

A General Purpose Tool for Simulating the Behavior of PV Solar Cells, Modules and Arrays

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Abstract- This paper describes the detailed implementation of a novel tool for simulating the behavior of photovoltaic devices under variable weather conditions, in which the effect of irradiance, temperature and wind speed are considered. The tool also takes into account the effect of the thermal capacitance of photovoltaic dispositives and it is suitable to work on both long-term and transient simulations. The proposed method is easily implementable in most simulation programs. In order to achieve this, a circuit-oriented model based on electrical and thermal equations is carried out. Finally, the proposed methodology is examined by comparing simulations in SABER, PSpice and SIMULIK with experimental data.

Index Terms- Photovoltaic modules model, solar cells, effective solar irradiation, temperature, thermal capacitance, modeling, simulation software.

I. INTRODUCTION

Worldwide, the use of the alternative and the renewable energy sources has been growing in the last years to a reason of about 25 percent annual [1]. This growth has been driven due the following facts including a bigger interest in the energy security, interest in green technologies, the increment in the petroleum prices, among others [2]. Solar energy is the most common among the other types of renewable energy sources. In the last years, photovoltaic (PV) systems have been studied with a lot of attention due the fact of the rapid growth in semiconductor and power electronics technology and their reduction of cost for the generation of electricity as a clear energy source [3]. Also, for the optimal design of a PV system, computational analysis and simulation methodologies had played a key role in this process [4].

At present, simulation represents a very important and indispensable part of design processes for power electronics systems. It is vital to count with both adequate circuit-oriented simulation platform and accurate circuit models, in order to obtain the desired results. There are many simulation programs widely used in power electronic systems, PSpice and SABER are good examples. However, these programs, like others, currently has no library focused on PV modules (PVM). Hereby, it is necessary to implement an appropriate simulation tool in order to be able to analyze and study a complete PV power electronic conversion system in simulation [5].

This work presents the development of a powerful tool easily implementable in most simulation programs. The output of the simulation model is the I-V characteristic corresponding to the load connected to it and the

environmental conditions, which are, solar irradiance, cells temperature and wind speed. The proposed tool can represents PV cells, modules and arrays of any technology. Furthermore, a methodology to estimate the thermal constant of a PVM is presented and validate experimentally.

The paper is divided in five sections as described in the next lines. Section II reviews existing simulation methods. Section III describes the models used to represent the electrical and the thermal behavior of photovoltaic devices, as well as the thermal capacitance model proposed in this work and the method to obtain it. Section IV gives a detailed explanation of the implementation process. Finally, section V presents simulated and experimental results.

II. EXISTING METHODS

Most methods presented in literature are based on physical models of solar panels such as a single-diode model and a double-diode model [5-9], and not all of them consider effective irradiation and temperature as dynamical inputs [5-7]. Some of these simulation models use many constants which are computed by means of complex and rigorous computational algorithms. In addition, they commonly use idealization factors, which result in modeling inaccuracy [10]. Furthermore, these models required several parameters that are not provided by the manufacturer, so it is necessary to calculate them by iteration, using experimental data. These methods also have the disadvantage that they do not consider the direct effect of the irradiance, wind speed and the ambient temperature over the PVMs temperature, neither its thermal dynamic. This last one is very important due to the fact that the power produced by PVM is considerably affected by its operating temperature [11]. However, the temperature does not change instantly like is assumed in the methods described above, instead it behavior is very close to the respond of a first order system.

To our knowledge, there are no papers presenting a circuit-oriented simulation method based on the electric model proposed by [12-13] and the thermal model presented by [14]. In the next section this models are presented and discussed.

III. MATHEMATICAL MODELS

The solar cell is the most fundamental PV component. Basically, it consists of a p-n union of some semiconductor material. Solar cells are combined in serial or in serial-parallel configurations to form solar modules, and modules are combined to form arrays. The following subsections will

describe the proposed model considering the electrical and thermal effect in the PVM behavior. The proposed model has the advantage that can represent any type of PVM.

A. PVM Electric Model

The proposed method is based on the electric PVM model offered in [11-12], where it considers the current, voltage, irradiance level, and temperature of a PVM. The model is described by (1) to (3). This PV model only needs six parameters (which are provided by the manufacturer data sheet), the numbers of in series and in parallels modules with the same electrical characteristics (s and p respectively) and the characteristic constant b of the PVM. The constant b is the only one that need be computed and it can be calculated using an algorithm based on the Fixed Point Theorem. The algorithm is given by (4) and the variable ξ is the maximum permitted error where a good choice could be in the order of 10^{-7} .

