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Comprehensive overview of grid interfaced solar photovoltaic systems

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A B S T R A C T

Grid-connected solar photovoltaic (PV) systems are increasingly attracting the attention of industry and academia mainly motivated by potential to provide an alternative to the conventional fossil fuel generation. This helps to meet out the increasing energy demands and to limit the pollution of environment caused by fossil emissions. This paper presents a comprehensive overview of the grid-connected solar PV systems. The intention of this review is to provide a wide spectrum on architecture of grid-connected solar PV system and its constituent components such as solar cell, PV array, maximum power point tracking, filters, DC-DC converters, single-phase inverters, and three-phase inverters to the researchers, designers, and engineers working on solar energy and its integration into the utility grid. Brief overview of control techniques for the single and three-phase inverters has also been presented. More than 100 research publications on the topologies, configurations, and control techniques of grid-connected solar PV systems and their major constituent components have been thoroughly reviewed and classified for quick reference.

1. Introduction

Renewable energy (RE) sources are very good solution to provide alternative energy to overcome the global energy problem. Further, the development in grid integration technologies, for these resources during the last decade, has increased the use of RE sources [1]. Solar photovoltaic (PV) system has become a promising RE source due to its capability of generating electricity in a very clean, quiet, and reliable way. The PV systems are solar energy supply systems, which either supply power directly to an electrical gazette in its stand alone mode or feed energy into the utility electricity grid in its grid-connected mode [2]. As the cost of PV panels production is continuously decreasing due to advances in the material and PV array fabrication technology, it is expected that the solar bulk power generation will be competitive with other forms of RE sources [3]. However, solar power generation has the problem of low conversion efficiency of the solar cells, and the output power of PV array is dependent on irradiation and temperature. Therefore, maximum power point tracking (MPPT) circuitry should be used for utilization of the PV array at full efficiency [4].

The solar PV systems have relatively low voltage output characteristics and demand high step-up voltage gain for grid integration. This is achieved by the use of high efficiency DC-DC converters for such practical applications [5]. These converters are able to interface different level inputs and combine their advantages to feed the different level of outputs for solar PV applications [6]. The inverter converts DC power to AC power through a solid state switching action used to feed energy generated by a PV generator into the utility grid. High efficiency of these converters is a major requirement [7]. The solution to control the power injected into the grid are essential for effectiveness of the system. In the real and reactive power control system, the real power output reference is a function of the incident solar irradiance and the temperature of the pn diode junction. The reactive power output reference is selected based on the system rating and adopted voltage regulation scheme [8].

This paper aims at presenting a comprehensive overview on the topic of grid-connected solar PV systems. Over 100 research publications [1–133] are critically reviewed and classified broadly into six categories. The first category [1–8] is based on general concepts of grid-connected solar PV systems. The second category [9–34] is on architecture of grid-connected solar PV system, which is sub classified into solar cell [11–17], PV array [18–23], MPPT [24–30], and filters [31–34]. Third category [35–56] includes DC-DC converters which is further sub classified into buck [41–43], boost [44–51], buck-boost [52,53], and cuk [54–56] converters. Fourth category [57–116] is on inverters used for grid integration of solar PV systems which is further sub classified in to structure topologies [61–65], single-phase [66–102] and three-phase [103–116] inverters. The fifth category [117–128] includes the control techniques for the grid-connected PV inverters. The sixth and final category [129–133] is related to the overall performance and cost estimation of grid connected solar PV systems. However, some publications include more than one category and have been classified based on their dominant field.

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This paper is divided into seven sections. Starting with an introduction in Sections 1, 2 covers the basic architecture of grid-connected solar PV system, solar cell, PV array, MPPT, and filters. The DC-DC converters such as buck, boost, buck-boost, and cuk used for the grid-connected solar PV applications have been demonstrated under the Section 3. The single and three-phase inverter topologies used for the grid-connected solar PV applications are presented in Section 4. Section 5 relates to the control techniques of single and three-phase inverters. The overall performance of solar PV system, cost estimation and future scope are detailed in the Section 6. Finally, the conclusions are drawn in the Section 7.

2. Grid-connected photovoltaic system

Grid-connected solar PV (GCPV) systems include building integrated PV (BIPV) systems and terrestrial PV (TPV) systems. TPV systems include plants in desert, tide, and saline-alkali land [9]. The major elements of a grid-connected solar PV system are shown in Fig. 1. Analysis of optimal photovoltaic (PV) array and inverter sizes for a grid-connected PV system in Saudi Arabia is presented in [10]. The inverters and DC-DC converters are discussed in separate sections, whereas all other components are detailed in the following subsections..

2.1. Solar cell

Solar cell consists of a p-n junction fabricated in a thin layer of semiconductor like a p-n diode. Its operational characteristics are also same as p-n diode and depend on the solar radiations as well as surface temperature [11]. An electrical equivalent circuit of a solar cell can be represented by a single or double diode model [12]. Although the double-diode model is more accurate under certain operating conditions, the single diode equivalent model has simplicity with sufficient accuracy [13], and allows for the development of explicit models [14]. Single diode equivalent circuit with parallel and series resistances is shown in Fig. 2..

