three phase inverter.

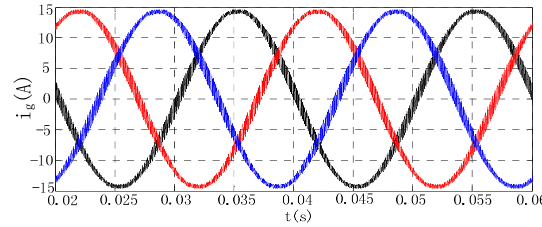


Fig. 8. The grid current of the traditional three phase two level inverter.

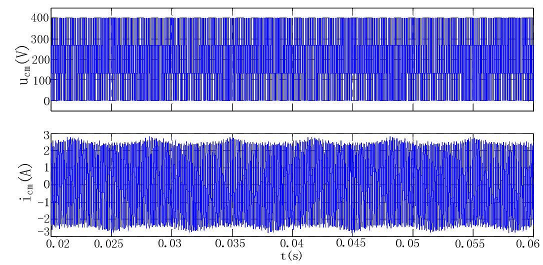


Fig. 9. The common mode voltage and leakage current of the traditional three phase two level inverter.

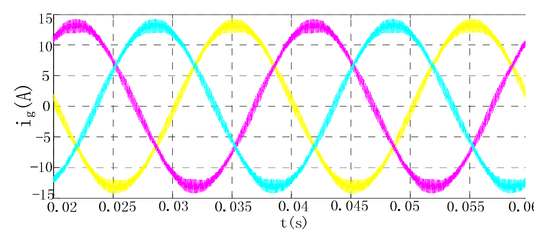


Fig. 10. The grid current of the proposed hybrid bypass three phase inverter.

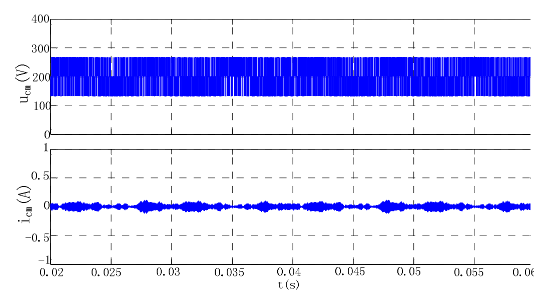


Fig. 11. The common mode voltage and leakage current of the proposed three phase hybrid bypass inverter.

IV. RESULTS

The simulation results are shown in this section. The proposed inverter with the hybrid modulation strategy was simulated in Matlab/Simulink. The DC voltage is 400V, and the grid voltage is 110V/50Hz. The switching frequency for the inverter is 10kHz. The output inductors are all 2mH. The stray capacitance between PV array and ground is 470nF.

Fig. 8 shows the grid current of the traditional three phase two level inverter. And in Fig. 9, the common mode voltage, u_{cm}, and leakage current, i_{cm}, of the traditional topology are captured. It can be observed that the u_{cm} is fluctuating between 0 and u_{dc}. Thus, the leakage current is large.

Fig. 10 shows the grid current of the proposed hybrid bypass three phase inverter. Fig. 11 gives the u_{cm} and i_{cm} of the proposed three phase inverter. It can also be observed that the common mode voltage is fluctuating between $u_{dc}/3$ and $2u_{dc}/3$, which is just 1/3 of the traditional topology' s fluctuation. And the leakage current is kept within 0.1A which satisfies the German standard VDE 0126-1-1 of 300mA.

V. CONCLUSION

This paper proposes a hybrid DC/AC bypass three phase inverter to eliminate the common mode voltage in the transformer-less PV inversion system. The conduction losses are reduced compared to the traditional three phase NPC inverter and DC bypass inverter. Also, the device cost is less than the traditional NPC inverters. A variation topology of the proposed three phase hybrid bypass inverter with negative DC bus connection is introduced in this paper. And the NPC improvement topologies based on the proposed inverter are analyzed to further reduce the leakage current. Finally, the simulation results have verified the theoretical analysis.

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