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Improved modulation strategy for single phase grid connected transformerless PV inverter topologies with reactive power generation capability

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ABSTRACT

In this study, several recently published topologies are analyzed for reactive power generation capability. It has been found that some of the topologies with their conventional modulation strategies are not suitable for reactive power applications. These are not able to generate zero voltage states during negative power flow. As a result, current is distorted and PV inverter injects current with high total harmonic distortion (THD) into the grid. In order to overcome these problems, modified modulation technique is proposed to achieve reactive power capability without having distortion in injected grid current. It provides path for current to flow in order to generate zero voltage states during negative power flow. With improved modulation strategies, reactive power generation is achieved in inverter topologies without any alteration on the converter structures. The controller software of these topologies is only required to be updated for reactive power generation. The implementation and generation of the proposed improved modulation techniques are straightforward and it can easily be realized. Moreover, single phase transformerless inverter topologies are classified for first time on the basis of reactive power handling capability. In order to verify the theoretical explanations, simulations have been carried out in Matlab/Simulink environment and validated through an experimental setup.

1. Introduction

The efficiency of PV modules is very low (around 15–20%). Therefore, PV generated power should not be wasted by employing inefficient power conversion systems (Silva, 2013; Liu et al., 2011). The PV inverters are the key interfaces between PV modules and the grid, which are usually classified as with-transformer and transformerless. Transformer can be line frequency on the ac side or high frequency (HF) on the dc side (Obi and Bass, 2016; Kjaer et al., 2005; Aganza-Torres et al., 2016). Besides voltage amplification, it also provides galvanic isolation between PV modules and the grid. Thus, it prevents flow of leakage current and dc current injection into the grid (Guo, 2017; Kwon et al., 2006). However, line frequency transformers are heavy, bulky, and expensive, and reduce the system efficiency because of power loss in windings (Li et al., 2015). Even though, significant reduction in size and weight can be achieved by using HF transformer. The efficiency of the entire system is still poor due to multiple converter stages (dc-dc and dc-ac) (Guo, 2017; Li et al., 2015).

Nowadays, single phase transformerless inverters are widely being adopted for small scale grid connected PV system due to their high efficiency, lower cost and high power density (Li et al., 2015). However, a direct galvanic connection is formed for leakage current to flow from PV module to the grid in absence of transformer. The leakage current increases total harmonic distortion (THD) of the grid current, electromagnetic interference (EMI), and system losses, and it causes personal safety problems (Xiao and Xie, 2010; Guo et al., 2018; Guo et al.).

In order to reduce the leakage current, conventional half bridge or full bridge (H4) inverters are used with bipolar sinusoidal pulse width modulation (SPWM) technique. However, a high input dc voltage (700 V) is required for the half bridge topologies (Guo, 2017; Rodriguez et al., 2010). For full bridge inverter with bipolar SPMW, high power losses and low efficiency are observed because of the two-level output voltage of inverters. Furthermore, bipolar SPMW increases the voltage stress across the filter inductors and current ripples. As a result, large inductors are required which increase cost and size of the PV systems (Calais et al., 1999; Babaei and Asl, 2016).

Many inverter topologies have been introduced, which have advantages of both unipolar and bipolar modulation techniques: high efficiency and low leakage current. These topologies can be classified

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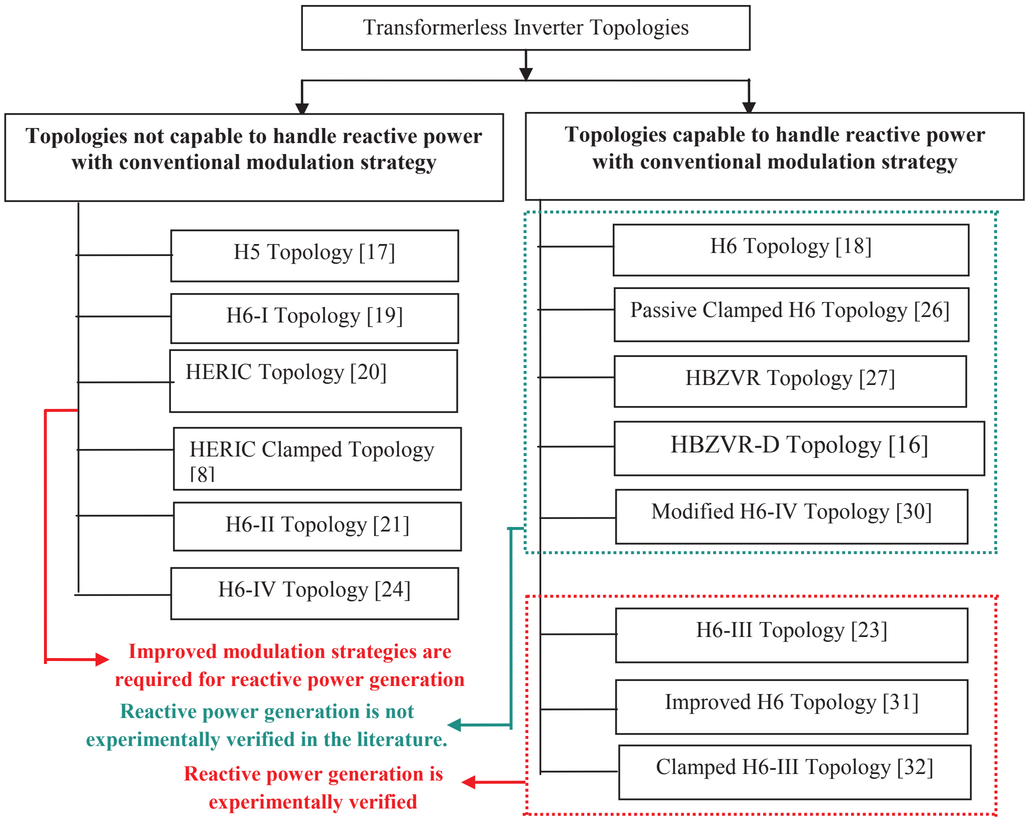

