Guocheng San, Hanhong Qi, Xiaoqiang Guo
Yanshan University

A Novel Single-Phase Transformerless Inverter for Grid-Connected Photovoltaic Systems

***Abstract**. Eliminating the leakage current is one of the most important issues for transformerless inverters in grid-connected photovoltaic system applications, where the technical challenge is how to keep the system common-mode voltage constant to reduce the leakage current. A novel single-phase three-level topology for transformerless photovoltaic systems is presented in this paper. Compared with the conventional H-bridge topology, it only needs two additional asymmetrically distributed switches, and the system common-mode voltage can be kept constant with a simple modulation scheme. Test results verify the theoretical analysis and the feasibility of the proposed topology.*

***Streszczenie.** W artykule przedstawiono nową trójpoziomową topologię jednofazowego przekształtnika w beztransformatorowym układzie pracującym z panelami fotowoltaicznymi. System pozwala na utrzymanie stałego napięcia common-mode, poprzez wykorzystanie dodatkowych łączników oraz prostego algorytmu modulacji . (**Nowa trójpoziomowa topologia z sześcioma łącznikami w beztransformatorowych systemach fotowoltaicznych**).*

Keywords: Leakage current, transformerless photovoltaic system, common-mode voltage
Słowa kluczowe: prąd upływu, beztransformatorowy system fotowoltaiczny, common-mode voltage

Introduction

Photovoltaic (PV) power generation systems are received more and more attention in recent years. According to the latest report of IEA-PVPS on installed PV power [1], by the end of 2010, the cumulative installed capacity is increased to almost 35 GW, of which the majorities (69%) are installed in Germany and Italy. The cumulative growth in PV capacity is illustrated in Fig.1, from which, it can be observed that most of them is grid-connected. Typically, a line frequency transformer is integrated into the grid-connected PV system for the galvanic isolation, dc injection and leakage current suppression [2]. However, the transformer brings in the additional cost and system efficiency reduction.

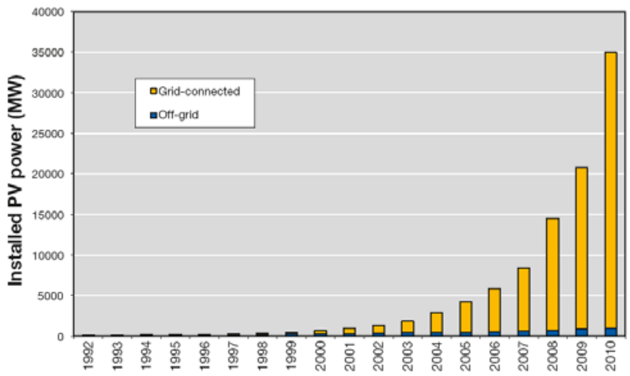


Fig. 1 Cumulative installed capacity between 1992 and 2010 in the IEA-PVPS reporting countries

On the other hand, the transformerless PV systems have been received more attention due to cost and size reduction, as well as efficiency improvement compared with the conventional transformer ones. A number of technical challenges may arise with increased grid-connected transformerless PV systems. One of the most important issues is how to reduce or eliminate the leakage currents through the parasitic capacitor between the PV array and the ground [3-10]. In general, the leakage current can be significantly mitigated from the viewpoint of system topology or modulation schemes. For example, the single-phase H-bridge topology with the bipolar modulation has the inherent feature of the leakage current reduction. However, it leads to the relatively more high frequency ripples due to the two-level output voltage. On the other hand, the unipolar modulation with three-level output voltage is beneficial in terms of low voltage ripples and small filter size, but the leakage current is significantly increased due to the time-varying high frequency common mode voltage.

In order to solve the abovementioned problem, many interesting topologies have been reported in the past few years. The basic idea behind them is to keep the system common mode voltage constant to eliminate the leakage currents. With the basic idea, a new single-phase three-level topology for transformerless photovoltaic systems is presented in this paper. Compared with the conventional H-bridge topology, it only needs two additional asymmetrically distributed switches, and the system common-mode voltage can be kept constant with a simple modulation scheme. The theoretical analysis and test results demonstrated that the proposed topology is very promising for transformerless PV systems.

