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Single phase transformerless inverter topology with reduced leakage current for grid connected photovoltaic system

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ABSTRACT

Leakage current is the main concern of the grid connected transformerless photovoltaic (PV) inverters. Many single phase transformerless inverter topologies with reduced leakage current have been introduced in the past few years. These are mainly classified on the basis of leakage current reduction methods Galvanic isolation without- common mode voltage (CMV) clamping and with-CMV clamping. It has been shown that leakage current generation is highly dependent on CMV. CMV of the topologies without- CMV clamping oscillates and oscillation amplitude depends on switches' junction capacitances and parasitic parameters of the topology. In order to eliminate the leakage current completely, CMV must be constant throughout the inverter operation. Moreover, inverter should also be capable to inject definite amount of reactive power into the grid, as demanded by the international regulations. In this study, reduced leakage current CMV clamped topology is proposed which can eliminate leakage current and capable of injecting reactive power into the grid. Total harmonic distortions (THD) of injected grid current at various solar irradiance levels are also analyzed. In order to verify the theoretical explanations, the proposed topologies are simulated in Matlab/Simulink environment. Finally, the simulated results are validated experimentally.

1. Introduction

PV systems are mainly categorized as: stand-alone system and grid connected system. Stand-alone system supply power directly to load or electrical appliance. It is integrated with energy storage (battery) system. In contrast, grid connected PV system supply generated energy into the utility grid for direct transmission, distribution, and consumption. As energy storage system is not needed, grid connected PV system is more cost effective and maintenance free [1–5]. It account for more than 99% of the globally installed PV power [6].

Based on the galvanic isolation, grid connected PV inverter topologies are grouped into transformerless and with transformer. The main functions of transformer are to provide voltage amplification and galvanic isolation between PV modules and the grid [7]. Thus, it prevents flow of dc current and leakage current injection into the grid [8]. Transformer can be of low frequency (LF) or high frequency (HF), depending on PV modules configuration. LF transformers are heavy, bulky and expensive and these reduce the system efficiency because of power loss in windings [9–11]. Even though, significant reduction in size and weight can be achieved by using HF transformer. The efficiency of the entire system is still low due to multiple converter stages (dc-dc and dc-ac) [12]. Hence, transformerless inverter topologies are introduced for PV application to overcome these issues. It can improve the system efficiency by 1–2% [13]. Furthermore, they are lighter, smaller and lower in cost.

Although the transformerless PV inverter has many advantages, high leakage current is the main concern. Because of the absence of transformer, a galvanic connection is formed which provide path for leakage current to flow from PV module to the grid [10,14]. At the same time, parasitic capacitor, which is formed between PV cells and metallic frame of module, generates high leakage current if high frequency potential is applied across it. The leakage current increases the total harmonic distortion (THD) of the grid current, electromagnetic interference (EMI) and system losses, and it causes personal safety problems [10,11,14–17].

There are mainly three modulation techniques: unipolar, bipolar and hybrid modulation, which can be used for single phase full bride (H4) transformerless PV inverter. CMV, leakage current and efficiency characteristics change according to the modulation schemes. In case of unipolar modulation and hybrid modulation three- level voltage ($0 \rightarrow +V_{PV} \rightarrow 0 \rightarrow -V_{PV} \rightarrow 0$) is generated across filter, yielding lower core loses [18]. However, they generate high

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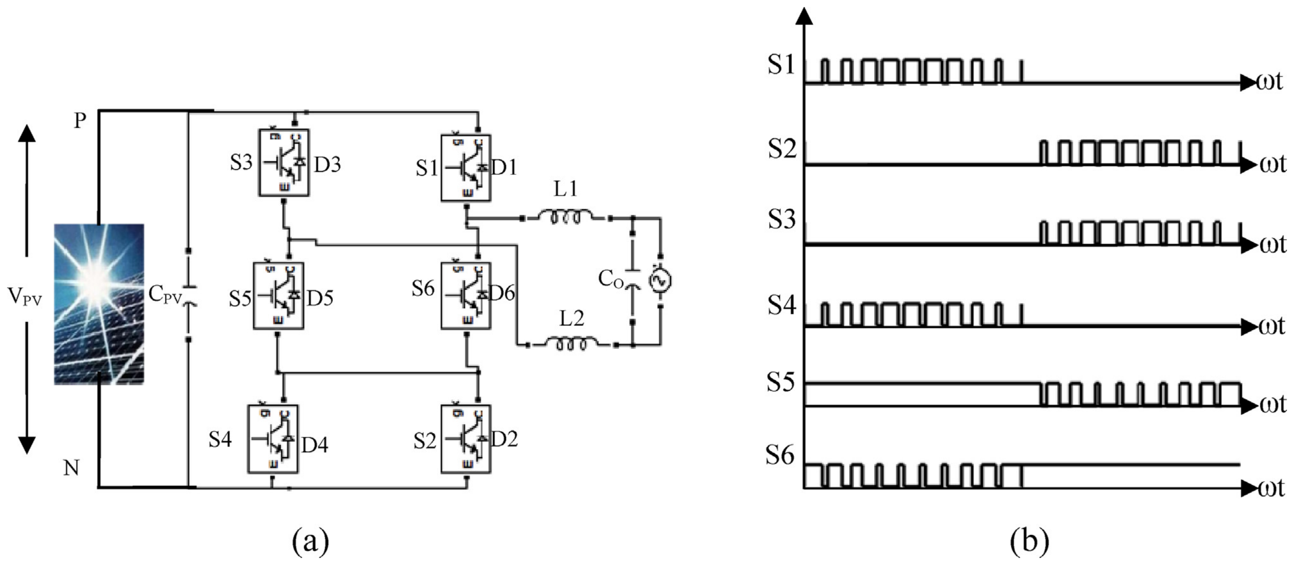

