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A Contribution of a Computer Tool Using ATP-EMTP TACS to the Modeling of a Photovoltaic (PV) Module

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Abstract. The access to electrical distribution systems with the use of solar photovoltaic's is becoming a viable alternative for the provision of generation through alternative sources of electricity. However, many studies of power quality and transient stability need to be made to meet the technical requirements of the network. Therefore, this article deals with the modeling of photovoltaic module in ATP-EMTP tool called TACS for future studies of the insertion of the PV system in medium and low voltage. To validate this model comparisons of the simulations with the data provided by the manufacturer, thus validating the developed model were performed.

Key words

ATP, distributed generation, modeling, PV module, grid connected PV system.

1. Introduction

With increasing global demand for energy, the need to further diversify the energy matrix and the relentless pursuit by the use of renewable and clean energy, there is the promotion of decentralized generation, connected directly in medium and low voltage. Thus arises the figure of distributed generators to assist in meeting the energy demand, with the primary objective of meeting loads next to them [1].

In this context, solar PV has emerged as an attractive alternative for the purposes of the supplementary generation in the electric system. Due to the continuous fall in the prices of modules and converters, coupled with government incentives, photovoltaics in many markets reached economic parity with other sources of energy, namely, photovoltaic electricity has been produced in even or lower price than conventional sources of electricity. Therefore, in many areas the use of solar energy presents itself as a technically and economically viable solution for urban uses of connected or isolated from the power authority electrical system [1, 2].

Brazil is in the early stage of this technology, but it has a huge potential, as photovoltaics competes with certain advantage compared to other renewable energy sources such as wind and hydropower, when referring to the possibility of expansion of electricity generation . As the country is blessed with high levels of solar radiation on its territory, the setup of solar photovoltaics can be taken in any region, unlike wind and hydroelectric energy.

One must recall the start of policies to encourage access of photovoltaics to low and medium voltage, by Normative Resolution 482/2012 of the National Electric Energy Agency (ANEEL), which were defined the characteristics of micro and mini-generation in distributed systems with respect to the national scenario[3]. Nevertheless Companhia Energetica de Minas Gerais (CEMIG) developed specific regulatory resolutions, ND-5.30 and ND-5.31, to establish the criteria for access to its electrical system.

Thus, it is possible to envisage the need to study what impacts and contributions may arise from the massive connection of Photovoltaic Systems Connected to the Network (SFCR) for the power quality, transient stability, planning and operation of electrical systems, to ensure excellence and reliability of distribution systems.

In this sense, the present paper aims to contribute to the modeling of photovoltaic modules, using the programming tool for the Alternative Transients Program (ATP) called Transient Analysis of Control Systems (TACS), and to validate the same results comparing simulated with values on the maker datasheet. For this, will be made a presentation of the components that make up a SFCR, subsequently will be presented the mathematical equations representing the module and then the computational results, making the substantiation of the results present in the module datasheet.

2. Composition of a typical SFCR

Installing a SFCR is basically composed of the PV module, voltage elevator converter (*boost converter*) and its control with tracking of the maximum power point (MPPT); inverter voltage with its integrated control with phase locked loop (PLL); and an coupling inductor. A simplified diagram is shown in Figure 1 [4].

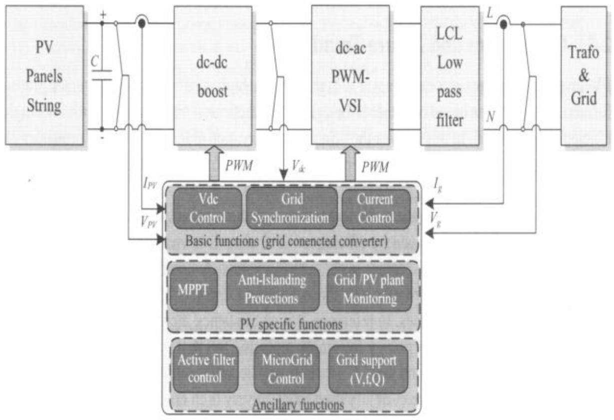

Fig. 1. Diagram os a SFCR.

