# Leakage Current Suppression with A Novel Six-Switch Photovoltaic Grid-Connected Inverter

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# Leakage Current Suppression with A Novel Six-Switch Photovoltaic Grid-Connected Inverter

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***Abstract* —In order to solve the problem of the leakage current in non-isolated photovoltaic (PV) systems, a novel six-switch topology and control strategy are proposed in this paper. The inductor-bypass strategy solves the common-mode voltage limitation of the conventional six-switch topology in case of unmatched inductances. And the stray capacitor voltage of the non-isolated photovoltaic system is free of high frequency ripples. Theoretical analysis and simulation are carried out to verify the proposed topology and its control strategy. Results indicate that the leakage current suppression can be achieved with the proposed solution.**

***Index Terms* —common-mode voltage, leakage current, grid-connected inverter, non-isolated, photovoltaic power generation**

## I. INTRODUCTION

NON-isolated photovoltaic power generation system has obtained more and more attention due to its advantages of small volume, low cost and high efficiency [1]. But, a common-mode current (leakage current) will be generated without the transformer. It will flow through the loop which is constituted by stray capacitance, the inverter, the filter and the grid [2-3]. It might cause grid current distortion, electromagnetic interference, and even threaten the safety of people [4-5]. So, measures should be taken to suppress the leakage current [6].

Reference [7] proposed an AC-bypass topology by adding auxiliary switches to the AC side of traditional single phase full bridge inverter, and reference [8] adds auxiliary switches to the DC side to make it as a DC-bypass topology. By doing so, the PV panels and the grid can be isolated during the current freewheeling time, and the leakage current can be effectively suppressed because of the constant common-mode voltage with unipolar modulation method. But, the abovementioned strategies require that the filtering inductors on the grid side be equal to each other. However, in real applications, the inductances of the filtering inductors will be changing because of the working conditions or the changing of external environment and even they are different from the very beginning during the production process [9]; thus, it is difficult to make sure that the inductors are perfectly matching. So the leakage current problem in the case of unmatched inductances should gain more researches [10].

To solve this problem, a novel six-switch topology and control strategy are proposed in this paper. The inductor-bypass strategy can make sure that there are no high frequency components in the common-mode voltage, so that the leakage current can be effectively suppressed even in case of unmatched inductors. Simulation results verify the effectiveness of the proposed solution.

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## II. CONVENTIONAL SIX-SWITCH TOPOLOGY

Fig.1 shows the HERIC six-switch topology. $C_{pv}$ is the stray capacitor between the PV array and the ground. $L_1$ and $L_2$ are the grid side filtering inductors. In the topology, $S_5$ and $S_6$ are the auxiliary switches to format the freewheeling path for the grid current. TABLE I shows its four working states. E, P and N reference grid voltage, positive half and negative half of grid voltage respectively [11]. And ON and OFF represent switched-on and switched-off respectively.

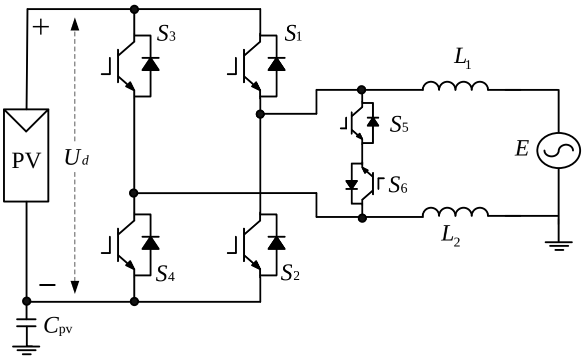



Fig.1. HERIC six-switch topology

TABLE I
SWITCHING STATES AND VOLTAGE DROP ON STRAY CAPACITOR

| $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $U_{Cpv}$ | States | E |
|---|---|---|---|---|---|---|---|---|
| ON | OFF | OFF | ON | OFF | ON | $U_1$ | 1 | P |
| OFF | OFF | OFF | OFF | OFF | ON | $U_2$ | 2 | |
| OFF | ON | ON | OFF | ON | OFF | $U_3$ | 3 | N |
| OFF | OFF | OFF | OFF | ON | OFF | $U_4$ | 4 | |

