

Methods to Improve Suppression of Leakage Current Generation in Single-phase Non-isolated Photovoltaic Grid-connected Inverters

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Abstract. Analysis of methods to suppress leakage current through the topology of a single-phase inverter is carried out, aiming to address the phenomenon that disturbs the normal operation of electrical equipment and poses risks to human life when equipment integrates the electrical system into the grid. The topology of a single-phase inverter is taken as the research object, whose issues will be researched and summarized. First of all, by analyzing the single-phase inverter circuit, a simplified equivalent circuit is obtained. Then during the simplification process, it can be concluded that the generation of leakage current is related to the rate of change of common-mode voltage. After that based on this phenomenon, the general direction for suppressing leakage current has been obtained: when the electrical equipment links to the grid: keep V_{cm} constant, and four clear methods to suppress leakage current. Then reanalyze the way some new non-isolated grid-tied inverter topology how to suppress leakage current. Eventually, the conclusion would be reached.

Keywords: Grid-connected inverter; leakage current; non-isolated; single-phase.

1. Introduction

Nowadays, power systems and electrical appliances have become an indispensable part of everyone's life, so the demand for safer and more efficient grid and electrical equipment is increasing day by day. The issue of leakage current is an important problem that cannot be ignored in the connection of power systems and electrical equipment: by ground connection, the parasitic capacitance of the inverter and various filter inductance in the inverter make up a resonant circuit which may cause a high current. The generation of the leakage current would increase the current harmonics and system losses, even causing security issues. The single-phase topology structure features a small size, low cost, and simple structure, making it easy to mass produce and popularize. This is highly attractive for grid-connected systems with high generation costs [1].

In recent years, experts and scholars have carried out much research on single-phase photovoltaic grid-connected inverters. Such as changing common-mode impedance Z under the premise of symmetrical circuit parameters to keep Z stay high impedance when high-frequency V_{cm} is the variation; in the case when V_{cm-dm} is constant, using appropriate sinusoidal pulse width modulation (SPWM) strategy to make V_{cm} constant; matching circuit parameters to ensure the sum of V_{cm} and V_{cm-dm} remains constant and so on. This article starts with an analysis of the mechanism for generating leakage current and single-phase topology structures and its improvements structure, by comparing the merits and faults of each topology structure to provide a prospect for the future optimization trends of single-phase topology structures and the technical challenges in the future, offering a reference for subsequent research.

2. Analysis of Single-phase Inverter Circuit and the Principle of Leakage Current Generation

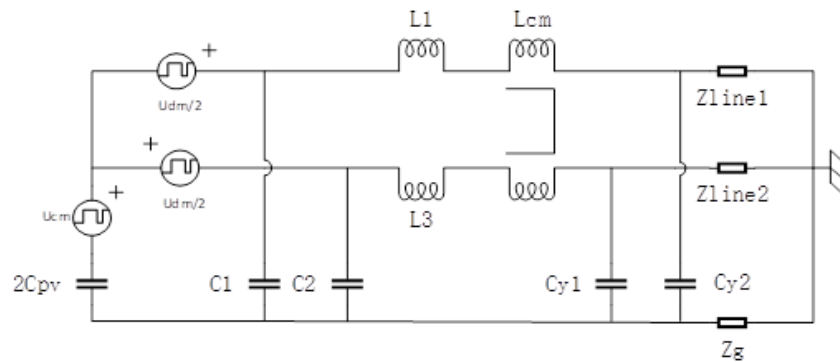


Fig 1. Common mode circuit model 1 for single-phase grid-connected inverter.

Due to the electrical connection between the solar panels and the grid, and the presence of parasitic capacitance, in the resonant circuit composed of parasitic capacitance from the solar panels, the LC filter, and the grid impedance, the switching action of the grid-tied inverter power devices generates high-frequency time-varying voltage. What's more, to optimize the efficiency of the converter, the impedance of the circuit would be low which leads to the common mode current exceeding the allowable range [3].

According to the literature [2], establishing the common-mode equivalent circuit model for single-phase full-bridge grid-connected inverters would explain the theory that the generation of leakage current is related to the rate of change of the common-mode voltage. The leakage current shall be zero if it remains a constant value [3]. The deduction simplification was conducted using the circuit depicted in Fig 1, resulting in the determination of the minimum common-mode equivalent circuit as shown in Fig 2[2].

