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Transformer-less single-phase grid-tie photovoltaic inverter topologies for residential application with various filter circuits

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ABSTRACT

This article presents an overview of different transformer-less single-phase grid-connected photovoltaic inverters with various filter circuits including immittance conversion topology for residential application. Various inverter topologies are presented, compared, and evaluated against components used, size, cost, self life, losses, and efficiency. To find the suitable topology, a number of factors are considered in the design of inverter: 1) the number of buck and boost stages in cascade; 2) the type of synchronization to align the PV output with the grid; 3) whether the inverter will be designed using a minimalist component strategy; 4) elimination of Total Harmonic Distortion (THD) and 5) efficiency. After a rigorous analysis, some of the topologies are pointed out as the best candidates for either single or multiple photovoltaic (PV) module applications.

1. Introduction

More than any form of energy, electricity has played a vital factor in the growth of human civilization in the past century. Nations that had access to reliable sources of electricity have traditionally seen rapid industrialization and modernization. With the increasing global population and rapid growth of the economy and trade, there has been a tremendous increase in the use of electricity. Global electricity demand is ascended up to 15,000 TW-hr in 2015. World energy production and demand gap is swelled at 14TW with in 2050 and 33TW by 2100. From world energy consumption it is depicted that petroleum is consumed 32.4%, coal is consumed 30.1%, natural gas is consumed 23.7%, hydro electricity is consumed 6.72%, nuclear energy is consumed 4.42%, whereas green energy (solar, wind, biogas and other) is consumed only 2.66% of total energy consumption [1].

The classical and conventional method of generating electricity by burning fossil fuels is no longer able to fulfill this exponential increase in global electricity demand. Burning of fossil fuel on a massive scale, as seen in the previous century, gave a huge impact on environmental problems and climate change including global warming, rising sea levels, and extreme weather patterns all over the world. The emission levels of harmful gases such as Carbon dioxide (CO_2), Carbon monoxide (CO), Sulfur dioxide (SO_2) are rapidly spiraling out of control and beyond the ability of the planet to heal itself. Adding to this, the cost of fossil fuel is increasing on a daily basis as the natural reserves get exhausted, thus creating a shortage of the world's energy. 'Statistical Review of World Energy' published British Petroleum in mid 2014 asserted, crude oil reserve will be finished within next 40.5 years, natural gas will be finished in next 54.7 years and coal will be finished subsequently in 108 years [1].

In such circumstances, the conventional method can no longer be thought as the optimum solution for the energy crisis. Current and future trend is to aim for zero or negative carbon footprint for electricity generation. Renewable energy sources have taken over the electricity generation process due to its ability to generate zero carbon electricity. Renewable energy sources are of many types such as solar, wind, biomass, hydro and tidal power. Among all of these energy sources, solar energy is one of the very significant sources of renewable energy. Bangladesh is a semitropical region lying northeastern part of South Asia and within the tropic of cancer, an area that receives a lot of sunlight throughout the year acquiring elevated irradiation of sun [2]. Bangladesh is also an area that suffers from chronic power shortages, especially during the hot summer months when frequent load shedding is common. Therefore implementing a highly efficient and cost effective solar module system should go a long way to minimize the power crisis during the summer months. Installing low-cost PV modules should help in producing large amount of power at very low cost. Hence, among all renewable energy sources, solar energy is one of the fastest

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growing energy sources in Bangladesh [3,4].

Photovoltaic (PV) energy is one of the potential sources of renewable energy, which receives more preference due to its availability, simplicity, less maintenance and reliability options [5,6]. Inverters are a category of power electronics that convert the constant or minimally varying direct current (DC) voltage output of the photovoltaic panels into a usable sinusoidal alternating current (AC) power that are transmitted via the national grid system [7]. Due to relatively high cost compared to conventional fossil energy sources such as oil, gas, coal, nuclear, hydro, and wind, a large number of PV systems are not connected to the grid in the past. Power electronics based inverters have been proven to be the best suited technology for putting PV systems into the grid. In the past, the price of the PV modules was the major contribution to the cost of these systems. Due to a massive increase in the production capacity, especially with China taking the lead in PV module manufacturing technology, the price for the PV modules are shown to be the downward tendency. Therefore, the cost of the grid-connected inverter is becoming more visible in the total price of the system. Therefore, the cost reduction per inverter watt is important to make PV generated power more attractive [8]. As a result, focus has been shifted to design of simple, cost effective and innovative inverters.

