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A review of inverter topologies for single-phase grid-connected photovoltaic systems

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ABSTRACT

The concept of injecting photovoltaic power into the utility grid has earned widespread acceptance in these days of renewable energy generation & distribution. Grid-connected inverters have evolved significantly with high diversity. Efficiency, size, weight, reliability etc. have all improved significantly with the development of modern and innovative inverter configurations and these factors have influenced the cost of producing inverters. In this review work, all aspects covering standards and specifications of single-phase grid-connected inverter, summary of inverter types, historical development of inverter technologies, classifications of inverter topologies are presented in a systematic manner. Finally, some transformer-less topologies based on bridge configuration and multilevel concept, and some soft-switching inverter topologies are remarked as desirable with respect to high efficiency, low cost, and compact structure. Areas of further works including use of advanced semiconductor devices, improvement of de-coupling capacitor etc. are also pointed out to draw attention of inverter designer for further increase of efficiency and lowering the cost.

1. Introduction

Renewable energy is increasingly considered essential for meeting current and future energy needs [1]. Photovoltaic (PV) power, as it is clean and unlimited source of energy, is probably the best technology amongst all renewable energy sources and therefore a considerable amount of research has been conducted recently in this field. To better utilize the PV power, grid interconnection of PV system is needed. PV power rendering to the utility grid has been the fastest growing renewable energy technology by far since it attracted the attention of policy makers [2]. The primary constraint to the use of PV power was the cost of the PV modules, which were typically ranged between 30% and 50% of the total cost of the system [3]. Due to the downward tendency in the price for the PV modules, the costs of the inverters were increasingly standing out while calculating the total cost of the grid-connected PV system. In the past 2–3 decades, grid-connected inverters have evolved significantly with high diversity and are considered one of the fastest developing technologies in present power electronics and power systems. Efficiency, size, weight, reliability etc. along with ease of installation have all improved significantly with the development of modern and innovative inverter configuration. These factors have influenced the cost of producing inverters. So many grid-connected PV systems have been installed in recent years mainly due to the downward tendency of the cost of such systems, and policy making and subsidy given by the governments to these kinds of technologies. But pressure to further cost reduction still remains.

The factors volume and weight of the inverter are inhomogeneous. It is not always true that inverter with line-frequency transformer has more volume and weight than inverter with high-frequency transformer, and similarly inverter with high-frequency transformer has more volume and weight than a transformer-less inverter [4]. Transformer-less inverters had leakage current problem, which has been solved in some transformer-less topologies up to a certain level. But anyway, transformer-less inverters are being produced mostly in recent days due to high efficiency and low cost [4,5]. Inverter cost further can be reduced if more than two-level output voltage could be generated. For this reason, some multilevel inverter topologies may be beneficial [6]. Another important factor is inverter efficiency which reaches near

Abbreviations: PV, Photovoltaic; IEC, International Electro technical commission; IEEE, Institute of Electronics and Electrical Engineers; NEC, National Electrical Code; DR, Distributed Resource; DC, Direct Current; AC, Alternative Current; THD, Total harmonics distortion; IGBT, Insulated Gate Bipolar Transistor; MOSFET, Metal Oxide Semiconductor Field-effect Transistor; PWM, Pulse width modulation; VSI, Voltage source inverter; CSI, Current source inverter; BJT, Bipolar Junction Transistor; MPPT, Maximum Power Point Tracking; GEC, General Electric Company; ZVS, Zero voltage switching; ZCS, Zero current switching; ZVT, Zero voltage transition; ZCT, Zero current transition; HERIC, High efficient and reliable inverter concept; EMI, Electromagnetic Interference; SiC, Silicon Carbide; R & D, Research and Development; USA, United States of America

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about 98% [4]. Further increase of 1% efficiency is very challenging. Further increase of efficiency needs soft-switching technologies to be used in inverters as these can reduce the switching losses in the power switching devices used in the inverter circuit.

In this review work, some transformer-less topologies based on half-bridge, full-bridge configuration and multilevel concept, and some soft-switching inverter topologies are remarked as desirable for grid-connected single-phase PV inverters with respect to high efficiency, low cost, and compact structure. But before getting into those inverter topologies, looking back to some fundamental and important matters related to single-phase grid-connected inverter is necessary. Therefore in this work, a systematic and step-by-step approach has been taken to describe properly the overview of single-phase grid-connected inverters developed till date. This work is organized in this order that, first the standards and specifications of single-phase grid-connected inverters are stated. Then, summary of inverter types, historical overview of inverter technologies, classifications of inverter topologies are presented one after the other.

