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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]

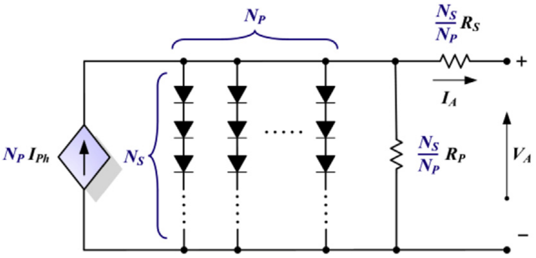


Fig. 1 – Equivalent circuit of a PV array.

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

where:

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

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

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).

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

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 through the incidence angle function as shown in Eq. (4) for different incident angle θ_I (in degrees).

$$f_{IA} = 1 - \sum_{i=1}^{5} b_i(\theta_I)^i \tag{4}$$

being b_1–b_5 the polynomial coefficients for fitting the incidence angle function of the analyzed PV cell material.

The solar cell reverse saturation current I_{RS} varies with temperature according to the following equation:

$$I_{RS} = I_{RR}\left[\frac{T_C}{T_R}\right]^3 \exp\left[\frac{qE_G}{Ak}\left(\frac{1}{T_R} - \frac{1}{T_C}\right)\right] \tag{5}$$

where:

I_{RR}: Solar cell reverse saturation current at STC
E_G: Energy band-gap of the PV cell semiconductor at absolute temperature, T_C

As can be clearly derived from the mathematical model described by Eq. (1) through (5), the PV array exhibits highly nonlinear radiation and temperature-dependent I–V and P–V characteristic curves.

2.2. *Power conditioning system*

The main purpose of a grid-connected solar PV energy conversion system is to transfer the maximum power obtained from the sun into the electric grid. This goal imposes the necessity of being constantly operating the PV system near the maximum power independently of the climatic conditions; therefore the use of an appropriate electronic interface with maximum power point tracking (MPPT) capabilities and the ability of effectively connecting to the AC power grid is required. The power conditioning system (PCS) is the electronic device that permits to achieve this objective, by successfully controlling the active power flow exchanged with the electric distribution system. Even more, with the appropriate PCS topology and its control design, the PV array is capable of simultaneously and independently performing both instantaneous active and reactive power flow control, as presently required for grid connection of new distributed generation system applications. To this aim, a hardware configuration of two cascade stages is used, which offers an additional degree of freedom in the operation of the grid-connected solar PV system when compared with the single-stage configuration. Hence, by including the DC/DC boost converter between the PV array and the inverter linked to the electric grid, various control objectives are possible to be pursued simultaneously and independently of the PV array operation without changing the PCS topology [8].

The detailed model of the proposed grid-connected solar PV system is illustrated in Fig. 2, and consists of the solar PV arrangement and its PCS to the electric utility grid. PV panels are electrically combined in series to form a string (and sometimes stacked in parallel) in order to provide the desired output power required for the DG application. The PV array is implemented using the aggregated model previously described in Eq. (1), by directly computing the total internal resistances, non-linear integrated characteristic and total generated solar cell photocurrent according to the series and parallel contribution of each parameter. A three-phase DC/AC voltage source inverter (VSI) using IGBTs (Insulated Gate Bipolar Transistors) is employed for connecting to the grid. This three-phase static device is shunt-connected to the distribution network in the so-called point of common coupling (PCC) by means of a coupling transformer and the corresponding line sinusoidal filter. The output voltage control of this VSI can be efficiently performed using pulse width modulation (PWM) techniques.

3. Control strategy of the grid-connected PV system

The proposed control of the three-phase grid-connected solar PV system consists of a multi-level hierarchical structure designed in the synchronous-rotating d-q reference frame, as described in detail in Ref. [9]. The control is divided into an external, middle and internal level, each one having its own control objectives. The external level control has the goal of rapidly and simultaneously controlling the active and reactive power exchange between the PV system and the utility grid, through an active power control mode (APCM) and a voltage control mode (VCM), respectively.

