# Probing Leakage Current Suppression Techniques for Non-Isolated Photovoltaic Inverters

Yangrui Cheng [1], Zhijunxi Lou [2], Yintong Lu [3] and Zexun Wang [4, *]

[1] School of Electrical Engineering and Automation, Anhui Polytechnic University, Wuhu, 241060, China

[2] School of Physics and Materials Engineering, Dalian Nationalities University, Dalian, 116600, China

[3] School of Energy and Power Engineering, Nanjing Institute of Technology, Nanjing, 211112, China

[4] School of Engineering, Architecture and Information Technology, The University of Queensland, Brisbane, 4072, Australia

* Corresponding Author Email: zexun.wang@uqconnect.edu.au

**Abstract.** The evolution of photovoltaic (PV) inverters has witnessed distinct trade-offs between isolated and non-isolated configurations. While isolated PV inverters grapple with challenges such as increased volume and suboptimal system efficiency due to transformer inclusions, their non-isolated counterparts offer a solution by eliminating these transformers. However, this lack of electrical isolation in non-isolated inverters engenders a distinct predicament: significant leakage currents. Such currents not only impede system operation but also curtail operational efficiency. Recognizing this, the suppression of leakage current has catapulted to the forefront of contemporary research. This manuscript elucidates the operational intricacies of non-isolated PV inverters. It then embarks on a panoramic review of prevailing leakage current suppression techniques, both domestic and international, contextualizing them with state-of-the-art inverter topologies such as the H7, H10, three-level neutral point clamped (NPC) and three-phase four-bridge arm configurations. The paper culminates with a prospective glance at future research trajectories in leakage current suppression, proffering seminal recommendations for academic and industry fraternities.

**Keywords:** Non-isolated type; PV inverter; leakage current; suppression.

## 1. Introduction

In 2021, Europe experienced an energy crisis, posing significant challenges to various countries' political and economic landscapes [1]. In response to this issue, nations implemented a range of measures. For instance, China set forth the goal of achieving a carbon peak by 2030 and carbon neutrality by 2060, while the United Kingdom devised a strategy that intertwines low-carbon transformation with energy security [2]. However, as energy demand rises, PV power generation has garnered considerable global attention as a clean, secure, and reliable energy source [3,4].

In the context of grid-tied PV inverters, parasitic capacitance exists between PV modules and the ground. The common-mode voltage generated by the inverter applies to this parasitic capacitance, resulting in leakage current. Leakage current can distort grid-tied currents, increase inverter losses, and impact system stability and safety [5]. Therefore, both at home and abroad attach great importance to the research of leakage current suppression. The research object in key literature is a three-level mid-point clamp PV inverter [6]. According to digital pulse width modulation 1 (DPWM1), this paper proposes a leakage current suppression method based on improved DPWM (I-DPWM) and the modulation system. At 0.93, the I-DPWM modulation strategy is superior to DPWM, which reduces the amplitude of the common-mode voltage, thus suppressing leakage current. For transformerless PV systems, a single vector finite control set model predictive controller is studied [7]. Compared with the traditional method (using multiple Insulated-Gate Bipolar-Transistor (IGBT) switches), this controller can reduce the common mode voltage without adding additional switches, thus suppressing leakage current. In literature, a common-mode equivalent circuit model of direct

current/direct current (DC/DC) converter considering transmission cables is proposed, and the resonant frequency of leakage current is designed near the switching frequency to reduce the high-frequency component and inhibit leakage current [8].

Grid-tied PV inverters can be categorized into isolated and non-isolated types. Due to the presence of transformers, isolated PV inverters suffer from drawbacks such as larger sizes and lower system efficiency. Non-isolated PV inverters address these issues but introduce leakage current concerns due to the absence of electrical isolation. Both domestic and international research efforts have been devoted to mitigating leakage current. Approaches include optimizing topology structures based on single-phase configurations, such as H5, H6, and highly efficient reliable inverter concept (HERIC), extending to new H-bridge inverters and three-phase configurations, including three-level NPC inverters and three-phase four-bridge arm inverters [9]. Novel modulation techniques have been developed to stabilize common-mode voltage, and common-mode filtering circuits have been constructed [10]. Based on the topology of the H-bridge inverter and different types of three-phase inverters, this paper concludes the principle of leakage current suppression from various angles and finally puts forward some suggestions for the research of leakage current suppression.