According to TABLE I, during the positive half of grid voltage, the switches $S_2$, $S_3$, and $S_5$ remain OFF $S_6$ remains ON, and the switches $S_1$ and $S_4$ work with SPWM. In working state 1, switches $S_1$ and $S_4$ switched-on, the common-mode voltage $U_{Cpv}$ equals to the voltage of the inductor $L_2$, which can be expressed as (1) [7].

$$U_1 = \frac{E - U_d}{L_1 + L_2} L_2 = \frac{E}{L_1 / L_2 + 1} - \frac{U_d}{L_1 / L_2 + 1} \tag{1}$$

When $S_1$ and $S_4$ switched-off, the common-mode voltage $U_{Cpv}$ equals to the sum of the voltage of the inductor $L_2$ and the voltage drop on the switch $S_4$, which can be expressed as (2).

$$U_2 = \frac{E}{L_1 + L_2} L_2 - \frac{U_d}{2} = \frac{E}{L_1 / L_2 + 1} - \frac{U_d}{2} \tag{2}$$

With the same principle, we can get the common-mode voltages on the conditions of other two working states during the negative half of the grid voltage as (3) and (4).

$$U_3 = E - \frac{E + U_d}{L_1 + L_2} L_1 = \frac{EL_2 / L_1 - U_d}{1 + L_2 / L_1} \tag{3}$$

$$U_4 = \frac{E}{L_1 + L_2} L_2 - \frac{U_d}{2} = \frac{E}{L_1 / L_2 + 1} - \frac{U_d}{2} \tag{4}$$

So, in the case of $L_1$=$L_2$, the common-mode voltage will maintain in constant ($E$-$U_d$)/2. It only contains DC component -$U_d$/2 and low frequency component $E$/2. According to the equation $i$=$C_{pv}$($dU_{Cpv}/dt$), the leakage current can be effectively suppressed [7]. But, if the filtering conductors are not perfectly matching, we can see that the common-mode voltage will changing in a high frequency according to (1)~(4).

The same problem exists in other DC-bypass or AC-bypass topologies [6], so more attention should be paid on suppressing the leakage current in the case of unmatched inductors [10].

## III. PROPOSED SIX-SWITCH TOPOLOGY

In order to solve the abovementioned problem, a novel six-switch inductor-bypass topology is proposed as shown in Fig. 2. The IGBTs $S_1$, $S_2$, $S_3$ and $S_4$ are the main switches, and the reverse-blocking (RB) IGBTs $S_5$ and $S_6$ are the auxiliary switches. With the RB-IGBT, it will reduce the switching loss compared to the combination of a normal IGBT and a diode[12].

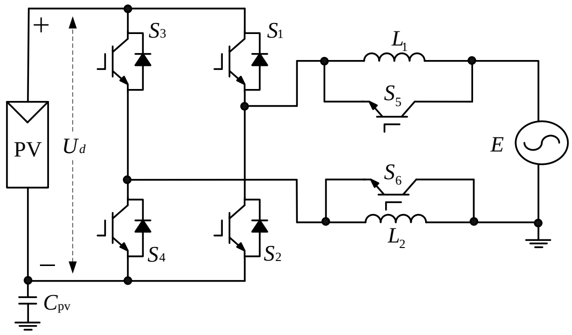
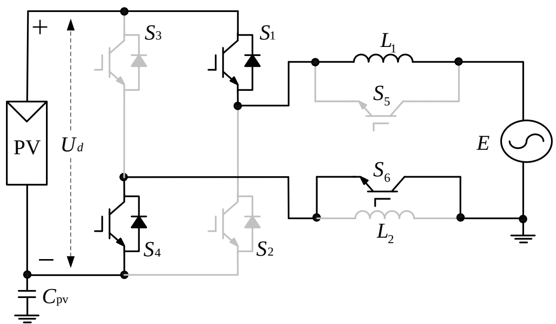



