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Three-phase multilevel inverter for grid-connected distributed photovoltaic systems based in three three-phase two-level inverters

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ABSTRACT

A multilevel three-phase voltage source inverter (VSI) for distributed grid-connected photovoltaic system is proposed in this paper. This multilevel inverter is based on a new topology using three three-phase two-level VSIs (T^3VSI) with isolation transformer. The photovoltaic panels are connected at the DC side of each three-phase VSI. The three-phase VSIs AC sides are connected to the three-phase isolation transformer with primary open-end windings, ensuring multilevel operation. The T^3VSI can be modulated using existing multilevel Pulse Width Modulation (PWM) schemes. A control system designed to ensure the transfer of the energy generated by the PV generators to the grid is also presented, together with a Phase Disposition PWM (PDPWM) adapted for the multilevel T^3VSI. Tests of the grid-connected PV multilevel T^3VSI will be shown through simulation and experimental results. Several results obtained from experiments confirm the expected characteristics of the multilevel T^3VSI photovoltaic system.

1. Introduction

The step up technological development experienced over the last decades has brought significant improvements in quality of life in many modern societies. Unfortunately, many of these improvements have been largely achieved at the expense of gradual earth conditions degradation, causing numerous arduous effects in the environment (Ascione, 2017; Burnett et al., 2014; Edenhofer et al., 2012; Ming et al., 2014). Nevertheless, it seems that the effects from global climate change have finally begun to change mindsets. Proof of this are the numerous works, projects and scientific publications related to the use of environmentally friendly renewable-energy sources over the last few years (González et al., 2016; Kabalci et al., 2017; Mason et al., 2014; Dai et al., 2015; Razykov et al., 2011). Amongst these sources, the solutions based on wind-power systems and photovoltaic (PV) are currently some of the most interesting alternatives for electric power generation in both grid-connected and stand-alone applications (Blaabjerg and Ma, 2017; Sherif et al., 2005; Antonanzas et al., 2016; Singh, 2013; Brown et al., 2016; Gow et al., 2000). According with the last report available from the International Energy Agency (IEA), during 2016 renewable energy sources broke new records, mainly because of solar photovoltaics (PV) deployment in China and around the world, motivated by government policy support, sharp cost reductions (Renewables, 2017) and research in power conversion and control strategies (Ayop and Tan, 2018; Lenz et al., 2017; Pires et al., 2016; Blaabjerg et al., 2004; Liang et al., 2001). Over 2016, the solar PV capacity installed around the world grew by 50%, reaching over 74 GW (Renewables, 2017). Despite the importance and contributions from all renewable energy sources available, this paper focuses in improving photovoltaic (PV) solutions for grid-connected applications.

Along with the fast proliferation of solar PV panels, new interface topologies have also emerged, allowing the development and integration of distributed generation systems. A big diversity of innovative isolated and non-isolated DC-DC and DC-AC converter configurations have been presented in literature (Fathabadi, 2016; Cha et al., 2016; Li et al., 2017; Pires et al., 2018; Bennett et al., 2012; Hsieh et al., 2014; Ardi et al., 2014; Kwon et al., 2009; Wai et al., 2008). An overview of these topologies can be found at (Carrasco et al., 2006). Most common grid-connected PV systems use the well known three-phase two-level inverter as interface with the power grid (Carrasco et al., 2006; Chaouachi et al., 2010; Ravi et al., 2011; Yu et al., 2005; Kim, 2009). Despite the control simplicity and reduced costs compared to other topologies, this inverter remains very limited concerning the output voltage level and harmonic distortion. To overcome these limitations,

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several multilevel converters have been considered for PV applications in the last years (Bandara et al., 2012; Daher et al., 2008; Zhou et al., 2009). Multilevel converters allow reduced current and voltage harmonics on the AC side, high voltage capability, reduced dv/dt stress on power semiconductors and minimize the occurrence of interference problems (Villanueva et al., 2009; Kang et al., 2005b). Depending on the desired quality for AC output voltages and the synthesized number of levels, they have the potential to avoid the use of output filters. Some of the most common multilevel topologies used in PV applications are the cascaded H-bridge multicell (Villanueva et al., 2009; Zhou et al., 2005; Sastry et al., 2014; Babaei et al., 2014; Rajkumar et al., 2013), neutral-clamped (Pouresmaeil et al., 2011; Ozdemir et al., 2009; Busquets-Monge et al., 2008; Agrawal and Jain, 2017) and flying capacitors (Sadigh et al., 2014).

Although less common, other interesting multilevel topologies based on classical two-level inverters have been presented by (Stemmler and Guggenbach, 1993, Lesnicar and Marquardt, 2003, Pires et al., 2017). Most of these multilevel inverters were applied to grid-connected PV systems. One of the solutions is based on the multiple transformer topology (Kang et al., 2005a). Another topology that has been studied and tested requires a three-phase transformer (Grandi et al., 2009; Pires et al., 2012; Kumar et al., 2017). This topology is very interesting since it uses the well-known three-phase two-level VSIs. Besides, it also allows for a distribution configuration where the solar panels are divided by the two VSIs. However, the topology is limited to a dual distribution. This problem has been studied in AC drives, regarding the increase of the number of inverters and maximum applied AC voltage (Pires et al., 2017).