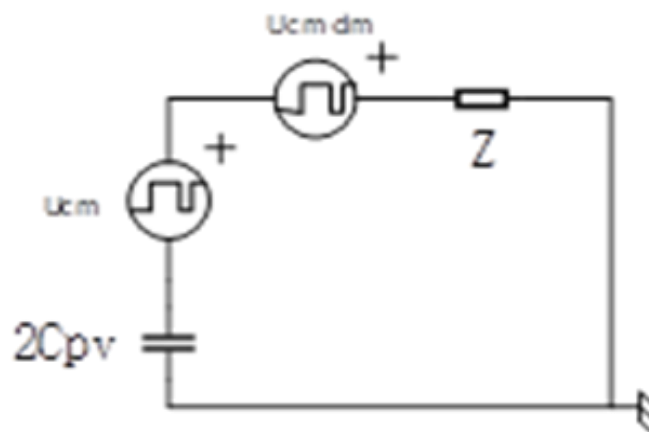


Fig 2. Simplest model for common mode of single-phase grid-connected inverter.

In Fig 2, V_{cm} is the common-mode voltage; V_{cm-dm} is the common-mode voltage caused by circuit asymmetry; C_{pv} is the total parasitic capacitance of the photovoltaic panel to the ground. Z is the common-mode impedance caused by other non-ideal factors, as detailed in reference [4].

Based on the equivalent model shown in Fig 2, four approaches for inhibiting leakage current can be derived: 1. Under the premise of symmetrical circuit parameters (V_{cm-dm} keeps a constant value), alter the common mode impedance Z , ensuring that Z maintains a high impedance during high-frequency variations; 2. Under the premise of symmetrical circuit parameters (V_{cm-dm} is a constant value), employ a suitable sinusoidal pulse width modulation (SPWM) strategy to maintain it constantly 3. By matching the circuit parameters, ensure that the sum of V_{cm} and V_{cm-dm} remains constant; 4. Alter the C_{py} by introducing a small capacitance in the loop, increasing the common mode loop impedance, and reducing leakage current.

3. The Topology of the Novel Non-isolated Single-phase Grid-tied Inverter

3.1. Topology Structure of H Series

3.1.1. Topology structure of H5

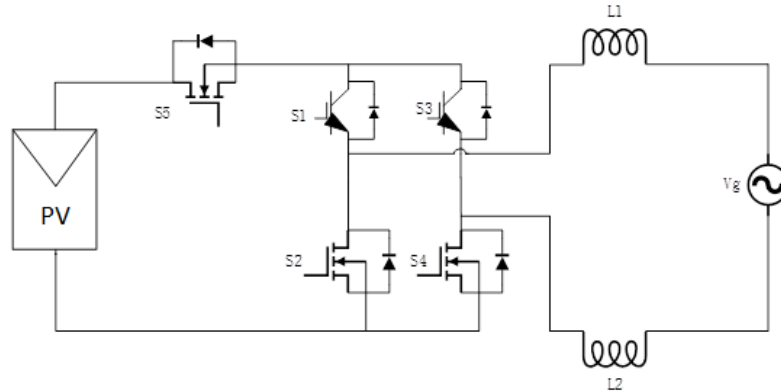


Fig 3. Topology structure of H5.

According to the literature [5], the H5 topology is based on the conventional full-bridge topology, with an additional switch S_5 connected in series at the DC input, as shown in Fig 3. The decoupling of the AC and DC sides is achieved through the switching modulation of S_5 , effectively suppressing the generation of leakage current. During the positive half-cycle, S_1 is always conducting, while S_4 and S_5 operate in a high-frequency modulation state, similar to the negative half-cycle. Compared to traditional bridge circuit topology, H5 only adds one additional switch device to achieve the goal of leakage current suppression. However, S_5 is constantly in a high-frequency modulation state throughout the entire grid cycle, resulting in high conduction and switching losses, which adds to the device design difficulty.