Fig. 2. Proposed six-switch topology

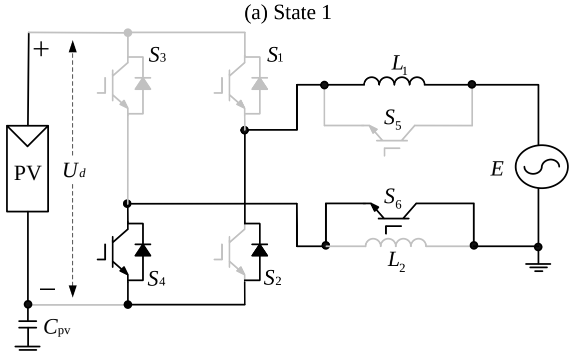
Compared to the HERIC topology, the filtering inductors $L_1$ and $L_2$ are paralleling connected with RB-IGBTs $S_5$ and $S_6$ respectively. With the proposed control strategy, the inductor $L_1$ works in the positive half of the grid voltage and the inductor $L_2$ works in another half. In real application, $L_1$ and $L_2$ can be replaced by a coupling inductor to increase the power density [13].

The working states and the modulation strategy are shown in Figs. 3 and 4, respectively. TABLE II shows the switching states and the corresponding common-mode voltage.

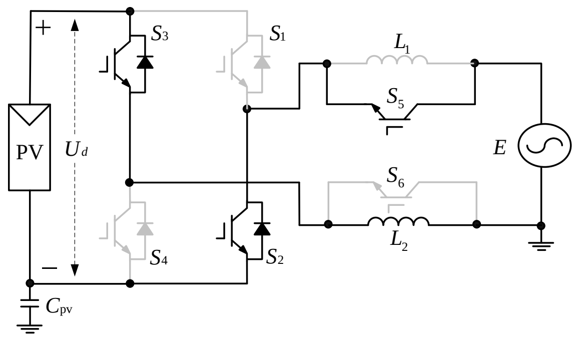
During the positive half of grid voltage, switches $S_4$ and $S_6$ remain ON, and switches $S_2$, $S_3$, $S_5$ remain OFF, only $S_1$ works in high frequency with SPWM. According to Figs. 3(a) and (b), the common-mode voltage $U_{Cpv}$ will be 0 whenever switch $S_1$ is in ON or OFF state.



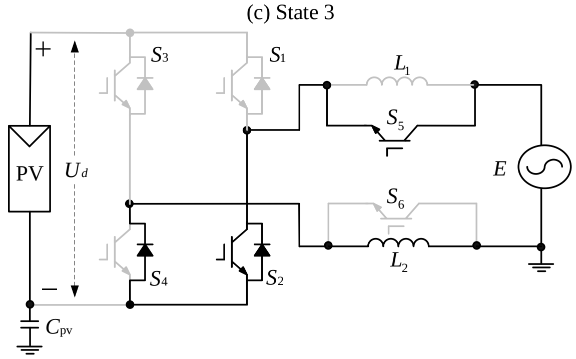

(a) State 1




(b) State 2




(c) State 3




(d) State 4

Fig. 3. Operation modes of proposed topology

During the negative half of grid voltage, switches $S_2$ and $S_5$ will remain ON, and switches $S_1$, $S_4$ and $S_6$ will remain OFF, only switch $S_3$ works in high frequency with SPWM. From Fig. 3(c) and (d), we notice that the common-mode voltage $U_{Cpv}$ will be the grid voltage ($U_m sin(\omega t+\psi)$) whenever switch $S_3$ is in ON or OFF state. And because the frequency of the grid voltage is much lower than the switching frequency, so it will just have a small effect to the leakage current.