The variables I and V represents the PVM output current and voltage respectively. I_{sc} and V_{oc} are short-circuit current and open-circuit voltage at 1000 W/m^2 and 25°C . V_{max} is the open-circuit voltage at 25°C and more than $1,200 \text{ W/m}^2$. V_{min} is the open-circuit voltage at 25°C and less than $1,200 \text{ W/m}^2$. V_{op} is the optimal voltage. T is the solar panel temperature in $^\circ\text{C}$. E_i is the effective solar irradiation (ESI) in W/m^2 . T_N is 25°C and the nominal ESI E_{iN} , is 1000 W/m^2 . TC_i is the temperature coefficient of I_{sc} in $\text{A}/^\circ\text{C}$. TCV is the temperature coefficient of V_{oc} in $\text{V}/^\circ\text{C}$.

The electric dynamic of the PVM is modeled by the differential equation given by (5), where Cx is the PVM internal capacitance. Fig. 1 shows a schematic of a PVM including the internal capacitance connected to a load.

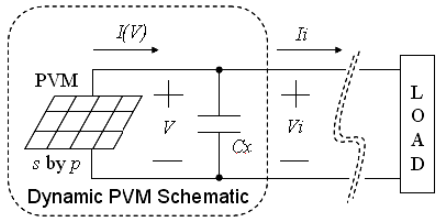


Figure 1. Schematic for a dynamic PVM model including the internal capacitance Cx .

$$I(V) = \frac{Ix}{1 - \exp\left(\frac{-1}{b}\right)} \cdot \left[1 - \exp\left(\frac{V}{b \cdot Vx} - \frac{1}{b}\right)\right] \quad (1)$$

$$Ix = p \cdot \frac{E_i}{E_{iN}} \cdot [I_{sc} + TC_i \cdot (T - T_N)] \quad (2)$$

$$Vx = s \cdot \frac{E_i}{E_{iN}} \cdot TCV \cdot (T - T_N) + s \cdot V_{max} - s(V_{max} - V_{min}) \exp\left(\frac{E_i}{E_{iN}} \ln\left(\frac{V_{max} - V_{op}}{V_{max} - V_{min}}\right)\right) \quad (3)$$

$$\text{while } |b_{n+1} - b_n| > \xi$$

$$b_{n+1} = \frac{V_{op} - V_{oc}}{V_{oc} \cdot \ln\left[1 - \frac{I_{op}}{I_{sc}} \cdot \left(1 - \exp\left(\frac{1}{b_n}\right)\right)\right]} \quad (4)$$

$$\frac{\partial V}{\partial t} = \frac{1}{Cx} \cdot [I(V) - Ii] = \frac{Ix}{Cx} \cdot \frac{\left[1 - \exp\left(\frac{V}{b \cdot Vx} - \frac{1}{b}\right)\right]}{1 - \exp\left(\frac{-1}{b}\right)} - \frac{Ii}{Cx} \quad (5)$$

B. PVM Thermal Model

The simple empirical-based model presented in [14] describes the effect of the solar irradiance, the wind speed and the ambient temperature over the steady-state temperature of a PVM, T_{ss} . The model is represented by (6) and (7). Here T_b is the back-surface module temperature in $^\circ\text{C}$, E_i is the effective irradiance, T_a is the ambient temperature, W_s is the wind speed in m/s . c is the empirically-determined coefficient establishing the rate at which module temperature drops as wind speed increases and a is the empirical-determined coefficient establishing the upper limit for module temperature at low wind speeds and high solar irradiance. ΔT is the temperature difference between the cell and the module back surface at an irradiance level of 1000 W/m^2 . This value depends on the PVM mounting. Some empirical-determined coefficients found to be representative of different module types and mounting are showed in Table I. These cases can be considered general for typical flat-plate PVMs from different technologies and fabricants. Wind speed was measured at the standard meteorological height of 10 meters [14].

$$T_b = E_i \cdot e^{a+c \cdot W_s} + T_a \quad (6)$$

$$T_{ss} = T_b + \frac{E_i}{E_{iN}} \cdot \Delta T \quad (7)$$

C. PVM Thermal Capacitance Model

Here, the authors propose to approximate the PVM temperature dynamics as a first order system with thermal time constant $\tau = 1/k$, which is expressed by (8).