3.1.2. Topology structure of H6

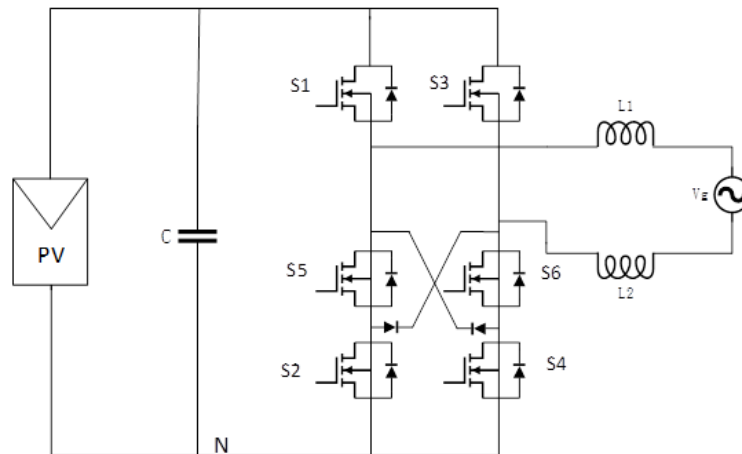


Fig 4. Topology structure of H6.

According to the literature [6], a supplementary circuit consisting of switching devices S_5 , S_6 , and diodes D_1 and D_2 is added to the single-phase full-bridge structure, as shown in Fig 4. This circuit provides a freewheeling path, allowing the battery side to be disconnected from the grid during the freewheeling stage, thereby suppressing the variations of common-mode voltage. During the positive half-cycle, S_6 is always conducting while S_2 , S_3 , and S_5 remain off, and a similar pattern applies to the negative half-cycle. Compared to the traditional full bridge topology, the voltage stress on the devices in this topology is reduced to $V_{PV}/2$, and S_5 and S_6 operate at the frequency of the power grid, reducing switching losses. However, since three devices are conducting during conduction, the conduction losses of the devices increase. In practical applications, it is advisable to choose switching devices with lower on-state voltage drops.

3.1.3. Topology structure of H7

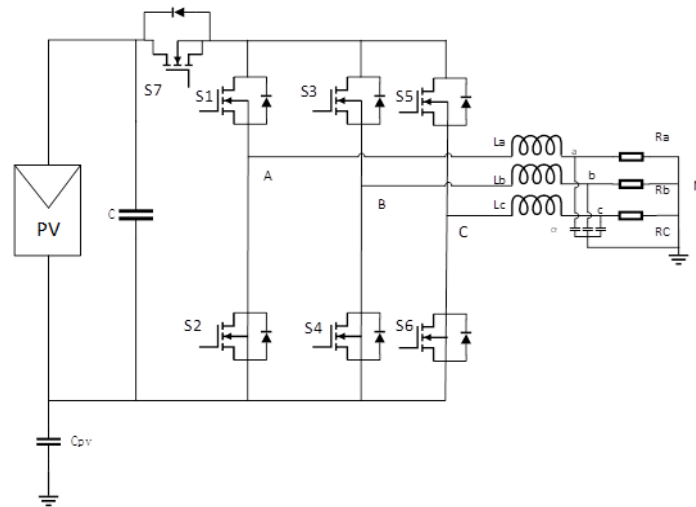


Fig 5. Topology structure of H7.

Based on the literature [7], it can be inferred that the common mode voltage of the H7 inverter topology varies between 0, $UPV/3$, and $2UPV/3$ throughout the entire inverting cycle as shown in Fig 5. During the freewheeling state, the isolation switch S7 is turned off, achieving electrical isolation between the DC input side and the AC output side. Compared to the traditional three-phase full-bridge inverter, although the range of common mode voltage variation is reduced and leakage current is reduced to a certain extent, there is no clamping circuit in the freewheeling state, hence, the common mode voltage in this state is unstable, and the suppression of leakage current is inadequate.

3.2. Enhanced bridged topology

3.2.1. Topology structure of oH5

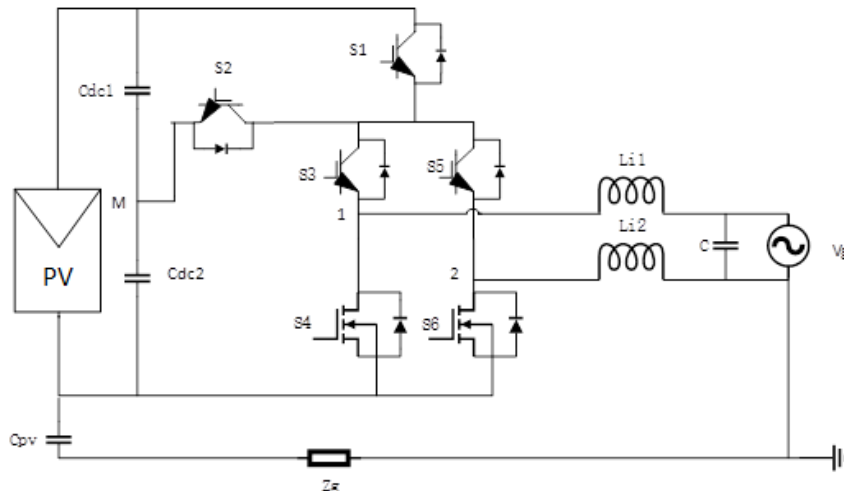


Fig 6. Topology structure of oH5.