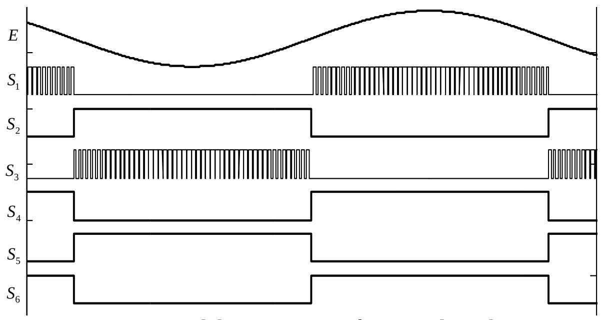



Fig. 4. Modulation strategy of proposed topology

TABLE II

SWITCHING STATES AND VOLTAGE DROP ON STRAY CAPACITOR

| $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $U_{Cpv}$ | E |
|---|---|---|---|---|---|---|---|
| ON | OFF | OFF | ON | OFF | ON | 0 | P |
| OFF | OFF | OFF | ON | OFF | ON | 0 | |
| OFF | ON | ON | OFF | ON | OFF | $U_m \sin(\omega t+\varphi)$ | N |
| OFF | ON | OFF | OFF | ON | OFF | $U_m \sin(\omega t+\varphi)$ | |

## IV. SIMULATION RESULTS

The control strategy of the novel six-switch topology is shown in Fig. 5. The current hysteresis control is used in the MATLAB simulation.

The principle of the control strategy is expressed as follows: according to TABLE II, only switch S1 works in high frequency during the positive half of grid voltage (E>0). When the error of grid current $i_g$ and the reference current ig* is higher than the set point $\Delta i$ ($i_g > i_g^* + \Delta i$), $S_1$ is switched-off; when the error is lower than $-\Delta i$ ($i_g < i_g - \Delta i$), $S_1$ is switched-on; and if grid current ig matches ($i_g^* - \Delta i \le i_g \le i_g^* + \Delta i$), S1 remains the former state, as expressed in (5). During the negative half, the control logic is shown in (6).

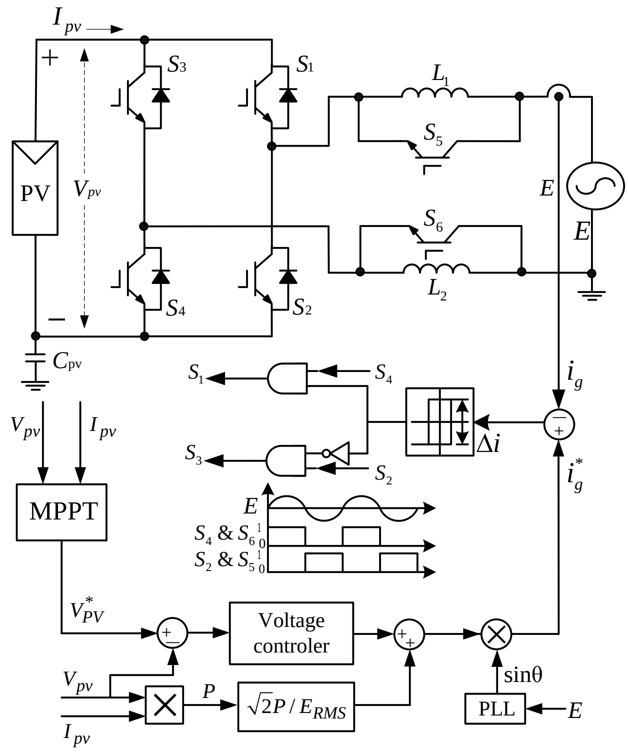



Fig. 5. System control strategy

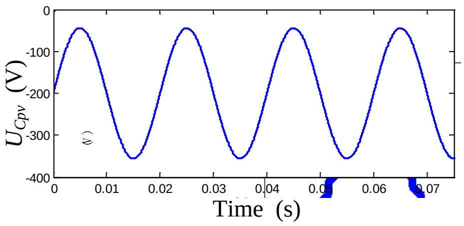
$$E>0\begin{cases} i_g(t) > i_g^*(t)+\Delta i \quad S_1 \quad \text{OFF} \\ i_g(t) < i_g^*(t)-\Delta i \quad S_1 \quad \text{ON} \\ S_4, S_6 \quad \text{ON}, \quad S_2, S_3, S_5 \quad \text{OFF} \end{cases} \tag{5}$$