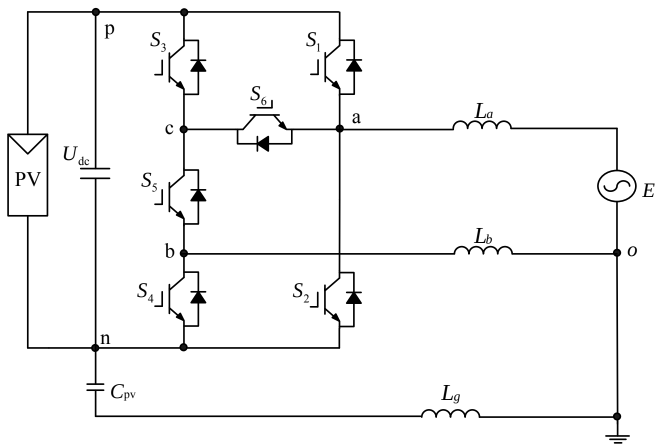


Fig. 2 Schematic diagram of the proposed topology

Proposed Topology

Fig. 2 illustrates the schematic diagram of the proposed topologies, where E is the grid voltage. L_a and L_b are the filter inductors. C_{pv} is the stray capacitance between the PV array and ground, and its value depends on the PV panel and frame structure, weather conditions, etc [6]. L_g is the inductance between the ground connection of the inverter and the grid.

In order to clarify how the leakage current generates, a generic common mode model is presented in Fig.3

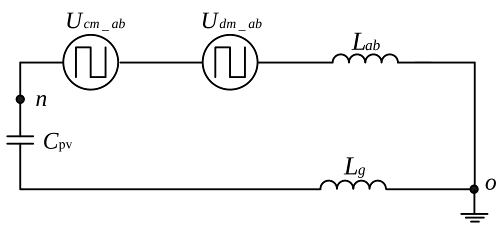


Fig. 3 System common mode model

In Fig.3, the common mode voltage U_{cm_ab} and differential mode voltage U_{dm_ab} are defined as follows:

(1) $$U_{cm\_ab} = \frac{U_{an} + U_{bn}}{2}$$

(2) $$U_{dm\_ab} = \frac{(U_{an} - U_{bn})(L_a - L_b)}{2(L_a + L_b)}$$

The total common-mode voltage can be derived from Fig.3 as follows:

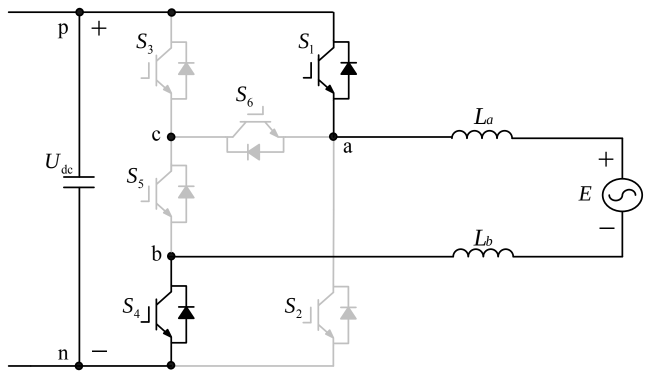
(3) $$U_{tcm} = U_{cm\_ab} + U_{dm\_ab} = \frac{U_{an} + U_{bn}}{2} + \frac{U_{ab}(L_a - L_b)}{2(L_a + L_b)}$$

Equation (3) indicates that the filter inductors should be symmetrically distributed in the loop, that is, $L_a = L_b$. Under this assumption, the system common-mode voltage can be rewritten as follows:

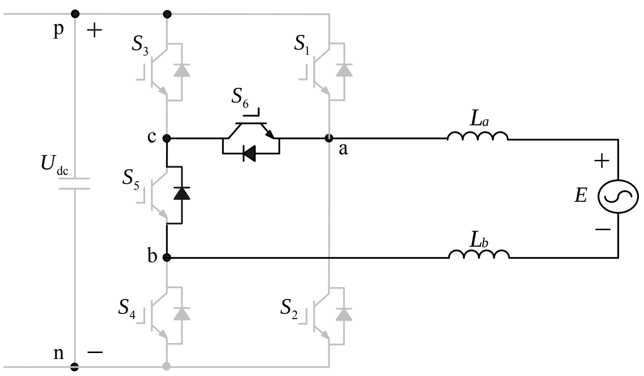
(4) $$U_{cm} = \frac{U_{an} + U_{bn}}{2}$$

Table I. Switch state and common mode voltages

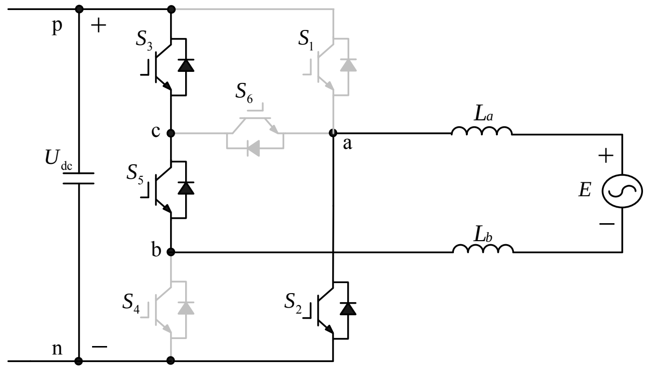
S_1	S_2	S_3	S_4	S_5	S_6	U_{an}	U_{bn}	U_{cm}	
1	0	0	1	0	1	U_{dc}	0	$U_{dc}/2$	P
0	0	0	0	0	1	$U_{dc}/2$	$U_{dc}/2$	$U_{dc}/2$	
0	1	1	0	1	0	0	U_{dc}	$U_{dc}/2$	N
0	0	0	0	1	0	$U_{dc}/2$	$U_{dc}/2$	$U_{dc}/2$	