This paper proposes a new three-phase multilevel voltage source inverter topology for grid-connected photovoltaic systems in distributed configurations. The proposed topology is based on three conventional three-phase two-level inverters combined with one open-windings transformer (T^3VSI). Instead of a dual distribution configuration as in dual multilevel inverter, the multilevel T^3VSI topology allows the extension for a triple distribution configuration. Additionally, the multilevel T^3VSI topology also allows the increase of the maximum voltage applied to the transformer, reducing their turns-ratio, cost, volume and weight. The characteristics of the T^3VSI topology will be confirmed through several simulation and experimental results.

2. Multilevel inverter for PV distributed system

2.1. Proposed topology

In PV systems with high power capability it is often required the use of parallel power switches since the individual switch current ratings are exceeded. In order to avoid the paralleling, the use of some multilevel topologies was proposed, in which the current is shared by switches. One of the topologies offering the current sharing capability is the dual inverter topology (Grandi et al., 2009; Pires et al., 2012; Kumar et al., 2017). This grid-connected dual inverter topology is also characterized by the use of distributed PV panels, although limited to two groups. It is based on a modular topology composed by three-phase two-level VSIs. The maximum voltage that this topology allows to apply to the transformer is $1.33V_{DC}$, being V_{DC} the PV panel DC voltage.

This paper proposes the multilevel T^3VSI topology (Fig. 1) that uses three-phase two-level VSIs and allows for distributed groups of PV panels. Moreover, instead of using only two groups of PV panels, the multilevel T^3VSI topology allows three groups. It is also characterized by higher AC voltage amplitude. In fact, instead of the $1.33V_{DC}$ maximum AC amplitude, it is possible to apply $2V_{DC}$, allowing the reduction of either the transformer turns-ratio, or the V_{DC} voltage. Due to the configuration of the multilevel T^3VSI it is also possible to achieve triple rated power. The reduction of the V_{DC} voltage might enable the use of low-voltage MOSFETs reducing also the on-state and switching losses, while increasing the topology efficiency. The multilevel T^3VSI can use existing multilevel Sinusoidal Pulse Width Modulation (SPWM) schemes, such as PDPWM.

Analysing the AC voltages V_{j1}, V_{j2}, V_{j3}, $j\in\{1,2,3\}$ in the multilevel T^3VSI (Fig. 1) several voltages levels can be found as functions of the switches state. The relationship between the state of the switches and the AC voltages of each of the inverters is given by (1). It should be noted that the switches state is represented with the binary variable b_{ji} (that are directly related with switch S_{ji} and is equal to 1 if the switch is ON and 0 if it is OFF).

$$\begin{cases} V_{j1} = b_{j1}\, V_{Coj} \\ V_{j2} = b_{j2}\, V_{Coj} \\ V_{j3} = b_{j3}\, V_{Coj} \end{cases} \tag{1}$$

Through the relationship in (1) and considering that the output voltage of the multilevel T^3VSI applied to each transformer winding is the difference between two inverters, the AC voltages at the terminals of the transformer windings can be expressed by:

$$\begin{cases} V_1 = (b_{11}-b_{13})\ V_{Co1}-(b_{32}-b_{33})\ V_{Co3} \\ V_2 = (b_{21}-b_{23})\ V_{Co2}-(b_{12}-b_{13})\ V_{Co1} \\ V_3 = (b_{31}-b_{33})\ V_{Co3}-(b_{22}-b_{23})\ V_{Co2} \end{cases} \tag{2}$$

From the analysis of (2) and considering that all the DC voltages are equal it is possible to apply to each of the transformer windings five voltage levels ($-2V_{DC}$, $-V_{DC}$, 0, $+V_{DC}$ and $+2V_{DC}$). These voltages are function of the states of the switches and for each winding they result from the combination of two inverter states. The combinations for each of the windings phase are: 1 and 3 for winding 1, 2 and 1 for winding 2 and 3 and 2 for winding 3. From the analysis it is also possible to conclude that the maximum voltage value applied to each of the transformer windings is $2V_{DC}$.

2.2. Topology comparisons

A comparison of the proposed converter with other equivalent topologies, more specifically, the cascaded H-bridge multicell and the dual bridge (Villanueva et al., 2009; Grandi et al., 2009) is presented in Table 1. From this table it is possible to see that the proposed topology requires the lowest blocking voltage tacking into consideration the maximum output voltage. Regarding the two-level inverters, the cascaded H-bridge requires six single-phase inverters while the proposed requires half of that number, but with three-phase modules. The dual bridge only requires two three-phase modules. However, under the point of view of the distributed PV panels, it is limited to two groups. The proposed allows for a distribution of three groups and the cascaded H-bridge six groups. Regarding the passive elements, the cascaded H-bridge is the only topology under study that does not requires a three-phase transformer. However, due to the need of the elimination of common-mode currents and sometimes the necessity to adapt the PV generator voltages with the grid, many times is required a transformer.

3. Control method

A specific control system was designed for the proposed multilevel T^3VSI with the objective of allowing the transfer of the PV generator energy to the grid. To accomplish this, it was necessary to couple a controller to a multilevel modulator to ensure the desired operation of the multilevel T^3VSI.

In this study it was considered that each PV generator consists into two main parts: the PV panel arrays and a DC-DC converter associated to a Maximum Power Point Tracking algorithm. In accordance with this, the control system must ensure the energy transfer from the PV generator to the grid following two tasks: the regulation of the DC voltage in the multilevel T^3VSI DC input and the control of the multilevel T^3VSI output AC currents. Thus, the primary controller that