The standard control block of major distributed energy resources is the VCM and consists of a voltage-droop

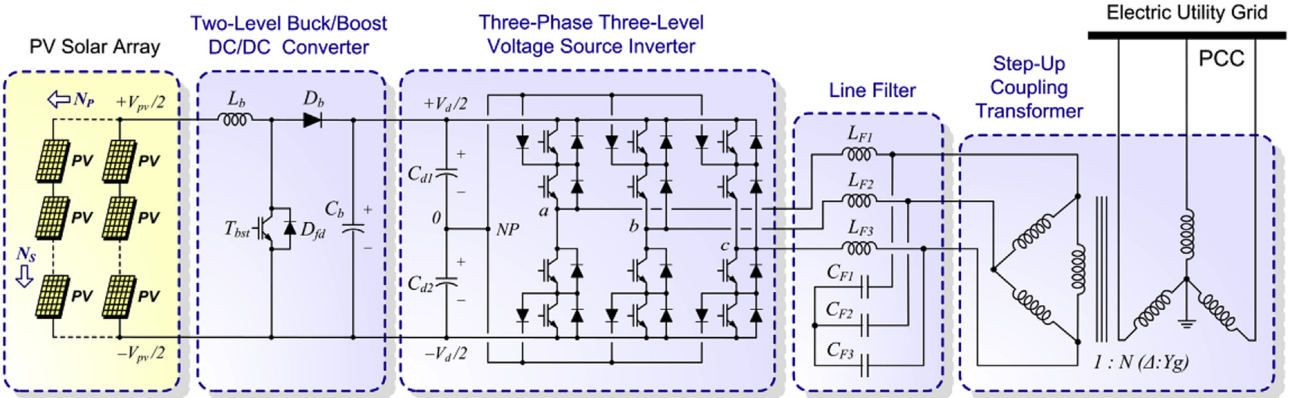


Fig. 2 – Full detailed model of the three-phase grid-connected solar photovoltaic system.

strategy used to modulate the reactive component of the VSI output current, aiming at controlling the voltage at the PCC of the PV system to the distribution grid. In fact, this reactive power is locally generated exclusively by the inverter and can be controlled simultaneously and independently of the active power provided by the PV array. On the other hand, the main purpose of a grid-tied PV system is to transfer the maximum available power into the electric system. In this way, the APCM aims at continuously matching the active power to be injected into the electric grid with the maximum instant power capable of being generated by PV modules, independently of the reactive power generated by the VCM. To this aim, the PCS and its controller must ensure the instantaneous energy balance among all the PV system components. With this objective, a maximum power point tracking (MPPT) approach is used. The MPPT strategy uses a simple structure and few measured variables for implementing an iterative method that permits matching the load to the output impedance of the PV array. This objective is fulfilled with a MPP tracker that employs a “Perturbation and Observation” (P&O) method for adjusting the DC/DC converter duty cycle. This method is widely used in commercial solar PV system applications with good results.

4. Overview of the PV simulation and evaluation tool (PVSET 1.0)

The grid-connected PV system is modeled, simulated and validated under the MATLAB/Simulink software environment and uses the SimPowerSystems (SPS), as depicted in Fig. 3. In this way, PV system designers have available an accurate and reliable tool in order to analyze the dynamic performance of grid-tied PV systems at any operating conditions, while being able to take advantage of the flexibility and capabilities for control design and electric power systems modeling already built-up in specialized toolboxes and block libraries of SPS. These features allow modeling grid-connected PV systems in detail, including their power electronics interfaces and advanced control techniques.

The MATLAB/Simulink model is highly efficient and has high performance with respect to the computational requirements and time to complete simulations. However, displaying variables of interest such as the generated power, output voltage and current of PV arrays and the operating temperature, among other major variables is not user-friendly, since some blocks dedicated to display these variables are at different hierarchical levels within the detailed model. In addition, the entry of variables for the various data bases, such as meteorological, geographical, PV modules, power electronic interfaces, control modules, among others, becomes confused and not very intuitive for users who are not familiar with the simulation model. For this reason, a software (called PVSET or PV Simulation and Evaluation Tool) with a graphical interface that relates the detailed model explained above with the common user has been developed. This software application is flexible, intuitive and easy-to-use in order to manage the input parameters and clearly observe how these changes affect the behavior of the PV system.