$$\frac{dT}{dt} = -k(T - T_{ss}) \quad (8)$$

TABLE I
EMPIRICALLY DETERMINED COEFFICIENTS USED TO PREDICT MODULE BACK SURFACE TEMPERATURE

PVM Type	Mount	a	c	ΔT
Glass/cell/glass	Open rack	-3.47	-0.0594	3
Glass/cell/glass	Close roof mount	-2.98	-0.0471	1
Glass/cell/polymer sheet	Open rack	-3.56	-0.0750	3
Glass/cell/polymer sheet	Insulated back	-2.81	-0.0455	0
Polymer/thin-film-steel	Open rack	-3.58	-0.113	3

T is the instantaneous temperature of the PVM's cells in °C. This is the temperature to be used in the electrical model described before. T_{ss} is the steady-estate temperature given by (7). Fig. 2 shows an overview of the proposed thermal experiment to estimate the value of τ . The PVM is heated up with a constant source of heat. In this case a lamp connected to a constant voltage source, until the temperature became a constant value. A data logger is used to record the temperature at constant time intervals. Later a linear regression method can be used to determine the value of k , and then τ .

IV. IMPLEMENTATION

Based on equations described previously, it results easy to implement the models in most simulation programs using their mathematical libraries, a controlled current source and a voltage sensor. In order to make comparisons, the proposed tool was implemented in SABER, PSPICE and SIMULINK.

In SABER, the models were developed using the existing blocks (graphical modeling) or the MAST language. In a similar way, for the implementation of the models in PSPICE, analog behavioral model (ABM) blocks were used. The implementation of the model in SIMULINK was very similar to the implementation in SABER and PSPICE. Blocks of mathematical functions were used to implement the equations. The general development process applied to create the block diagrams in the three softwares was as described below.

A. Defining parameters and inputs

Constant sources for each parameter of the PVM models are created, and the additional inputs for the environmental variables are defined. These variables are E_b , T_a and W_s . s and p are also defined as inputs in order to enable them to get different values during a simulation. This method can be useful when studying array reconfigurations such as in [15].

B. Building the equations

In order to get the variable T , equations (6), (7), and (8), are created using mathematical blocks and some of the constant sources and the defined inputs created previously. Then, in a similar way, (2) and (3) (I_x and V_x) are developed. Given I_x and V_x , the value of I is obtained creating (1) with some additional mathematical blocks. A current controlled source is used to convert the numeric value of I to a electric one, in this case to a current value. Since the value of I is a function of the output voltage, an ideal voltage sensor is used to sense V at the current controlled source output, then it is putted into (1). The effect of the internal capacitance C_x , given by (5), is implemented connecting a capacitor in parallel to the current controlled source output. As an example, Fig. 3 shows the block diagram developed in SABER

C. Development of a new component

In order to make the tool more user-friendly, the block diagram was saved as a new component. Fig. 4 shows the created component and its window properties. In this window, the parameters for a specific cell, PVM or an array are introduced. The terminals V_p and V_m of the new part are the positive and the negative output terminal for the component being modeled. S and P are the in series and in

parallels PVMs forming an array respectively. For example, in case that only one PVM is going to be modeled, a constant source with a value of 1 must be connected to the S and P inputs. For E_b , T_a and W_s , variable or constant sources can be used depending on the kind of analysis to be carried out.

V. RESULTS

This section presents simulated and experimental results for the PVMs showed by Table I-II [16]-[18]. Fig. 4 shows the result of the thermal capacitance experiment for a SX-10 module. It can be seen that the behavior of the temperature of the PVM is very similar to the response of a first order system, like the charge and the discharge of a capacitor. For a SX-10, the thermal time constant is around 810 s.

The first test for the proposed method was the comparison among simulated and measured values of voltage and current for two different PVMs. Figs. 5 and 6 show the experimental and simulated I-V curves for a SA-5 module at two different environmental conditions: a) $T = 55^\circ\text{C}$ and 1015W/m^2 at Mayaguez, Puerto Rico (Sept 10, 2007), and b) $T = 25^\circ\text{C}$ with irradiance at the maximum intensity light (1:30pm) at Lansing, Michigan (May 10, 2005). The test shows that the model implemented is quite accurate comparing between the measured and simulated data for the three softwares.

Fig. 7 presents another example. A PV array 2S-15 is linked to a voltage-controlled dc-dc converter (z-converter) in SABER. Fig. 8 shows the PV array and the converter output current. Fig. 9 shows the PV array and the converter output voltage. In order to prove the convergence of the simulation model under sudden changes, abrupt alterations by the ESI and the load were introduced during the simulation. First, at 8.5 ms the ESI changes from 1000W/m^2 to 700W/m^2 , and second, at 12 ms the load is increased 20%.