According to reference [7], the improved H5 topology (referred to as oH5 topology) adds a switch S2 based on the H5 topology. Unlike the traditional H5 topology that uses a unipolar SPWM strategy, the low-frequency switches S3 and S5 are complementary to S1 during the non-working half-cycle and are turned on at high frequency, providing a path for reactive current, as shown in Fig 6. The circuit can operate at any power factor. During the freewheeling stage, S2 conducts, clamping the potential of point H at the midpoint of the capacitor, V_{cm} , to a constant value ($U_{ca}/2$). This achieves the goal of eliminating high-frequency leakage current using suppression path 2. Compared to the H5 topology, the addition of switch S2, with its very small current, does not significantly increase losses but achieves a better suppression effect on leakage current.

3.2.2. Topology structure of oH7

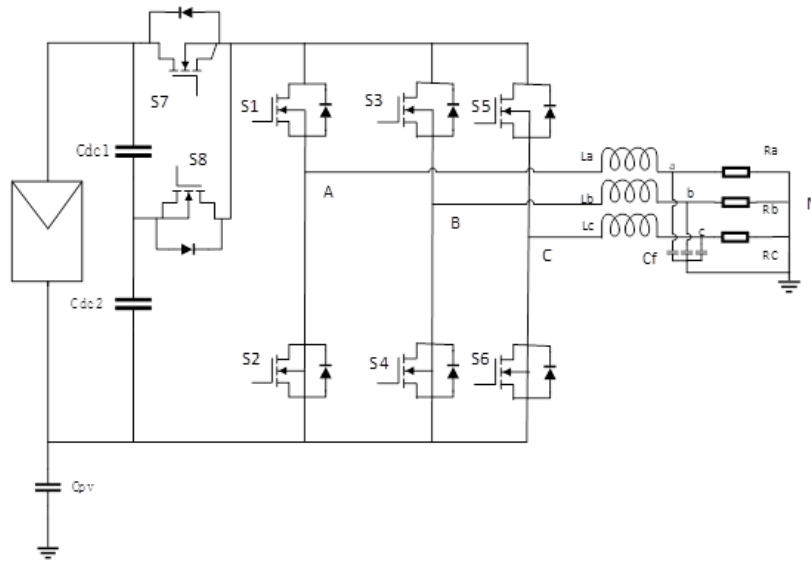


Fig 7. Topology structure of oH7.

The literature [7] indicates that the common-mode voltage of the oH7 inverter topology varies between $U_{pv}/3$, $U_{pv}/2$, and $2U_{pv}/3$ throughout the entire inverter cycle, as shown in Fig 7. In comparison to the H7 inverter, the common-mode voltage exhibits a smaller fluctuation amplitude in this topology. Furthermore, the addition of clamp circuits leads to improved stability of the common-mode voltage in the freewheeling state and reduces leakage current. However, it is worth noting that the common-mode voltage frequency in this topology can only be equal to the switching frequency, lacking a high-frequency control scheme. Therefore, there is still room for improvement in suppressing leakage current.

3.3. Other Topology Structure

3.3.1. Topology structure of Heric

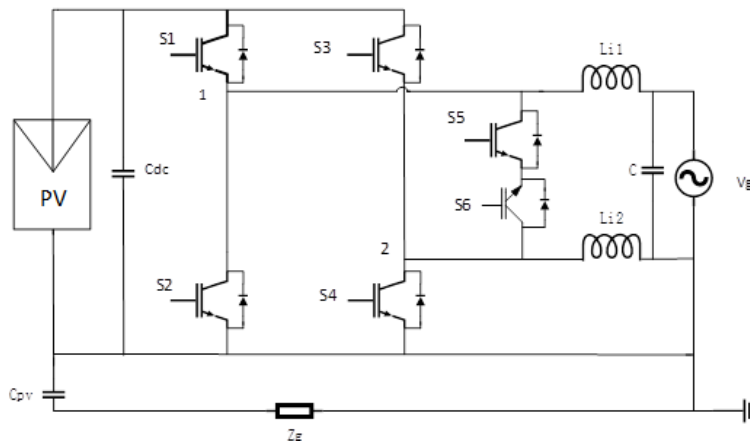


Fig 8. Topology structure of Heric.

