Highly reliable inverter topology with a novel soft computing technique to eliminate leakage current in grid-connected transformerless photovoltaic systems☆

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ABSTRACT

Grid-connected transformerless photovoltaic inverters are widely accepted in the renewable energy market, owing to their high power density, low cost, and high efficiency. However, the leakage current is the main issue in these inverters, which is to be investigated carefully. In this study, leakage current analysis of both transformer and transformerless bridge inverter topologies are widely investigated. Based on that, a new topology and modulation technique is proposed to eliminate the leakage current in the system. The mechanism of a creating high-impedance path between the photovoltaic module and the system, by properly isolating them in the freewheeling state and maintaining a constant common mode voltage in all the switching states, is elaborately discussed in this paper. The experimental results are finally presented to validate the proposed topology with respect to other conventional topologies.

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1. Introduction

Photovoltaic (PV) systems have become very popular in the renewable energy market. This popularity is mainly due to their wide usage in all the energy markets such as the residential, commercial, and industrial sectors. Although many solar thermal methods have been developed to tap the energy from the sun, the PV system is considered as a most effective, because of its high efficiency, small size, low cost, and light weight. PV systems are mostly designed either as standalone or grid-connected modules. The latter is widely used in the market, because it feeds energy into the grid.

Generally, a PV array, inverter, and grid filters are used in a grid-connected PV system. PV modules are the basic structural units of a PV array. They exhibit capacitance with respect to ground, called parasitic capacitance [1–3]. This parasitic capacitance increases if there is a large conducting surface and powerful electric field in the PV arrays. Broadly, transformer and transformerless topologies are used in the inverter sections. In transformer inverter topology, the use of a low-frequency transformer (LFT) provides better galvanic isolation between the PV modules and the grid. However, they reduce the overall efficiency by 2% and also increase the bulk size. The problem of bulk size is resolved by using a high-frequency transformer (HFT). It only reduces the size of the system, but the overall efficiency of the system is further reduced because it needs additional power frequency conversion stages [4,5].

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However, the transformerless PV inverter is more efficient, compact, and small in size. In these methods, the PV panels are directly connected with the grid. This creates a conduction loop between the PV panel and the grid by parasitic capacitance, the stray capacitance of the panel and grid. If the high-frequency common mode voltage is not maintained constant in the power transmission and freewheeling mode of the inverter operation, then a large amount of high-frequency leakage current is injected into this path. This leakage current affects the system performance by creating harmonic current, power loss, electric shock, and electromagnetic interference [6,7]. Therefore, the leakage current should be limited within certain level to comply with standards and improve the reliability of the systems.

Various methods and techniques have been proposed to reduce the leakage current in the transformerless PV inverters. In one of the proposals, a resonant circuit is formed between the parasitic capacitance and stray capacitance of the PV panel and grid filter through this conduction loop. However, predicting the parasitic capacitance of the PV panel becomes cumbersome as it depends on weather conditions (humidity), conducting surface of the PV panels, and the passive elements used in the inverters and filters. Therefore, precise control of leakage current is not possible in this method [8].

Experiments have been performed to estimate the parasitic capacitances, and obtained an approximate figure of 50–150 nF/kW. However, the leakage current issue is related to the safety and security of people. Therefore, approximations are not acceptable for this issue. Standards such as DIN VDE 0126-1-1 impose the standards for this issue, which state that the maximum allowable leakage current is 300 mA [9].

Many studies proved that the frequency and value of the leakage current depend on the inverter topology and modulation strategies. Various inverter topologies were proposed to eliminate the leakage current in PV systems. The basic idea behind all the topologies is to isolate the PV module from the system in the freewheeling mode. This arrangement creates a high impedance in the common path between the parasitic capacitance of the PV module and the stray capacitance of the system. Therefore, the leakage current in the common path is effectively controlled by this large impedance [10,11].

Half-bridge converter topologies are more economical than full-bridge converters. Meanwhile, it also had the ability to overcome the leakage current issue. However, it needs a high direct current (DC) input voltage, which is double the DC bus voltage needed for a full-bridge converter. Therefore, a boost converter is required on the DC side. This increases the overall size and cost of the converter and reduces its efficiency by 92% [12]. Another possible solution is to clamp the potential of the PV panel directly to the ground of the grid. Various studies have been carried out in this area, such as clamping the midpoint or negative terminal of the DC bus with ground of the grid. In one of the proposals, even a virtual DC bus is created by switched capacitors to clamp with the grid ground. These methods effectively suppress the leakage current in the PV system. However, usage of more active and passive components in the system reduces the reliability [13,14]. For these reasons, many studies have been carried on full-bridge converters for limiting the number of switches and effective common leakage current path between the PV panels and the grid.

Example topologies for full bridge converters include the H$_5$ topology from SMA and the Highly Efficient and Reliable Inverter Concept (HERIC) topology from Sunways. Both of these topologies are widely accepted in industrial practices. In the H$_5$ topology, the leakage current is effectively suppressed by adding only one switch with an H-bridge inverter. Even though this method is cheap, the conduction loss is relatively high as compared to the HERIC topology. However, in the HERIC topology, two switches are proposed on the alternating current (AC) side of the H-Bridge. This arrangement ensures only two switches are active, both in the freewheeling and power transmission modes. This reduces the conduction loss and increases the overall efficiency of the system. Many topologies derived from the H$_5$ and HERIC topologies have been developed. These works mainly concentrate on conduction loss and maintaining high impedance on the common path between the PV panel and the grid [6,15–17]. In view of this, this paper proposes a novel transformerless PV inverter topology that resolves the issues in both the H$_5$ and HERIC topologies. It has fewer switches than the H$_5$ topology, and at the same time it has less conduction loss than in the HERIC topology.

This paper is organized as follows. The second section presents a simplified common mode model of a single-phase transformerless grid-connected PV inverter regarding leakage current in the system. The third section presents the total power losses in metal–oxide–semiconductor field-effect transistors (MOSFETs) and antiparallel diodes in the PV inverter topology with proper equations. The fourth section analyses the various transformer and transformerless PV inverter topologies focussed on the performance regarding leakage current and conduction losses. In the same section, the common mode voltage is calculated for all the switching states and depth analysis of unipolar sinusoidal pulse width modulation (SPWM) strategy is presented. In the fifth section, a novel improved transformerless grid-tied inverter topology is proposed with a depth analysis of its operation. In section six, a validation of the proposed controller is carried out by comparing the experimental results with conventional controllers. Conclusions are presented in the last section.

2. Simplified common mode model

The clear idea about the leakage current passing through the parasitic capacitance of the PV panel is given in [2] as a common mode model. This model gives the relationship between the common mode voltage and leakage current. Generally, the common mode voltage (V_{CM}) is calculated by taking the averages of the PV inverter terminal voltages V_a and V_b, which are measured between the each leg of the PV inverter to the negative of DC terminal, as shown in Fig. 1 [18].

$$V_{CM} = \frac{V_a + V_b}{2}$$

(1)