The photovoltaic module is responsible for converting solar energy into electricity through the photovoltaic effect, which arises from the excitation of electrons in semiconductors in the presence of sunlight [4]. There are three main types of modules, the compounds of monocrystalline cells, polycrystalline and amorphous silicon. The most used types of modules are monocrystalline and polycrystalline, monocrystalline being the most efficient at converting solar energy into electrical energy, but have a more complex, rigorous and expensive construction[5].

The boost converter is responsible for extracting the maximum power available in the module, through the techniques of Maximum Power Point Tracking (MPPT). While the inverter is responsible for injecting the extracted power from the module into the grid, through a coupling inductor. This inductor have a current controller which ensures that the power injected into the network is following the required standards.

3. Modeling of a PV module

A photovoltaic cell that composes a photovoltaic module can be represented by an electric model, as shown in Figure 2. Equations, and this electrical model of the photovoltaic cell was taken from the references [4,6].

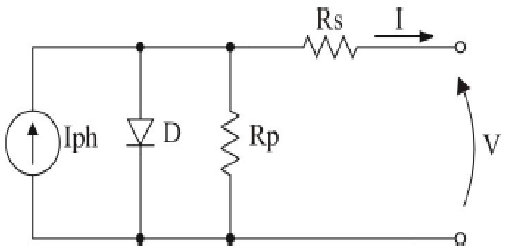

Fig. 2. PV cell electric equivalent circuit.

In Figure 2, I_{ph} is the photocurrent, the diode D is the p-n junction of the module material, the resistance R_p characterizes the leakage current occurring at the extremities of the solar cell, the resistance R_s is the voltage drop between the semiconductor material and the outer contact, V and I are respectively the voltage and current at the output terminals of the photovoltaic cell.

With the equationing of the above circuit, we get that the output current of the solar cell is given by equation (1).

$$I = I_{ph} - I_r . \left[e^{\left(\frac{q(V+I.R_S)}{n.k.T}\right)} - 1 \right] - \frac{V + I.R_S}{R_P} \qquad (1)$$

Where:

I_r - Cell reverse saturation current.
q - Elementary electron charge.
n - p-n junction quality factor.
k - Boltzmann constant.
T - Room temperature.

Photocurrent is given by equation (2).

$$I_{ph} = \left[I_{SC} + \alpha \left(T - T_{ref} \right) \right] . \frac{S}{S_{ref}} \qquad (2)$$

Where:

I_{sc} - Short circuit current pe cell.
α - I_{sc} current temperature coefficient.
T_{ref} - Reference temperature.
S - Intensity of solar irradiation of the environment.
S_{ref} - Intensity of solar irradiation of reference.

Saturation current is given by equation (3).

$$I_r = I_{rr} . \left(\frac{T}{T_{ref}} \right)^3 . e^{\left[\frac{q.E_g}{n.k} . \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right]} \qquad (3)$$

Where:

I_{rr} - Saturation current of reference.
E_g - The forbidden energy band.

The last equation is the saturation current of reference that is given by equation (4).

$$I_{rr} = \frac{I_{SC} - \frac{V_{OC}}{R_P}}{e^{\left(\frac{q.V_{OC}}{n.k.T_{ref}}\right)} - 1} \qquad (4)$$

Where:

V_{oc} - Open circuit voltage per cell.

Equation (1) can be modified to Equation (5) in order to present a null root when I become the actual current of the photovoltaic cell.

$$f(I) = I_{ph} - I - I_S \cdot \left[e^{\left(\frac{q(V+I.R_S)}{n.k.T}\right)} - 1 \right] - \frac{V + I.R_S}{R_P} \qquad (5)$$

The output current at the solar cell terminals with zero initial value, is used in an iterative process that approximates (5) from its root, using for this the Newton-Rhapson method. In mathematical form, the method is shown in (6), where *n* indicates the *nth* iteration of the algorithm, and $f'(x_n)$ the derivative of the function at x_n.