VI. CONCLUSIONS

In this paper, a general purpose simulation tool for describing the behavior of PV dispositives that could be implemented in most simulation programs has been validated. The method was developed in SABER, SIMULINK and PSPICE. Its suitability was validated by way of simulation and experimental results. The simulation results from the three softwares were very matched to the experimental data measured. In addition, a simple method to estimate the thermal capacitance constant was presented and validated.

The proposed tool has the following advantages: a) it takes in consideration the effect of the ESI, the ambient temperature and the wind speed over the PVM temperature, b) it takes in consideration the thermal capacitance of the PVM, and c) it is very easily to implement since it is based on non-complex mathematical models. All these characteristics make the propose method a convenient tool in the power systems area.

TABLE II
PVM SPECIFICATIONS

PVM	I_{sc}	V_{oc}	I_{op}	V_{op}	b
Solarex SA5	0.3A	25.0V	0.34A	15.0V	0.1390
Solarex SX5	0.3A	20.5V	0.27A	16.5V	0.0847
Solarex SX10	0.65A	21.0V	0.59A	16.8V	0.0839

TABLE III
PVM SPECIFICATIONS (CONT.)

PVM	TC_i	TC_V	V_{min}	V_{max}
Solarex SA5	0.3mA/°C	-60mV/°C	21.0V	25.500V
Solarex SX5	0.2mA/°C	-80mV/°C	17.43V	21.115V
Solarex SX10	0.2mA/°C	-80mV/°C	17.85V	21.630V

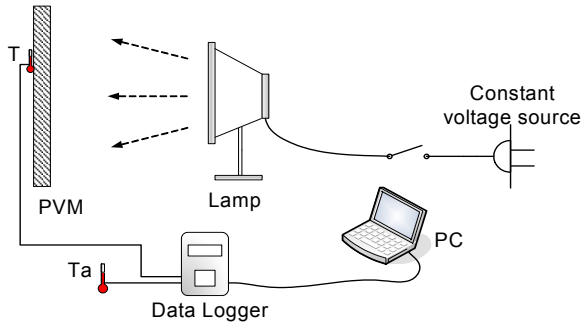


Figure 2. Overview of the proposed method to estimate the thermal constant of a PVM