Fig. 1. The existing H6- topology and switching waveforms.

leakage current because of high frequency CMV. In case of bipolar modulation two-level voltage (+V_{PV}, −V_{PV}) is generated, yielding higher core losses. Moreover, it generate constant CMV, hence leakage current is low.

Leakage current problems can be solved by using bipolar sinusoidal pulse width modulation (SPWM) technique. However, efficiency of bipolar SPWM inverter is lower compared to unipolar SPMW inverter because of higher core losses of filter inductors and switching losses [7]. Thus, many inverter topologies have been introduced, which have advantages of both unipolar and bipolar modulation techniques: high efficiency and low leakage current. These topologies are mainly classified on the basis of leakage current reduction methods: Galvanic isolation without- CMV clamping and with-CMV clamping. The detailed classification was presented in Ref. [18]. CMV of the topologies based on without-CMV clamping oscillates and oscillation amplitude depends on switches' junction capacitances and parasitic parameters of the topology [13,19]. It has been shown that leakage current generation is highly dependent on CMV, especially, high frequency components. In order to minimize the leakage current completely, CMV must be constant throughout the inverter operation (power transfer states and zero voltage states). Moreover, inverter should also be capable to inject definite amount of reactive power into the grid as demanded by the international regulations [20]. It is reported [21] that without CMV clamped topologies, such as HERIC, H5 and H6 families, do not comply with IEEE-1547 standard [22] and these inject more than 5% grid current THD at low solar irradiance levels. It is due to oscillation of CMV during zero voltage states. Hence, these topologies are equipped with extra common mode filter (CMF) which burdens on cost and power density of the inverters [13].

In this paper, reduced leakage current CMV clamped topology is proposed which can eliminate leakage current and is capable of injecting reactive power into the grid. The CMV of the proposed topology remains constant throughout inverter operations and it eliminates the requirement of extra CMF. Moreover, THD analysis of the proposed topology is carried out at various solar irradiance levels (100–1000 W/m2) and the results are found within specified limit.

This paper is organized as follows. Section 2 presents analysis on existing H6 transformerless inverter topology. Leakage current generation and switches' junction capacitances are discussed in Section 3. Proposed topologies are presented in Section 4. In Section 5, simulation analysis is carried out. Section 6 presents power loss and junction temperature calculation. Experimental results are presented in Section 7 and finally, Section 8 concludes the paper.

2. Analysis on existing H6 topologies

In Ref. [23], a H6 without CMV clamped topology, as shown in Fig. 1(a), was proposed to overcome the drawback of the MOSFET based H6 topologies presented in Refs. [24,25]. These MOSFET based topologies were not capable to handle the reactive power flow. The existing H6 topology composed of six active switches S1–S6 which was derived from H4 topology by inserting two additional switches S5 and S6. Control strategies of switches are illustrated in Fig. 1(b). Depending on grid voltage polarity, switches S1–S4 are commutated diagonally at switching frequency to generate unipolar inverter output voltage. During positive grid voltage, S1 and S4 are switched at high frequency; S2 and S4 are OFF, S5 is ON and S6 is switched complementary to S1 and S4. During negative grid voltage, S1 and S4 are switched at high frequency; S2 and S4 are OFF, S5 is ON and S6 is switched complementary to S1 and S4. The switches S5 and S6 and their anti-parallel body diodes D5 and D6 provide path for freewheeling current during zero voltage state.

In this without-CMV clamped topology, output terminals (A and B) are connected to positive V_{PV} and negative V_{PV} (N) during active modes of inverter. Hence, during conduction periods, CMV can be $V_{PV}/2$ (e.g. during positive grid voltage polarity, $V_{CMV} = (V_{AN} + V_{BN})/2 = (V_{PV} + 0)/2 = V_{PV}/2$). However, during zero voltage or freewheeling periods, PV modules are disconnected from the grid. Therefore, the inverter output terminals (A and B) are floating with respect to the dc link. Hence, CMV ($V_{CMV} = (V_{AN} + V_{BN})/2$) is oscillating during this period and can not be determined by switching state. The CMV amplitude oscillation depends on switches' junction capacitances and parasitic parameters of the topology. Common mode (CM) and differential mode (DM) voltages of existing H6 topology are given in Table 1.

3. Leakage current generation and switches junction capacitances

In practical applications, junction capacitance of switches' varies from several hundred picofarads to few nanofarads [13] which cannot be ignored. When inverter commutates from power transfer state to freewheeling state (galvanic isolation or decoupling state),