PVSET 1.0 aims at helping the understanding and mathematically predicting the behavior of PV systems and facilitates their design in a fast and simple way, without having a comprehensive knowledge of the model. The software application is developed using the graphical user interface (GUI) development environment (GUIDE) of MATLAB [5]. GUIDE is a visual programming environment provided by MATLAB in order to perform and execute simulation programs in a simply way with all the same basic features of visual programs such as Visual Basic or Visual C++.

Fig. 4 shows the graphical interface of the software developed with the visual tool GUIDE of MATLAB. The left side of the screenshot contains four panels with groups of buttons and text boxes each one in order to entry geographical data, astronomical data, environmental data and PV module parameters, respectively. All these data allow creating the database required for the model of Fig. 3. The panel for geographical data entry includes the longitude, latitude,

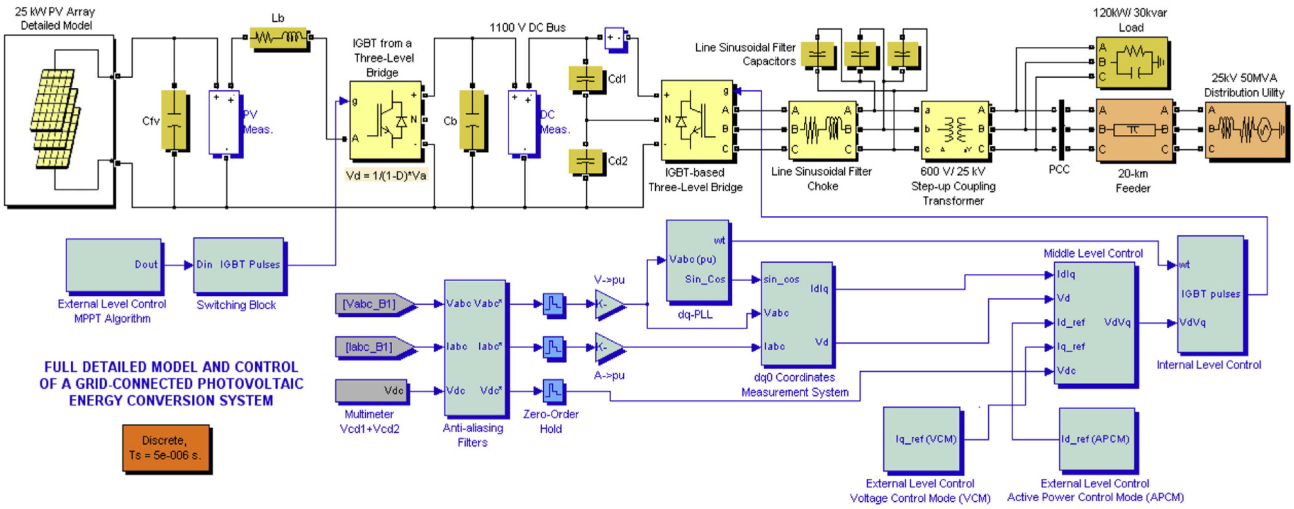
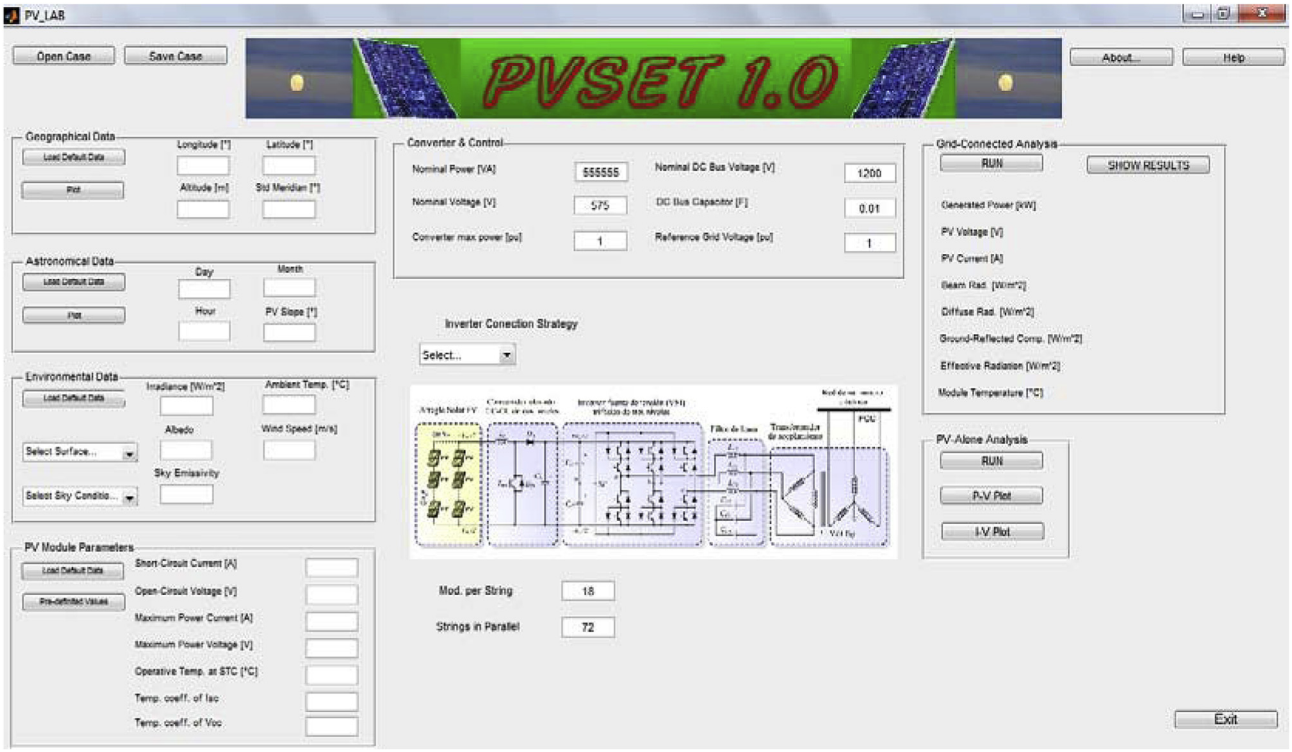


