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Modeling and simulation of grid-connected photovoltaic energy conversion systems

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ABSTRACT

Solar power generation using PV (photovoltaic) technology is a key but still evolving technology with the fastest growing renewable-based market worldwide in the last decade. In this sector with tremendous potential for energy security and economic development, grid-connected PV systems are becoming today the most important application of solar PV generation. Based on this trend, PV system designers require an accurate and reliable tool in order to predict the dynamic performance of grid-tied PV systems at any operating conditions. This will allow evaluating the impact of PV generation on the electricity grids. This paper presents a detailed characterization of the performance and dynamic behavior of a grid-connected PV energy conversion system. To this aim, a flexible and accurate PV simulation and evaluation tool (called PVSET 1.0) is developed. The PV system is modeled, simulated and validated under the MATLAB/Simulink environment. The accuracy of simulation results has been verified using a 250 Wp PV experimental set-up.

1. Introduction

The world constraint of fossil fuels reserves and the ever rising environmental pollution have impelled strongly during last decades the development of renewable energy sources (RES). The need of having available sustainable energy systems for replacing gradually conventional ones demands the improvement of structures of energy supply based mostly on clean and renewable resources. At present, solar photovoltaic (PV) generation is assuming increased importance as a RES application because of distinctive advantages such as simplicity of allocation, high dependability, absence of fuel cost, low maintenance and lack of noise and wear due to the absence of moving parts. Furthermore, the solar energy characterizes a clean, pollution-free and inexhaustible energy source. In addition to these factors are the declining cost and prices of solar modules, an increasing efficiency of solar cells, manufacturing-technology improvements and economies of scale [1].

The grid integration of RES applications based on photovoltaic systems is becoming today the most important application of PV systems, gaining interest over traditional stand-alone systems. This trend is being increased because of the many benefits of using RES in distributed (aka dispersed, embedded or decentralized) generation (DG) power systems. These advantages include the favorable incentives in many countries that impact straightforwardly on the commercial acceptance of grid-connected PV systems [2,3]. This condition imposes the necessity of having good quality designing tools in order to predict the dynamic performance of grid-tied PV systems at any operating conditions. This implies not only to

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identify the current–voltage (I–V) characteristics of PV modules or arrays but also the dynamic performance of the power conditioning system (PCS) required to convert the energy produced into useful electricity and to provide requirements for power grid interconnection. This will allow evaluating accurately the impact of PV generation on the electricity grids.

This paper presents a detailed characterization of the performance and dynamic behavior of a grid-connected PV energy conversion system. The model of the PV array proposed uses theoretical and empirical equations together with data provided by the manufacturer, and meteorological data (solar radiation and cell temperature among others) in order to precisely predict the I–V curve. The PCS developed in this work utilizes a two-stage energy conversion system topology that meets all the requirements of high quality electric power, flexibility and reliability imposed for applications of modern distributed energy resources (DERs) [4]. To this aim, a flexible and accurate PV simulation and evaluation tool (called PVSET 1.0) is developed. The PV system is modeled, simulated and validated under the MATLAB/Simulink environment [5]. This environment allows design engineers taking advantage of the capabilities for control design and electric power systems modeling already built-up in specialized toolboxes and blocksets of MATLAB, and in dedicated block libraries of Simulink. These features allows assessing the dynamic performance of detailed models of grid-connected PV systems used as DER, including power electronics devices and advanced control techniques for active power generation using maximum power point tracking (MPPT) and for reactive power compensation of the electric grid. The proposed models have been validated against data obtained from a 250 Wp grid-connected PV experimental set-up installed at the Renewable Energies Laboratory (SEPEA) of the IEE/UNSJ.

2. Model of the grid-connected PV system

2.1. *Solar photovoltaic module/array*

The building block of the PV array is the solar cell, which is basically a p–n semiconductor junction that directly converts solar radiation into DC current using the photovoltaic effect. PV cells are grouped together in larger units known as PV modules or arrays, which are combined in series and parallel to provide the desired output voltage and current. The well-known equivalent circuit of solar cells arranged in N_P-parallel and N_S-series is shown in Fig. 1. It is composed of a light-generated current source, a diode representing the nonlinear impedance of the p–n junction, and series and parallel intrinsic resistances. The mathematical model that predicts the power production of the PV generator becomes an algebraically simply model, being the current–voltage relationship defined in Eq. (1) [6,7]

$$I_A = N_P I_{Ph} - N_P I_{RS}\left\{\exp\left[\frac{q}{AkT_C}\left(\frac{V_A}{N_S}+\frac{I_A R_S}{N_P}\right)\right]-1\right\} - \frac{N_P}{R_P}\left(\frac{V_A}{N_S}+\frac{I_A R_S}{N_P}\right) \quad (1)$$

where:

I_A: PV array output current
V_A: PV array output voltage
I_{Ph}: Solar cell photocurrent

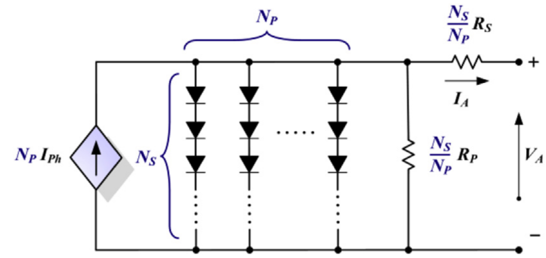

Fig. 1 – Equivalent circuit of a PV array.

I_{RS}: Solar cell reverse saturation current (aka dark current)
q: Electron charge, 1.60217733e−19 Cb
A: P–N junction ideality factor, between 1 and 5
k: Boltzmann's constant, 1.380658e−23 J/K
T_C: Solar cell absolute operating temperature, K
R_S: Cell intrinsic series resistance
R_P: Cell intrinsic shunt or parallel resistance

The photocurrent I_{Ph} for any operating conditions of the PV array is assumed to be related to the photocurrent at standard test conditions (STC) as follows:

$$I_{Ph} = f_{AM_a} f_{IA}\left[I_{SC} + \alpha_{Isc}(T_C - T_R)\right]\frac{S}{S_R} \quad (2)$$

where:

f_{AM_a}: Absolute air mass function describing solar spectral influence on the photocurrent I_{Ph}
f_{IA}: Incidence angle function describing influence on the photocurrent I_{Ph}
I_{SC}: Cell short-circuit current at STC
α_{Isc}: Cell temperature coefficient of the short-circuit current, A/module/diff. temp. (K)
T_R: Solar cell absolute reference temperature at STC, K
S: Total solar radiation absorbed at the plane-of-array, W/m^2
S_R: Total solar reference radiation at STC, 1000 W/m^2

The absolute air mass function accounting for the solar spectral influence on the "effective" irradiance absorbed on the PV array surface is described through an empirically-determined polynomial function, as expressed in Eq. (3).

$$f_{AM_a} = \sum_{i=0}^{4} a_i (AM_a)^i = M_P \sum_{i=0}^{4} a_i (AM)^i \quad (3)$$

where:

a_0–a_4: Polynomial coefficients for fitting the absolute air mass function of the analyzed cell material
AM_a: Absolute air mass, corrected by pressure
AM: Atmospheric optical air mass
M_P: Pressure modifier

An algorithm for computing the solar incidence angle (IA) for both fixed and solar-tracking modules has been documented in Ref. [7]. In the same way, the optical influence of the PV module surface, typically glass, was empirically described

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