## 2. Main Overview

### 2.1. Analysis of Novel Inverter Topology Structure

#### 2.1.1 New H-Bridge inverter topology structure

In reference, scholars proposed an enhanced version of the H7 inverter (Fig. 1), which is well-suited for leakage current suppression [11]. Compared to the conventional H7 inverter's circuit topology, this improved H7 inverter introduces an additional clamping circuit based on the original H7 structure and significantly increases the frequency of the common-mode voltage. Specifically, a high-frequency control mode is applied to the common-mode voltage: common-mode voltage frequency = 3 * switching frequency.

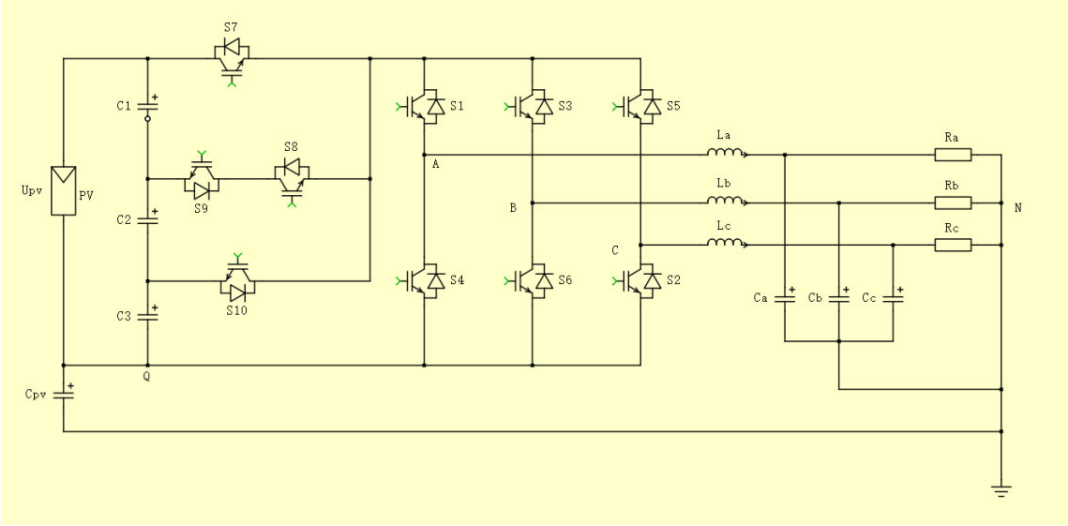



**Fig. 1** Enhanced H7 inverter circuit topology [11]

In reference, researchers proposed an H10 three-phase non-isolated PV inverter that can be utilized for leakage current suppression [12]. Due to differences in circuit clamping methods, the H10 three-phase inverter can be divided into two categories: forward clamping and reverse clamping. Fig. 2 depicts the topology structure of the forward clamping circuit, while Fig. 3 illustrates the topology structure of the reverse clamping circuit. The fundamental feature of these two distinct three-phase inverters is adding four switching devices on the DC input side.

