

# Comparison and Analysis of Single-Phase Transformerless Grid-Connected PV Inverters

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**Abstract**—Leakage current minimization is one of the most important considerations in transformerless photovoltaic (PV) inverters. In the past, various transformerless PV inverter topologies have been introduced, with leakage current minimized by the means of galvanic isolation and common-mode voltage (CMV) clamping. The galvanic isolation can be achieved via dc-decoupling or ac-decoupling, for isolation on the dc- or ac-side of the inverter, respectively. It has been shown that the latter provides lower losses due to the reduced switch count in conduction path. Nevertheless, leakage current cannot be simply eliminated by galvanic isolation and modulation techniques, due to the presence of switches' junction capacitances and resonant circuit effects. Hence, CMV clamping is used in some topologies to completely eliminate the leakage current. In this paper, several recently proposed transformerless PV inverters with different galvanic isolation methods and CMV clamping technique are analyzed and compared. A simple modified H-bridge zero-voltage state rectifier is also proposed, to combine the benefits of the low-loss ac-decoupling method and the complete leakage current elimination of the CMV clamping method. The performances of different topologies, in terms of CMV, leakage current, total harmonic distortion, losses and efficiencies are compared. The analyses are done theoretically and via simulation studies, and further validated with experimental results. This paper is helpful for the researchers to choose the appropriate topology for transformerless PV applications and to provide the design principles in terms of common-mode behavior and efficiency.

**Index Terms**—Common-mode voltage (CMV), leakage current, photovoltaic (PV) system, transformerless.

## I. INTRODUCTION

**T**ODAY, the energy demand is increasing due to the rapid increase of the human population and fast-growing industries. Hence, renewable energy plays an important role to replace traditional natural resources such as fuel and coal. Photovoltaic (PV) energy has recently become a common interest of research because it is free, green, and inexhaustible [1]–[3]. Furthermore, PV systems are now more affordable due to government

incentives, advancement of power electronics and semiconductor technology and cost reduction in PV modules [2], [3].

Generally, there are two types of grid-connected PV systems, i.e., those with transformer and without transformer. The transformer used can be high frequency (HF) transformer on the dc side or low frequency transformer on the ac side [4]–[13]. Besides stepping up the voltage, it plays an important role in safety purpose by providing galvanic isolation, and thus eliminating leakage current and avoiding dc current injection into the grid. Nevertheless, the transformers are bulky, heavy, and expensive. Even though significant size and weight reduction can be achieved with HF transformer, the use of transformer still reduces the efficiency of the entire PV system [9]. Hence, transformerless PV systems are introduced to overcome these issues. They are smaller, lighter, lower in cost, and highly efficient [4]–[13].

However, safety issue is the main concern for the transformerless PV systems due to high leakage current. Without galvanic isolation, a direct path can be formed for the leakage current to flow from the PV to the grid. At the same time, the fluctuating potential, also known as common-mode voltage (CMV), charges and discharges the stray capacitance which generates high leakage current. Besides safety issue, this leakage current increases grid current ripples, system losses, and electromagnetic interference.

In order to reduce the leakage current to meet the standard in [14], conventional half bridge inverter or full-bridge inverter with bipolar modulation technique are used in transformerless PV systems to generate constant CMV to reduce the leakage current. However, a 700-V dc-link voltage is required for the half bridge and diode-clamped topologies [15]–[17]. For full-bridge bipolar modulation, high losses and reduced efficiency are observed due to two-level bipolar output voltage. As a result, the voltage stress across the inductors is doubled and current ripples increase. Larger filter inductors are required, increasing the cost and size of the PV systems.

Hence, many research works have been proposed recently to eliminate the leakage current via galvanic isolation and CMV clamping techniques. Galvanic isolation topologies such as H5 [18], H6 family [19]–[22], and HERIC [23] introduce dc-decoupling and ac-decoupling to disconnect the PV and the grid. It is found that ac-decoupling provides lower losses due to reduced switch count in the conduction path. Nevertheless, the galvanic isolation alone cannot completely eliminate the leakage current due to the influence of switches' junction capacitances and parasitic parameters [21], [28]. Therefore, CMV clamping has been used in oH5 [24], H6 [25], and H-bridge zero-voltage

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