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \qquad (6)$$

Looking at equation (6) can be observed that is necessary to calculate the derivative of equation (5), which is shown in equation (7).

$$f'(I) = -1 - I_S \cdot \left[e^{\left(\frac{q(V+I.R_S)}{n.k.T}\right)} \cdot \left(\frac{q.R_S}{n.k.T}\right) \right] - \frac{R_S}{R_P} \qquad (7)$$

With the equations for the PV cell shown above, it is assumed that the photovoltaic module may be represented by a cell. Then, the photovoltaic module was modeled on TACS, given that this model have a lower data processing time when compared to the MODELS tool, because it has all the control functions predefined in a feasible environment for the realization of mathematical routines [7].

4. Simulation of the developed model and comparison with the manufacturer datasheet

The photovoltaic module chosen for data extraction and comparison of curves contained in its datasheet will be the Kyocera brand model KD135SX-UPU [8]. But it is noteworthy that the model programmed into ATP is generic, and could be compared with any brand of commercial photovoltaic panel.

It is well known that the resistance values of the module is function of temperature. That is, for each value of temperature resistance of the module will vary, thus changing the system response curves. At this point it becomes necessary to use specific numerical methods, such as the trust region method[9]. However, in this paper, as in [4], will be used a series resistance of 0.0085 Ω and a parallel resistance of 1000 Ω for all simulations, even with sudden changes in temperature.

The quality factor of the pn junction is 1.2 and the energy band is 1.1 eV [4, 6]. The constants used as input parameters are the electron charge that is $1.6\text{x}10^{-19}$ C and the Boltzmann constant that equals $1.38\text{x}10^{-23}$.

The parameters related to the model adopted will be the open circuit voltage, short circuit current and the current temperature coefficient, where their values are found in its datasheet, as shown in Figure 3.

■Electrical Perfomance under Standard Test Conditions (*STC)	
Maximum Power (Pmax)	135W (+5%/–5%)
Maximum Power Voltage (Vmpp)	17.7V
Maximum Power Current (Impp)	7.63A
Open Circuit Voltage (Voc)	22.1V
Short Circuit Current (Isc)	8.37A
Max System Voltage	600V
Temperature Coefficient of Voc	$-8.0\text{x}10^{-2}$ V/°C
Temperature Coefficient of Isc	$5.02\text{x}10^{-3}$ A/°C
*STC : Irradiance 1000W/m², AM1.5 spectrum, cell temperature 25°	

Fig. 3. Electrical specifications of the PV module.

Following will be made model simulations to the same conditions of the datasheet and values will be compared with each other for validation.

A. Constant Irradiance

The first simulation performed consists to keeping irradiance constant and equal to 1000 W/m² for different temperatures.

With these specifications datasheet provides its characteristic curves, shown in Figure 4.

Figure 5 shows the curves encountered by the model developed in this study, which curves in red, green and blue represent temperatures of 25°C, 50°C and 75°C respectively.

It is noticed that the curves of the datasheet and ATP model have the same behavior, but the values do not match indeed. This is because the resistors used does not fit to the sudden temperature change for this test, which makes necessary the execution of a specific algorithm for obtaining new values of resistance variations upon the temperature of the system [9].

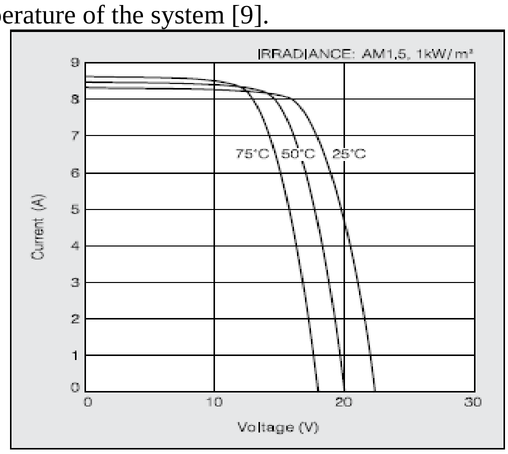

Fig. 4. Characteristic curves for constant irradiance in datasheet.