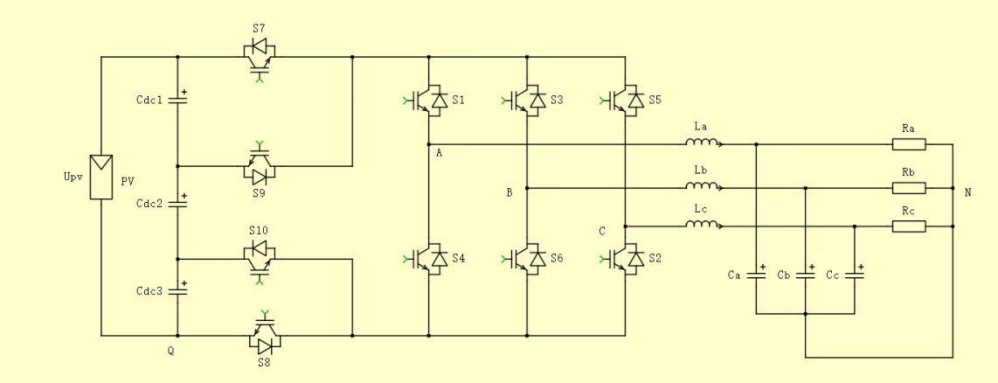



**Fig. 2** Topology of forward clamping circuit for H10 three-phase inverter [12]

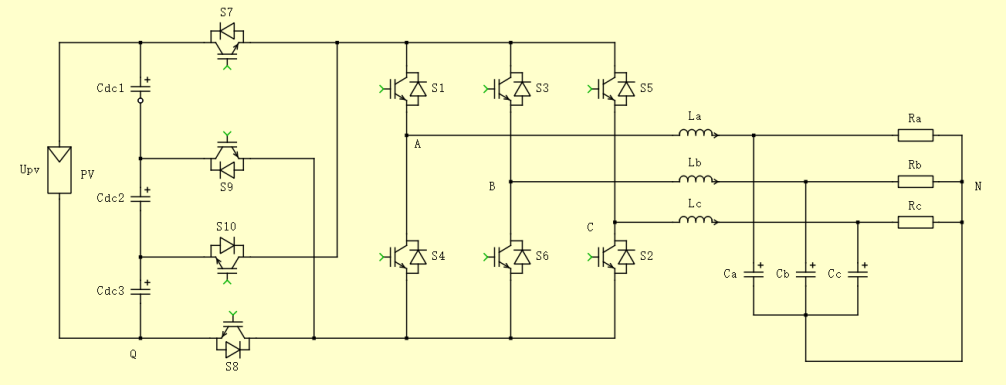



**Fig. 3** Topology of reverse clamping circuit for H10 three-phase inverter [12]

### 2.1.2 New three-level NPC inverter topology structure

A leakage current suppression method based on neutral point capacitance is proposed. The improved non-isolated three-phase three-level inverter is presented in reference, as depicted in Fig. 4 [10]. In the traditional topology, disconnecting switch S is sufficient. However, in the enhanced topology, a filter capacitor $C_f$ and a damping resistor $R_d$ connect the DC neutral point to the alternating current (AC) neutral point, forming an inductor & capacitor (LC) filter circuit. Through analysis, it is determined that the high-frequency component of voltage $u_{no}$ is reduced, thereby playing a certain role in suppressing leakage current.