2. Standards and specifications of grid-connected PV inverter

The Distribution Network Operators are responsible for providing safe, reliable and good quality electric power to its customers. The PV industry needs to be aware of the issues related to safety and power quality and assist in setting standards as this would ultimately lead to an increased acceptance of the grid-connected PV inverter technology by users and the electricity utility industry. And for the system to be operated safely and reliably, these standards must be adopted, which will cater to build electricity consumer's trust, reduce costs and further flourish grid-connected PV inverter development [7]. There are several standards on the market dealing with the interconnection of PV energy sources with the utility grid like International Electro technical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE) and National Electrical Code (NEC). Amongst them the most popular standards are IEC 61727 [10], IEEE 1547–2003 [11], IEEE 929–2000 [8] etc. which are discussed in Table 1. These standards fix the limits for the inverter voltage changes, its operating frequency changes, power factor, harmonics in the current injected into grid, injection of DC current into the grid to avoid distribution transformers saturation [9] and also address grounding issue. These also contain information regarding islanding of PV systems when the utility grid is not connected to control voltage and frequency of the inverter, as well as techniques to avoid islanding of PV energy sources. In islanding state, the utility grid has been removed from the inverter, which then only supplies power to local loads. In addition to these standards, there are a few more among which the IEEE 1373 standard recommends practice for field test methods and procedures for grid-connected PV system, IEC 62116 standard recommends test procedure of islanding prevention measures for grid-connected PV inverters, IEC 61173 standard gives guidance on overvoltage protection for PV power generating system, IEC 61683 recommends the procedure for measuring efficiency of the PV system.

3. Summary of grid-connected PV inverter topology

In the grid-connected PV system, the DC power of the PV array should be converted into the AC power with proper voltage magnitude, frequency and phase to be connected to the utility grid. Under this condition, a DC-to-AC converter which is better known as inverter is required. The inverter is therefore an important component in grid-connected PV systems [12–20,23,24]. There are various kinds of grid-connected PV inverters as shown in Fig. 1. The line-commutated inverter, in which the utility grid dictates the commutation process (the commutation process is initiated by reversal of the AC voltage polarity), uses power switching devices like commutating thyristors. The turn-on operation of this device can be controlled by the gate terminal of the device while the turn-off cannot be controlled by the same. Turn-off of such device is performed with the help of an add-on circuit to the device. Contrarily, the self-commutated inverter, where the current is transferred from one switching device to another in a controlled manner, is characterized in that it uses such a power switching device, the potential at the gate terminal of which can control both the turn-on and the turn-off operation, such as Insulated Gate Bipolar Transistor (IGBT) and Metal Oxide Semiconductor Field Effect Transistor (MOSFET). Power MOSFETs are used for low power typically less than 10 kW and high-frequency switching operation (20–800 kHz) and IGBTs are used for medium-to-high power exceeding 100 kW, but very high-frequency switching is not possible using IGBTs as the switching frequency is limited to 20 kHz. In case of grid-connected inverter, high-frequency switching is required to reduce an inverter's output-current harmonics, size of the magnetic (filter) used, and weight of the inverter [1]. The self-commutated inverter uses a pulse width modulation (PWM) switching techniques to generate an AC waveform at the output. The self-commutated inverter can control both voltage waveform as well as current waveform at the output side of inverter, and adjust or correct the power factor and suppress the harmonics in the current waveform which is required for grid-connected PV system, and is highly resistant to utility grid disturbances. In present days, due to evolution of advanced switching devices like Power MOSFETs and IGBTs, most inverters for distributed power systems such as PV systems now employ a self-commutated inverters rather than line-commutated inverters.

The self-commutated inverters may be voltage source inverter (VSI) or current source inverter (CSI) based on voltage or current waveforms at their input DC side. In VSI, the input side is a DC voltage source, the input voltage holds the same polarity, the average power flow direction through the inverter is determined by the polarity of the input DC current, and at the output side, an AC voltage waveform of the constant amplitude and variable width can be obtained. To limit current flow from the inverter to the utility grid a tie line inductor is used along with VSI. The input DC side terminals of a VSI are typically connected in parallel with a relatively large capacitor that resembles a voltage source. In CSI, the input side is a DC current source, the input current holds the same polarity, and therefore the average power flow direction through the inverter is determined by the polarity of the input voltage and at the output side, an AC current waveform of the constant amplitude and variable width can be obtained. The input DC side of the CSI is typically connected in series with a relatively large inductor that maintains the current continuity. A VSI can be operated in voltage control mode as well as in current-control mode and in many times, VSI with current control mode is preferred for grid-connected PV system. Figs. 2 and 3 shows configurations of line-commutated CSI and self-commutated VSI. In Table 2, some basic differences between a VSI and a CSI are presented.

Table 3 shows the differences between the voltage control mode and the current control mode of a voltage source inverter. For the inverter of stand-alone PV system without any grid connection, voltage control mode should be used. However, both voltage control mode and current control mode can be used for the inverter of grid-connected PV system. In grid-connected PV system, inverter with the current control mode is extensively used because a high power factor can be obtained by a simple control circuit, and also suppression of transient current is possible when any grid disturbances occur.

4. Development of grid-connected PV inverters

4.1. Centralized

The first grid-connected PV inverters were line-commutated inverters by means of commutating thyristors (see Fig. 4(a)) with power ratings of several kilo watts based on electrical drive system technology.