$$E<0\begin{cases} i_g(t) > i_g^*(t)+\Delta i \quad S_3 \quad \text{OFF} \\ i_g(t) < i_g^*(t)-\Delta i \quad S_3 \quad \text{ON} \\ S_4, S_6 \quad \text{OFF}, \quad S_1, S_2, S_5 \quad \text{ON} \end{cases} \tag{6}$$

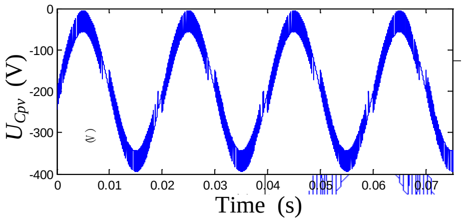
In order to verify the effectiveness of the proposed novel six-switch topology and its control strategy in the case of unmatched inductors, in the simulation the inductances of the filtering inductors are different from each other. The parameters of the simulation are shown in TABLE III.

TABLE III
PARAMETERS OF THE SIMULATION

| | |
|---|---|
| Maximum power of PV array | 5.4kW |
| Voltage at $P_{max}$ ($V_{mp}$) | 356V |
| Current at $P_{max}$ ($I_{mp}$) | 15.15A |
| stray capacitance | 470nF |
| filtering inductors | $L_1$=5mH<br>$L_2$=3mH |
| Light intensity | 1000W/m$^2$ |
| Temperature of PV panels | 25℃ |

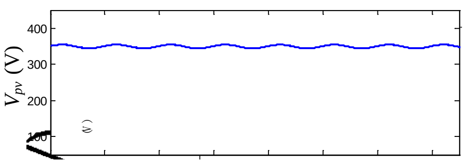



(b) $L_1 = 4$mH, $L_2 = 4$mH

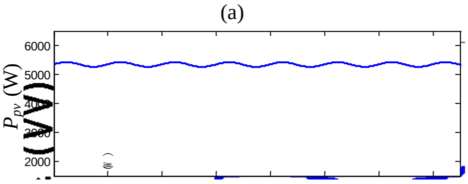



(b) $L_1 = 5$mH, $L_2 = 3$mH
Fig. 6. Voltage of stray capacitor

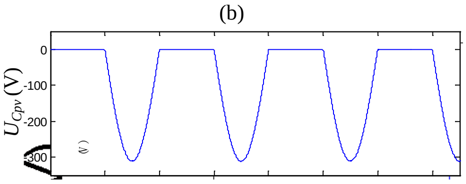
Simulation results of the HERIC are shown in Fig. 6 with both cases of matched and unmatched filtering inductors. It can be seen that the common-mode voltage $U_{Cpv}$ contains both low frequency and high frequency in the case of unmatched filtering inductors which is the same as analysis.



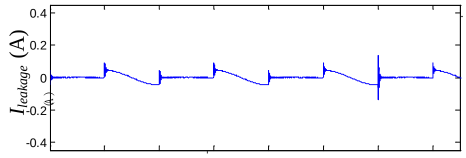

(a)



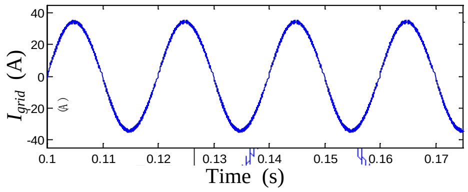

(b)




(c)




(d)




(e)

Fig. 7. Simulation results of the proposed topology. (a) Voltage of the PV array. (b) Out-put power of the PV array. (c) Common-mode voltage. (d) Leakage current. (e) Grid current.