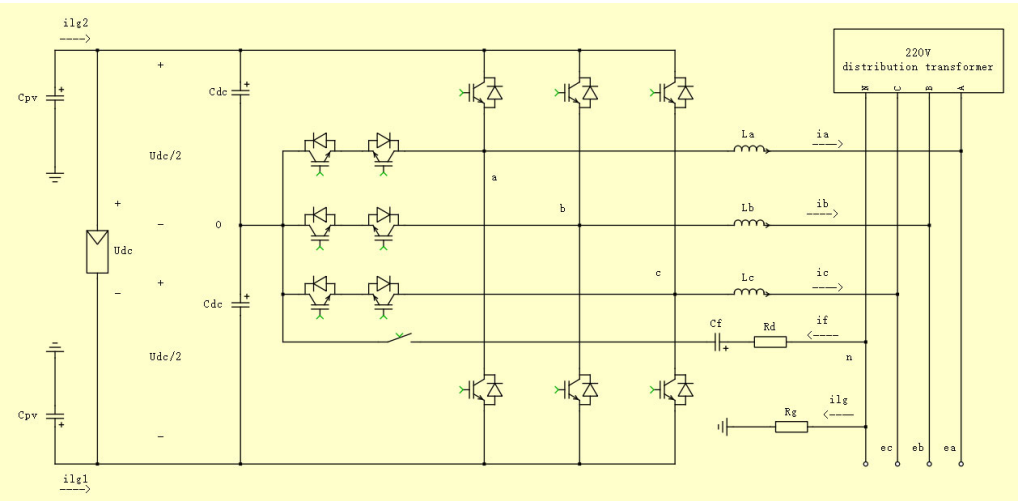



**Fig. 4** Enhanced non-isolated three-phase three-level inverter [10]

## 2.2. Modulation Strategy

### 2.2.1 Carrier PWM

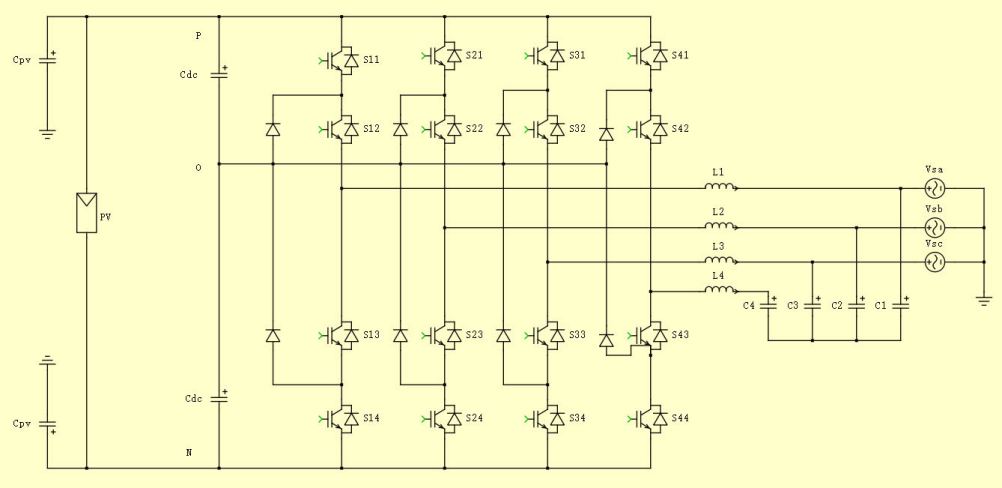



**Fig. 5** Schematic diagram of three-level three-phase four-bridge arm PV inverter [13]

According to the reference, Fig. 5 illustrates the schematic diagram of a three-level three-phase four-bridge arm PV inverter [13]. Through analysis, it is determined that the common-mode voltage primarily causes the leakage current issue. The modulation strategy for the three-level inverter is primarily carrier-based modulation. In the case of the four-bridge arm PV inverter, the conventional carrier-based modulation employs carrier stacking for the first three bridge arms, while the fourth bridge arm obtains modulation through zero-sequence components compared to triangular carriers. However, through examination, it is found that the system's common-mode voltage cannot be stabilized.

Therefore, as indicated in reference, the three-level three-phase four-bridge arm PV inverter operates with the common-mode voltage constantly maintained at $V_{dc/2}$, which is conducive to leakage current suppression [13]. Furthermore, this modulation method considers large, medium, and small vectors, thereby enhancing the utilization of DC voltage.

### 2.2.2 Space vector modulation (SVM)

SVM offers advantages such as simple control and high voltage utilization efficiency. A recent work focused on the Type I NPC three-level inverter, where a comparison was made between virtual space vector PWM (VSVPWM) and variable VSVPWM (VVSVPWM) methods [14]. An enhanced VVSVPWM algorithm was proposed, known as the improved-VVSVPWM (I-VVSVPWM) algorithm. It involves selecting and determining the corresponding vector sequences for two pairs of redundant small vectors within the virtual medium vector. Additionally, the reference introduced the phase duty ratio method to adjust the output states, reducing the dynamic switching frequency [14].