Fig. 1. Classification of transformerless inverter topologies based on reactive power capability.

on the basis of reduction methods of leakage current: galvanic isolation with and without common mode voltage (CMV) clamping (Li et al., 2015; Bradaschia et al., 2011; Freddy et al., 2014; Victor et al., 2008; Yang et al., 2012; San et al., 2012; Heribert et al., 2003; Yu et al., 2011; Ji et al., 2013; Islam and Mekhilef, 2015; Cui et al., 2011; Xiao et al., 2011; Gonzalez et al., 2007; Kerekes et al,. 2011; Tey and Mekhilef, 2016; Islam and Mekhilef, 2014; Ahmad and Singh, 2017). The galvanic isolation can be achieved by incorporation of extra switches either on ac side or dc side of full bridge (H4) inverter topology for ac or dc decoupling respectively. However, it has been shown that merely by galvanic isolation, leakage current cannot be reduced to zero due to stray capacitances (formed between switch terminal and heat sink and resonant circuit effects. Some topologies utilize clamping method to fix the CMV to half of dc-link voltage to completely eliminate the leakage current. A detailed classification of the topologies is reported in Islam and Mekhilef (2014). The topologies based on galvanic isolation alone such as HERIC (San et al., 2012), H5 Freddy et al., 2014 and H6 families (Bradaschia et al., 2011; Freddy et al., 2014; Victor et al., 2008; Yang et al., 2012; Heribert et al., 2003; Yu et al., 2011; Ji et al., 2013; Islam and Mekhilef, 2015; Cui et al., 2011; Xiao et al., 2011; Gonzalez et al., 2007; Kerekes et al., 2011; Tey and Mekhilef, 2016; Islam and Mekhilef, 2014; Ahmad and Singh, 2017) generate higher leakage current due to oscillation of CMV during zero voltage states. Hence, these topologies are equipped with extra common mode filter (CMF). The CMV clamped topologies are reported earlier (Cui et al., 2011; Xiao et al., 2011; Gonzalez et al., 2007; Kerekes et al., 2011; Tey and Mekhilef, 2016; Islam and Mekhilef, 2014; Ahmad and Singh, 2017; Ahmad and Singh, 2017). In these topologies, CMV is clamped to half of the dc link voltage during zero voltage states. Hence, leakage current is reduced to a very low value.

Although methods leakage current reduction have been matured, reactive power handling capabilities of single phase transformerless inverter topologies are not properly explored. The most of the topologies are designed to operate at unity power factor. However, the reactive power support is essential for next-generation grid connected PV inverters in order to allow high penetration of PV system. According to VDE-AR-N4105 (Ahmad and Singh, 2018; Collins and Ward, 2015; Liu et al., 2015), the capability of reactive power generation is essential for the inverters employed in grid-connected PV applications. Even though various single phase transformerless topologies with reactive power capability have been introduced, their modulation strategies and structures are complex which increase the cost, losses, and complexity of the design (Yang et al., 2014; Islam et al., 2016; Barater et al., 2016; Chen et al., 2016). In order to generate reactive power, Freddy et al. (2017) presented modulation strategy for H5 and HERIC topologies and discussed reactive power generation.

In this study, several recently published topologies are analyzed for capability of reactive power generation. Some of the topologies with their conventional modulation strategies are not suitable for reactive power applications. These are not able to generate zero voltage states during negative power flow. As a result, current is distorted and PV inverter injects current with high total harmonic distortion (THD) into the grid. In order to overcome these problems, modified modulation techniques are proposed to achieve reactive power capability without distortion in the injected grid current. Improved modulation techniques provide path for current flow in order to generate zero voltage states during negative power transfer. With modified modulation strategies, reactive power generation capability is achieved in the inverters without any alteration on the converter structures. The implementation and generation of the proposed improved modulation techniques are straightforward and it can easily be realized.

This paper is organized as follows. In Section 2, analysis of reactive power handling capability is explained. Improved modulation strategies are presented in Section 3. Power control is discussed in Section 4. In Section 5, simulation analysis is presented. Experimental results are discussed in Section 6, and finally, Section 7 concludes the paper.