Fig. 7 shows the simulation results of the proposed six-switch topology and the corresponding control strategy in the case of unmatched filtering inductors. According to the wave forms of $V_{pv}$ and $P_{pv}$, the PV array reaches the maximum power; and it can be noticed that the common-mode voltage $U_{Cpv}$ only contains DC and low frequency components compared to the Fig. 6. The leakage current $I_{leakage}$ can be effectively suppressed, its RMS value is lower than 25mA, and its peak value is lower than 200mA. It matches the German DIN VDE 0126-1-1 standard [14]. At the same time, sinusoidal grid current $I_{grid}$ is obtained.

## V. CONCLUSION

This paper has proposed a novel six-switch inductor-bypass topology and a corresponding control strategy. With this solution, the leakage current can be effectively suppressed even in the case of unmatched filtering inductors which is different from the existing AC-bypass or DC-bypass topologies. And there is only one switch working in high frequency at any time which can reduce the switching loss.

## REFERENCES


[1] Gubía E，Sanchis P，Ursúa A，et al．Ground currents in single-phase transformerless photovoltaic systems [J]． Progress in Photovoltaics：Research and Applications，2007，15(17)：629-650．

[2] Su Na, Xu Dehong. Analysis and verification of ground current for grid connected transformerless photovoltaic system[J]. Automation of Electric Power System, 2012, 36(12): 30-35.

[3] Xiao H, Xie S．Leakage current analytical model and application in single-phase transformerless photovoltaic grid-connected inverter[J]．IEEE Trans. on Electromagnetic Compatibility，2010，52(4)：902-913．

[4] Araneo R，Lammens S，Grossi M，et al．EMC issues in high-power grid-connected photovoltaic plants[J]． IEEE Trans. on Electromagnetic Compatibility，2009，51(3)：639-648．

[5] Hernández J C，Vidal P G，Medina A．Characterization of the insulation and leakage currents of PV generators：Relevance for human safety[J]．Renewable Energy，2010，35(3)：593-601．

[6] Zhang L, Sun K, Feng L, et al. A family of neutral point clamped full-bridge topologies for transformerless photovoltaic grid-tied inverters[J]. IEEE Trans. on Power Electronics, 2013, 28(2): 730–739.

[7] Kerekes T，Teodorescu R，Rodriquez P，et al．A new high-efficiency single-phase transformerless PV inverter topology[J]．IEEE Trans. on Industrial Electronics，2011，58(1)：184-191．

[8] Xiao H, Xie S, Chen Y, et al. An optimized transformerless photovoltaic grid-connected inverter[J]. IEEE Trans. on Industrial Electronics，2011，58(5)：1887-1895．

[9] Wu T，Chang C，Lin L，et al．Two-phase modulated digital control for three-phase bi-directional inverter with wide inductance variation[J]．IEEE Trans. on Power Electronics，2013，28(4)：1598-1607．

[10] Na Su，Dehong Xu，Junbing Tao．Ground current suppression for grid connected transformerless PV inverter with unbalanced output filter inductors[C]．IEEE ECCE- 2010, Atlanta，2010，3247-3252．

[11] S. Heribert, S. Christoph, and K. Jurgen, “Inverter for transforming a DC voltage into an AC current or an AC voltage,” Europe Patent 1 369 985 (A2), May 13, 2003.

[12] Motto E R，Donlon J F，Tabata M，et al．Application characteristics of an experimental RB-IGBT (reverse blocking IGBT) module [C]. IEEE IAS, 2004, 1540-1544.

[13] Balog R S，Krein P T．Coupled-inductor filter：A basic filter building block[J]．IEEE Transactions on Power Electronics，2013，28(1)：537-546．

[14] *Automatic disconnection device between a generator and the public low-voltage grid*, German standard, DIN V VDE V 0126-1-1, Feb. 2006 .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