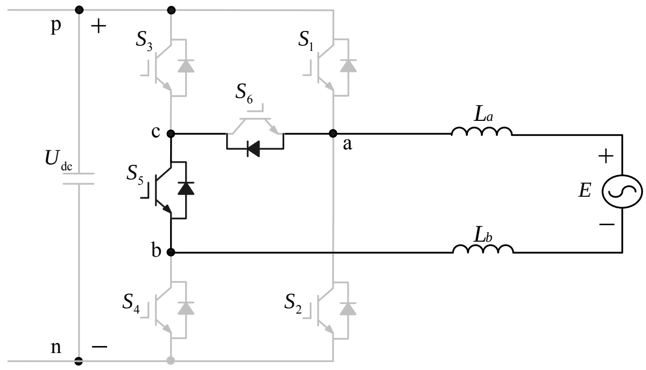
(a)



(b)



(c)



(d)

Fig. 4 Operation modes

From Fig.3 and (4), it can be concluded that the leakage current [$i_{cm} = C_{pv}(dU_{pv}/dt)$] will be zero on condition that the common mode voltage U_{cm} is kept constant.

Operation Analysis

Fig.4 shows the four operation modes of the proposed six-switch inverter. During the positive half cycle, S_6 is on and S_2 , S_3 and S_5 is off. S_1 and S_4 commutate at the switching frequency, as depicted in Fig.5. The common mode voltages in this case are summarized in Table I, from which it can be observed that the common voltages remain unchanged during the positive half cycle.

In the similar manner, during the negative half cycle, S_5 is on and S_1 , S_4 S_6 is off. S_2 and S_3 commutate at the switching frequency, as depicted in Fig.5. The common mode voltages remain unchanged in this case, as summarized in Table I.

Performance Evaluation

In order to verify the feasibility of the proposed topology and its control scheme, the performance evaluation is carried out in MATLAB/Simulink. The system parameters are as follows: DC bus voltage: 400V, Grid voltage: 220V/50Hz, Switching frequency: 10 kHz. The rated power is 3kW. LCL filter is used for attenuating the high frequency harmonics associated with the switching feature of the inverter. Its parameters are 2mH, 9.4uF and 2mH respectively. A small resistor is in series with the filter capacitor for passive damping. The stray capacitance between the PV array and ground is 100nF. P + Resonant (PR) controller is used for grid current regulation with zero steady-state error. Fig.6 shows the modulation strategy of the proposed topology.