According to the literature [8], switch S5 and S6 are added to the full-bridge circuit. The topology still adopts a unipolar SPWM strategy. The addition of S5 and S6 provides a new freewheeling path, separating the photovoltaic panel from the power grid during the freewheeling stage, as shown in Fig 8. A large impedance is serially connected in the common mode loop to achieve the purpose of leakage current suppression. Since the current flows through only two switches during the power transmission and freewheeling stages, the conduction losses are small, resulting in high efficiency. However, compared to the H5 topology, this topology uses an additional power switch, leading to an increase in component cost.

3.3.2. Topology structure of oHeric

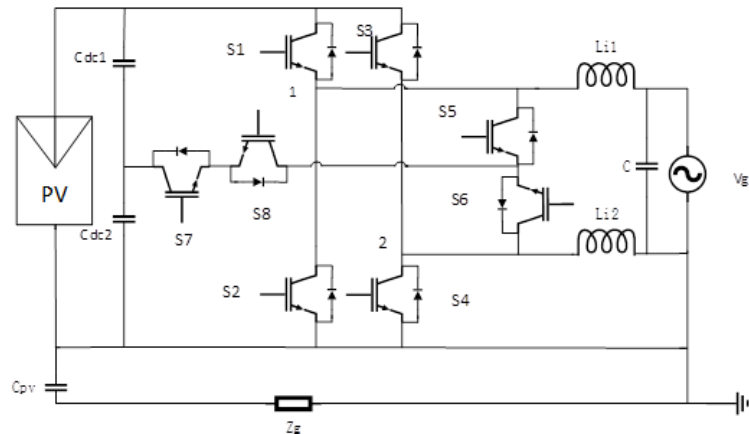


Fig 9. Topology structure of oHeric.

According to literature [8], it can be concluded that: based on the Heric topology, bidirectional switches composed of S7 and S8 are added, as shown in Fig 9. The leakage current suppression mechanism of this topology is consistent with the oH5 topology. In the freewheeling stage, S7 and S8 conduct to clamp the potential of point H to the midpoint M of the capacitor, thereby keeping the common-mode voltage V_{cm} constant at a value of $V_a/2$ and eliminating high-frequency leakage current. Compared to the Heric topology, although additional switches S7 and S8 are added, the increase in losses is not significant since the current flowing through S7 and S8 is very small. However, the suppression effect of leakage current can be improved.

4. Summary

According to the literature[5][9-11], for the various common types of suppressible leakage current topologies mentioned above, the number of switching devices, diodes, input capacitors, and the ability to suppress leakage current is depicted in Table 1.

Table 1. Comparison of single-phase topologies related to leakage current suppression.

Inverter Types	The number of Switching	The number of Diode	The number of Input capacitance	The Inhibitory Effect of I_{cm}
H5	5	0	1	B
H6	6	2	1	A
H7	7	0	1	A
oH5	6	0	2	B
oH7	7	0	2	A
Heric	6	2	1	A
oHeric	8	0	2	A

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5. Conclusion

Through the study, this paper presents the simplest and unified equivalent model of the common-mode loop of single-phase inverters. Therefore, based on this model, the mechanism of leakage current suppression is clarified, and four approaches to suppress leakage current are summarized. The existing main bridge topologies are systematically analyzed and classified based on whether they are bridge circuits and their improved types. A brief description of multiple single-phase new non-isolated grid-connected inverter topologies and their working principles and leakage current

suppression effects is provided. The main contribution of this paper is to help beginners quickly and effectively understand the leakage current suppression issues and their generation mechanism in the topologies of single-phase new non-isolated grid-connected inverters. However, it is regrettable that the current analysis of the mechanism of leakage current generation in this paper is relatively basic, and the analysis and improvements are based on single-phase non-isolated topological inverters, without involving multi-phase inverters. Nevertheless, the leakage current suppression approaches and improvement methods proposed in this paper should apply to multi-phase inverters, providing more theoretical support for the development of inverter topology structures to suppress leakage current.

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