The relationship between output voltage (V) and output current (I) for the single-diode equivalent circuit of a solar cell can be described by the following relation [15,16]

$$I = I_{ph} - I_0\left\{\exp\left[\frac{q(V + IR_s)}{AkT}\right] - 1\right\} - \left(\frac{V + IR_s}{R_{sh}}\right) \tag{1}$$

where I_{ph} is the PV cell photo-current; I_0 is the PV cell saturation current; A is the curve fitting factor of a solar cell; R_{sh} is the PV cell shunt resistance; R_s is the PV cell series resistance; q is the electron charge (1.602×10^{-19} C); and k is the Boltzmann constant (1.38×10^{-23} J/K). An explicit double-diode modelling method based on Lambert W-function for solar cells and PV arrays with bypass diodes is proposed by the authors in [12]. Psarros et al. [14], presented single-diode model of solar PV cell with negative diode breakdown operation. Detailed survey on the solar PV cell characteristics and mathematical formulations is presented in [17].

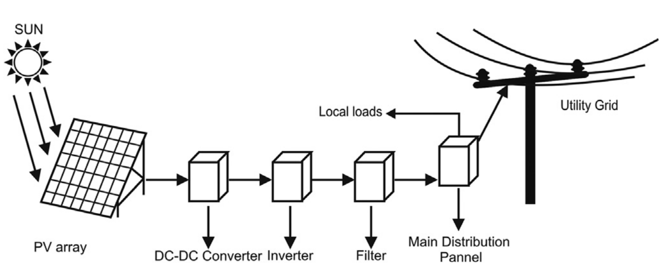

Fig. 1. Grid-connected solar PV system.

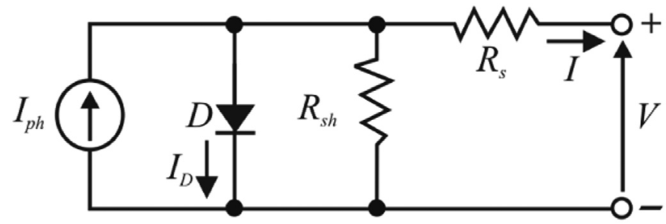

Fig. 2. Single-diode equivalent circuit of a solar cell.

2.2. PV array

The output power from a single PV cell is relatively small. The required voltage and power is produced by grouping the PV cells in series and parallel forming the modules. Modules are combined to form PV panels. These panels are connected together to build up the entire PV array and any desired current-voltage characteristics could be generated [18,19]. Different connection topologies of solar PV array are detailed in Fig. 3. These connection topologies of solar PV arrays have been utilized in both grid-connected BIPV and TPV systems. However, the PV inverter topologies may differ depending on the rooftop area available for the installation of BIPV systems. The grid connected large scale BIPV systems are gaining momentum due the introduction of net-metering concept by the utilities for the electricity users..

The value of R_{sh} can be assumed to be infinite at short circuit conditions, where slope of the I-V characteristics is almost zero [15]. In this case, I_{ph} is equal to the short circuit current (I_{sc}) and Eq. (1) for solar cell reduces to the following relation [11]

$$I = I_{sc} - I_0\left\{\exp\left[\frac{q(V + I.\ R_s)}{AkT}\right] - 1\right\} \tag{2}$$

For a PV array arranged in N_p parallel and N_s series connected solar cells, the Eq. (2) reduces to [17]

$$I = N_pI_{sc} - N_pI_0\left\{\exp\left[\frac{q(V + I(N_s/N_p)R_s)}{N_sAkT}\right] - 1\right\} \tag{3}$$

An extended model of a PV module based on single exponential representation of the PV cell taking into account the ground coupling effect, leakage inductive and stray capacitive parameters is proposed in [20]. All parameters of the proposed model are characterized on the basis of experimental results obtained in real conditions. Castellano et al. [21], proposed a shading model that optimizes the minimization of distance between the rows of fixed photovoltaic panels. Proposed method is based on the exact calculation of shadows of panels for different positions of the sun. The shadow depends on the latitude of facility, throughout course of the day and for all planned hours of the solar gain. Effects of vortex shedding in arrays of long inclined flat plates and ramifications for ground mounted photovoltaic arrays is presented in [22]. Importance of cleaning concentrated photovoltaic arrays, in a desert environment, is presented by the authors in [23].

2.3. Maximum power point tracking

The basic principle of maximum power point tracking (MPPT) algorithm depends on the exploitation of voltage and current variations caused due to pulsations of instantaneous power. Analysing these variations allows us to obtain power gradient and evaluate, if the solar PV system operates close to the maximum power point [24]. The maximum power delivered by the solar PV array is given by the relation

$$P_{max} = V_{mpp}I_{mpp} \tag{4}$$

where V_{mpp} and I_{mpp} are respectively the optimal operating voltage and current of PV array at the condition of maximum power output. The solar cell exhibits non-linear V-I characteristics, therefore a MPPT