## 2.3. Common-Mode Filter Circuit

According to the reference, Fig. 6 illustrates the topology of a three-phase Buck rectifier with a common-mode filter circuit [15]. Unlike traditional three-phase Buck rectifiers, this novel rectifier's inductors $L_P$ and $L_n$ are connected to the positive and negative terminals of the load, respectively. This arrangement reduces the potential fluctuation at the negative terminal of the output, effectively minimizing electromagnetic interference radiation (EMI). Furthermore, the midpoint of the output capacitor is connected to the midpoint of the input filter capacitor, providing a low-impedance pathway for high-frequency currents, further reducing the generation of EMI.

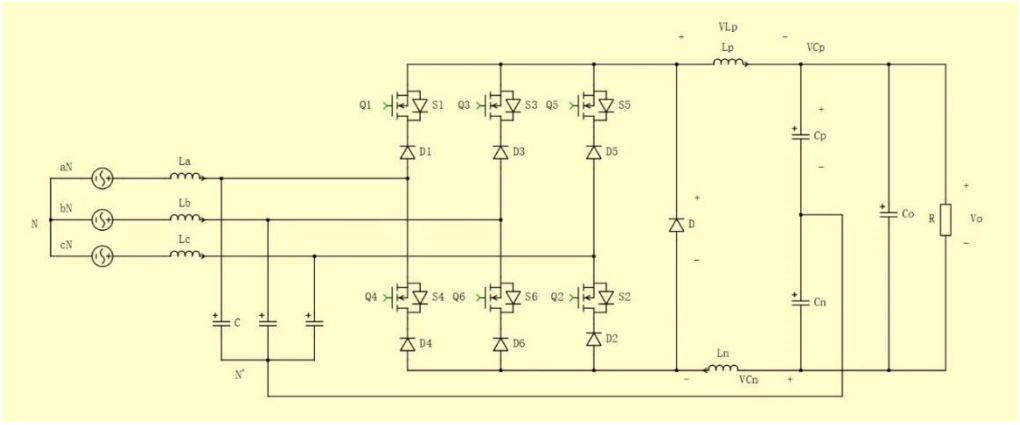



**Fig. 6** Topology of three-phase buck rectifier with common-mode filter circuit [15]

## 3. Conclusion

Researching the suppression of leakage current holds significant significance in electrical engineering and electronics. Its objective is to eliminate, to the greatest extent possible, the generation of leakage current within circuits and electrical devices, thereby enhancing the efficiency and safety of power systems. This pertains to the safety of individuals and electrical equipment and bears close relevance to energy utilization and environmental conservation. This paper provides an overview of methods for suppressing leakage current in non-isolated PV inverters, with a primary focus on three aspects: enhanced novel inverter topologies, modulation strategies, and common-mode filtering circuits.

Regarding novel inverter topologies, the paper predominantly summarizes the circuit topologies and characteristics of improved H7 inverters, H10 three-phase non-isolated inverters, and novel three-level NPC inverters. These innovations effectively mitigate leakage current by introducing clamping circuits, incorporating additional switching devices, or constructing LC filtering circuits. In the realm of modulation strategies, the paper delves into research and analysis concerning carrier-based PWM and SVM for three-level three-phase PV inverters. Both modulation techniques boast the advantage of high voltage utilization efficiency, thus effectively curtailing leakage current.

Moreover, common-mode filtering circuits play a pivotal role in suppressing leakage current. These circuits bring about changes in the connection of inductors within the circuit, thereby reducing the frequent fluctuation of the negative terminal potential at the output. Additionally, they provide a low-impedance pathway for high-frequency currents, aiding in reducing EMI radiation emitted by inverters. In a word, for the effective reduction of leakage current generation in non-isolated PV inverters, optimization and enhancement can be achieved through various avenues, encompassing the improvement of inverter circuit topologies, modulation strategies, and common-mode filtering circuits.

## 4. Author contribution

All the authors contributed equally, and their names were listed in alphabetical order.

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