Fig. 3 – Detailed model and control scheme of the grid-connected solar PV system in the MATLAB/Simulink environment.



Nominal Power [VA] 555555
Nominal Voltage [V] 575
Converter max power [pu] 1
Nominal DC Bus Voltage [V] 1200
DC Bus Capacitor [F] 0.01
Reference Grid Voltage [pu] 1
Mod. per String 18
Strings in Parallel 72

Fig. 4 – Graphical interface of the software developed with GUIDE of MATLAB.

altitude and time zone of the PV system. The panel for astronomical data entry includes the day, month, hour and slope of the solar PV panels with respect to a horizontal flat surface. The panel for environmental data entry includes the irradiance, ambient temperature, wind speed, albedo and sky emissivity. The panel for the PV module parameters entry includes the characteristic values of the solar PV module, such as the short circuit current, open circuit voltage, maximum power point (MPP) current, MPP voltage, operating temperature of the module at standard test conditions (STC) and the temperature coefficients for the short circuit current and open circuit voltage.

5. Digital simulations results

In order to verify the accuracy of the results given by the computer software PVSET 1.0, and consequently to investigate the effectiveness of the proposed models and control algorithms of the three-phase grid-connected PV system, dynamic simulations have been performed. To this aim, the simulation of a 250 Wp (peak power) PV solar array has been compared with experimental data of a field implementation, composed of a string of 5 high-efficiency polycrystalline PV modules ($N_S = 5$, $N_P = 1$) of 50 Wp model Solartec KS50 (built with Kyocera cells). Fig. 5 depicts the I–V characteristic curve of the 250 W PV array for different climatic conditions, such as the level of solar radiation and the cell temperature. The characteristic curve at 25 °C and 200/600/1000 W/m^2 have been evaluated using simulations of the proposed model (blue solid line) with the software package developed and measurements obtained from the experimental set-up (blue dotted line). This proposed model of the PV array shows a very good agreement with measured data at all levels of solar radiation.