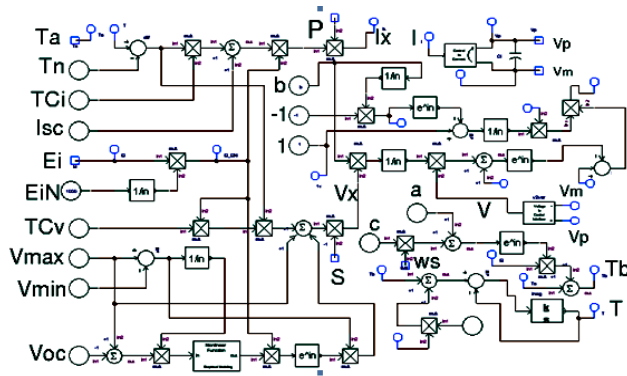


Figure 3. Block diagram implemented in SABER

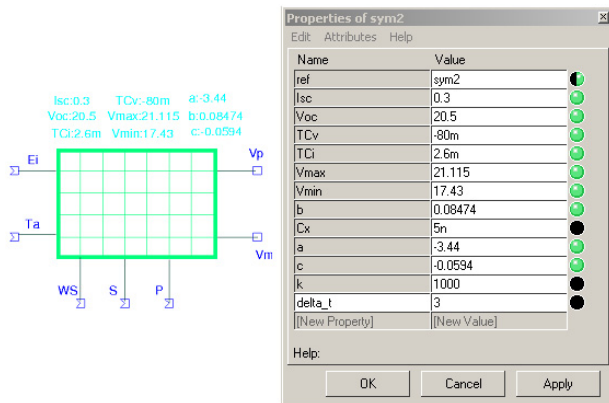


Figure 4. Part created in SABER and its window properties

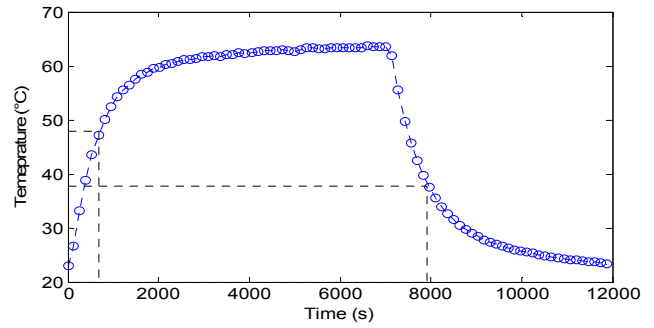


Figure 5. Time response of the temperature for a SX-10 PVM

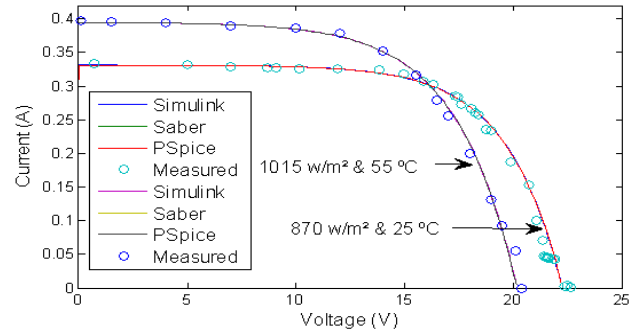


Figure 6. Simulated and experimental P-V curves for a SX-5 PVM.

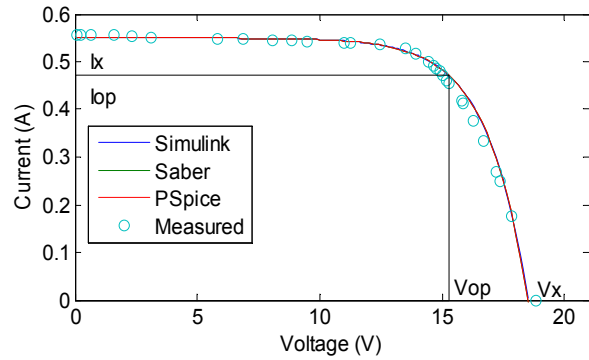


Figure 7. Simulated and experimental P-V curves for a SX-10 PVM.

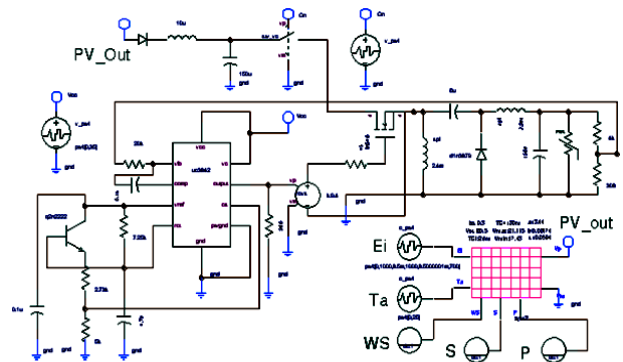


Figure 8. Z-Converter implemented in SABER.

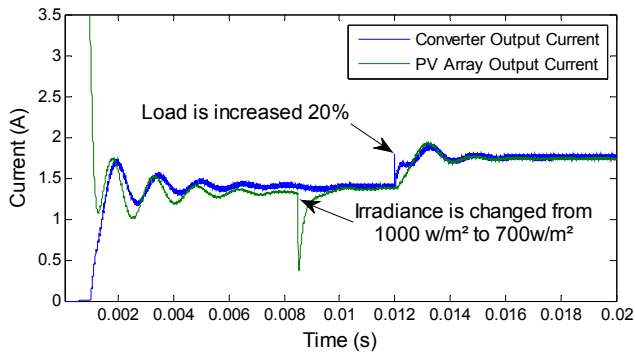


Fig. 9: PV array output current and converter output current.

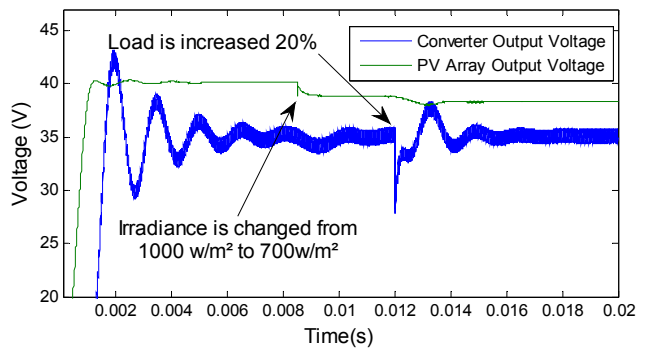


Figure 10. PVM array output voltage and converter output voltage.

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