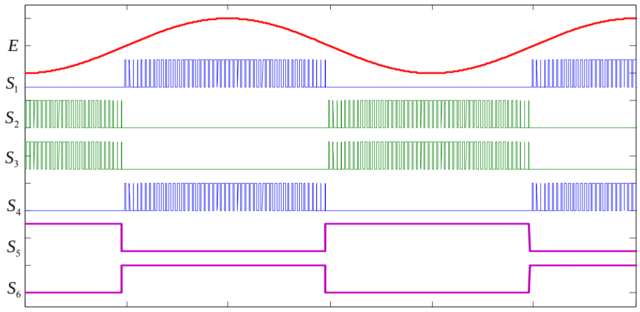


Fig. 5 Modulation scheme

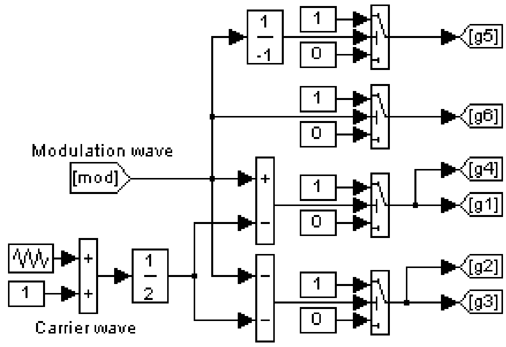


Fig. 6 Modulation strategy of the proposed topology

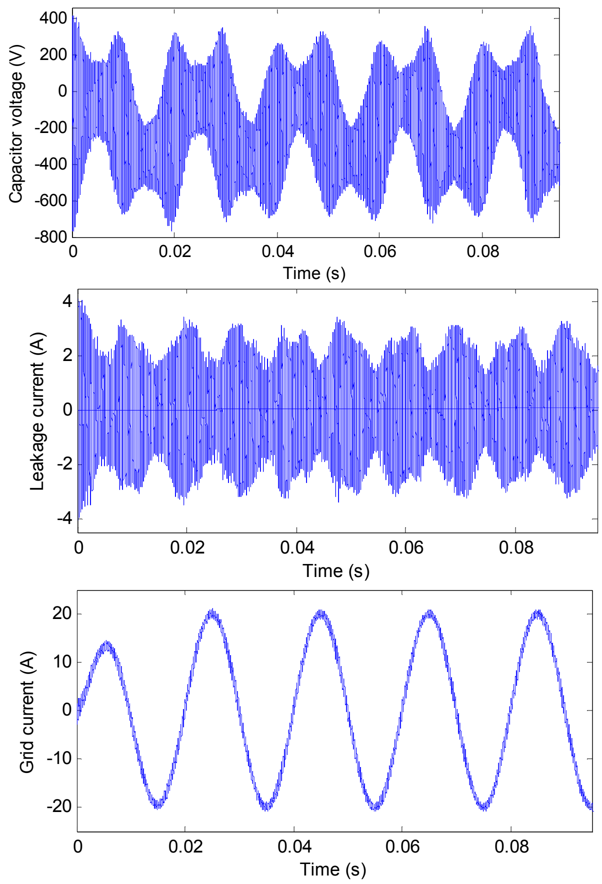


Fig. 7 Conventional H-bridge topology

Fig. 7 shows the performance evaluation results of the conventional H-bridge topology with unipolar modulation. As expected, the stray capacitance voltage is C_{pv} fluctuates with the high frequency pulses. Therefore, the peak value of the leakage current flowing through the stray capacitance is very high, which is far beyond the acceptable level. Aside from that, the grid current is polluted with the high frequency ripples, which is not in compliance with IEEE Std.929-2000.

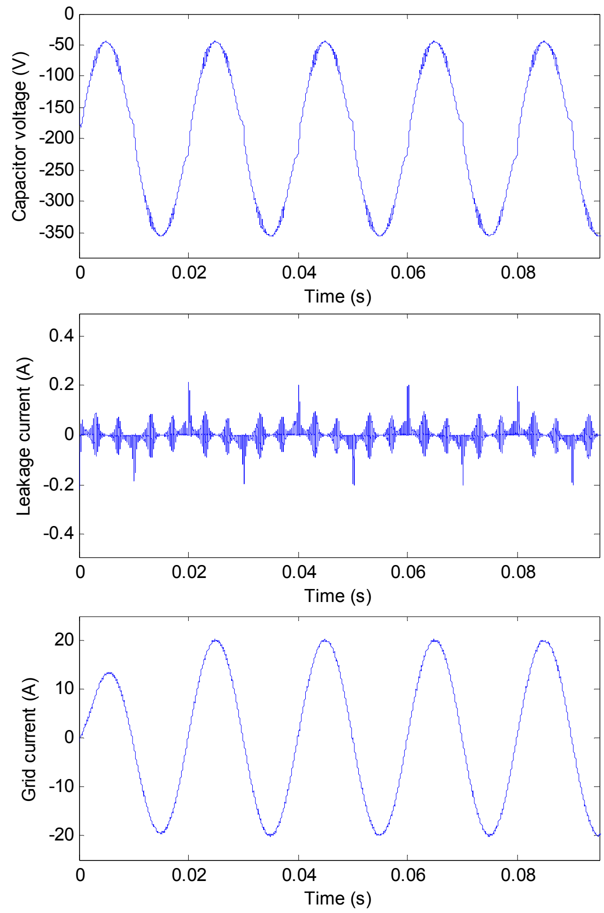


Fig. 8 Proposed six-switch topology

On the other hand, the stray capacitance voltage fluctuates at a low frequency with the proposed topology, as shown in Fig.8. It should be noted that the frequency of this voltage fluctuation associated with the grid voltage is so low that it has no significant impact on the leakage current. From Fig.8, it can be observed that the peak value of the leakage current is well below 300mA, as specified in VDE 0126-1-1. Also, the grid current is sinusoidal and free of high frequency harmonics'

Conclusions

This paper has presented a new single-phase three-level six-switch topology for transformerless photovoltaic systems. Theoretical analysis and performance evaluation results indicate that the proposed topology can effectively reduce the leakage current to an acceptable level, which is well below 300mA, as specified in VDE 0126-1-1.

Acknowledgment

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Corresponding Author
Xiao-Qiang. Guo, Key Lab of Power Electronics for Energy Conservation and Motor drive of Hebei province, Department of Electrical Engineering, Yanshan University, Qinhuangdao 066004, China. Email: gxq@ysu.edu.cn