Fig. 6 presents a comparison of actual, measured and simulated output power trajectory within a 10-h period of analysis for a cloudy day with high fluctuations of solar radiation, for the proposed 250 W PV system with and without the implementation of the MPPT algorithm. The time data series shown in light blue solid line represents the actual maximum power available from the PV array for the specific climatic conditions, i.e. the MPP to be tracked at all times. Simulations

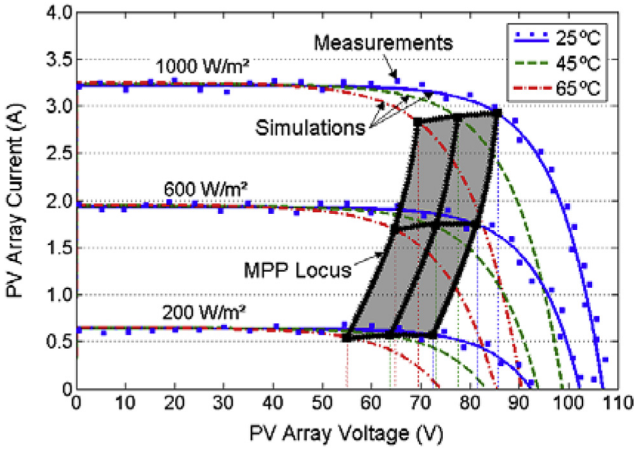


Fig. 5 – Simulated and measured I–V curve of a string of 5 Solartec KS50 PV modules for various climatic conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

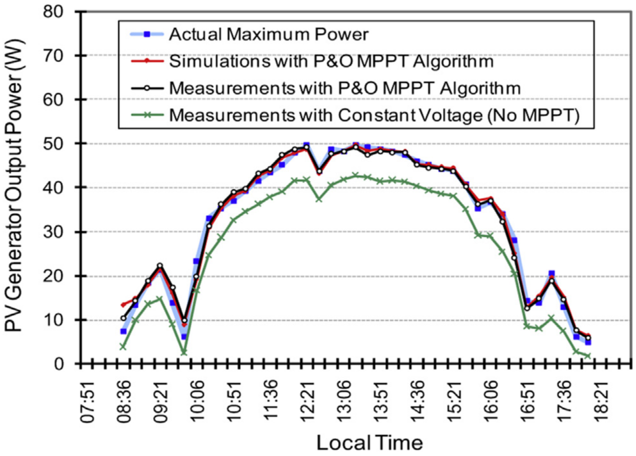


Fig. 6 – Comparison of actual, measured and simulated output power trajectory for the proposed 250 W PV system with and without the MPPT algorithm implementation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

obtained with the MPPT algorithm are shown in red solid lines. In the same way, the two time data series shown in black and green solid lines, respectively, represents the measurements obtained from the experimental setup with the control system with the MPPT activated (black) and with no MPPT (green). As can be observed, the MPPT algorithm follows accurately the maximum power that is proportional to the solar radiation and temperature variations. In this sense, it can be noted a very precise MPP tracking when soft variations in the solar radiation take place, while differing slightly when these variations are very fast and of a certain magnitude. It can be also derived from the results obtained that there is a good correlation between the experimental and the simulation data. In addition, the deactivation of the MPPT control results in a constant voltage operation of the PV array output at about 60 V for the given prototype conditions. In this last case, a significant reduction of the installation efficiency is obtained, which is worsen with the increase of the solar radiation. This preceding feature validates the use of an efficient MPPT scheme for maximum exploitation of the PV system.

6. Conclusion

A flexible and accurate PV simulation and evaluation tool called “PVSET 1.0” has been developed and presented in this work. A detailed mathematical model and a control scheme of a three-phase grid-connected PV system have been proposed. The proposed model of the PV array uses theoretical and empirical equations together with data provided by the manufacturer and meteorological in order to accurately predict the module characteristic curve. The control algorithms incorporate a maximum power point tracker (MPPT) for dynamic active power generation jointly with reactive power compensation of distribution utility system. The PV system is modeled, simulated and validated under the MATLAB/Simulink environment by using the PV simulation software developed using GUIDE. The digital simulation results obtained with this tool has been verified using a 250 Wp PV experimental set-up. The results demonstrate the accuracy of the proposed software and the effectiveness of the detailed models and control methodologies presented.

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