In PV system there needs to be a conversion of the solar energy into electrical one through PV arrays using inverter circuit. In conventional inverters, step-up transformers of forward, push-pull, or fly back type were used to convert unregulated voltage of the PV cells into regulated voltage for the inverter input [9–11]. The main drawback of using a transformer is that it is heavy, bulky, costly and it suffers from very high Total Harmonic Distortion (THD). That is why research on transformer-less inverter technology using solid state electronics has become paramount [12,13]. PV systems basically performs two core tasks: 1) extracting maximum energy from PV arrays, 2) using the most dependable, robust, efficient, and economic configuration for the power converter that injects only active current into the grid. Grid injections should consist of pure sinusoidal current that is in phase with the grid voltage [9]. Grid-connected PV system configurations can be designed using various methodologies, including the centralized module architecture, the AC module architecture, and the modular architecture that fits perfectly with an intelligent PV module concept [5].

This paper compares six different transformers-less inverters using buck-boost topology, evaluating them against demands, lifetime, efficiency, and cost, and points out the best candidates for either single PV module or multiple PV module applications. These grid-connected single phase inverters can be classified as single-stage [14] and two-stage [15], or three switch mode [18] and single switch mode [19] configurations. Furthermore, the inverter can utilize a separate buck and boost stage, or just have the boost stage with a voltage divider circuitry replacing the buck stage [16], or a combined buck-boost stage [17] to reduce number electronic components in the inverter. Such inverter systems have DC-DC coupling or DC-AC-DC coupling converters to achieve a raised DC voltage before inversion.

2. Design specifications of PV module

At first, under Standard Test Condition (STC) Sanyo HIP-210HKHA6 panel with a maximum output power of 2 kW is being tested. Table 1 shows the system parameters of photovoltaic module. At STC condition of 25-degree temperature and irradiance of 1000 W/m^2 the panel is stimulated, the output voltage of which is found to be 24 V as shown in Fig. 1.

3. Grid synchronization

The design of a grid-tie inverter (GTI) varies slightly from the design of a traditional stand-alone inverter. The GTI's output is required to meet two main criteria before the inverter can be connected to the grid.

Table 1
System parameters of PV module [16].

Parameter	Value
Manufacturer	Sanyo
Solar panel model	HIP-210HKHA6
Short circuit current (I_x)	5.57 A
Open circuit voltage (V_x)	30.9 V
Maximum power (P_{max})	160 W
Characteristic constant (b)	0.0773
Number of cells	100

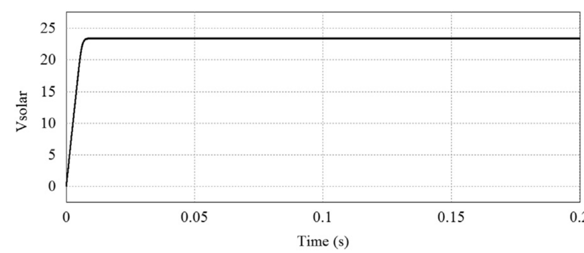

Fig. 1. PV module voltage [16].

- The magnitude and phase of inverter output must be same as grid.
- The frequency of the inverter output must match with the grid frequency.

The real and reactive powers extracted from the solar panel are given by,

$$P = \frac{|V_{inv}||V_{grid}|}{z_t} sin\phi. \tag{1}$$

$$Q = \frac{|V^2{}_{inv}|}{z_t} - \frac{|V_{inv}||V_{grid}|}{z_t} cos\phi. \tag{2}$$

Where, z_t=linking line impedance, V_{inv}=output voltage of inverter, V_{grid}=grid power voltage, ϕ=angle different between V_{inv} and V_{grid}. From (1), it is apparent that the phase angle (ϕ) must be 90° to send maximum real power to the grid. Practically, for stability reasons, the phase angle should be kept less than 90°.

4. PV inverter topologies

There are four inverter topologies those can be used to connect multiple PV modules, and each comes with their own advantages and disadvantages.

4.1. Centralized inverters

In the past, inverter's technology was based on centralized topology where a large number of PV modules are interfaced to the grid [20]. In this topology, the connectivity of PV modules is divided into series, called a string, so that each string can generate sufficiently high voltage and can avoid amplification. These strings were then connected in parallel, called a group, through diodes, to attain a sufficiently high power levels. This inverter topology provides large current harmonics and poor power quality since the the grid-connected stage is usually line commutated by means of thyristors. Some other sever limitations of this centralized inverter topology, such as power losses due to a centralized MPPT, HVDC cables needed between the PV modules and the inverter, losses between the PV modules due to mismatch, losses in the string diodes, and a non-flexible design prevent it from the benefits of mass production (Fig. 2).