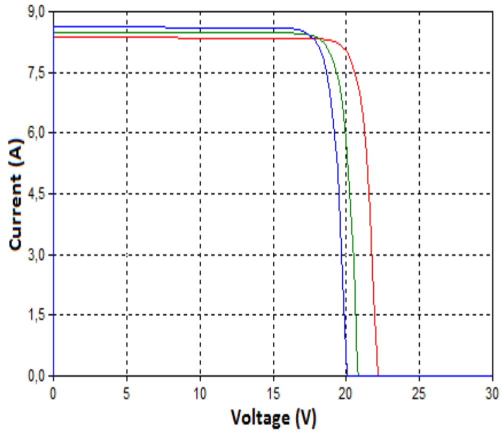

Fig. 5. Characteristic curves for constant irradiation model in ATP.

B. Constant Temperature

The second simulation shows constant temperature and equal to 25°C, but with variations in irradiance. Figure 6 shows the curves for the datasheet for this test.

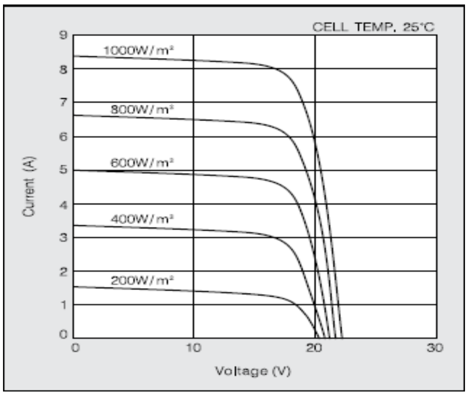

Fig. 6. Characteristic curves for constant temperature in datasheet.

For the same situation of Figure 6, Figure 7 shows the curves obtained by simulation of the model, where red, green, blue, pink and brown represent irradiance of 1000, 800, 600, 400 and 200 W/m^2, respectively.

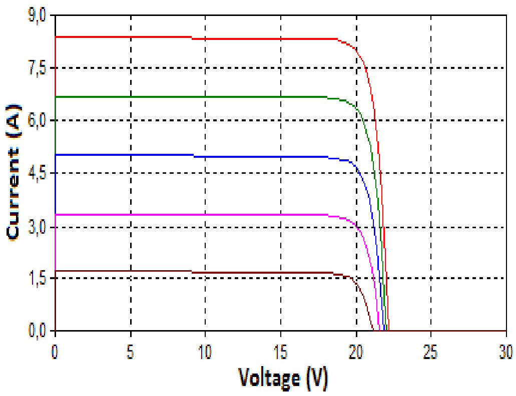

Fig. 7. Characteristic curves for constant temperature model in ATP.

The great similarity in the values and behavior of the curves is observed. In datasheet, as shown in Figure 3, which the manufacturer provides the short circuit current at 25°C and 1000 W/m^2, or voltage zero is equal to 8.37 A. In the computational model we obtain a short circuit current of 8.3699 A, that is, an error of only 0.0001 A.

Another value supplied in the datasheet for these conditions is the open circuit voltage, or current zero, which is equivalent to 22.1 V, in the ATP model is obtained a value of 22.1 V, no error is observed. It is noteworthy that at 25°C and 1000 W/m^2, the series and shunt resistance values are adequate.

C. Test Contained in Datasheet

For purposes of final validation of the module model, the last test is performed. In this case the ambient temperature is 47.9 °C and irradiance of 800 W/m^2, as shown in Figure 8, taken from the datasheet.

Electrical Performance at 800W/m², *NOCT, AM1.5	
Maximum Power (Pmax)	95W
Maximum Power Voltage (Vmpp)	15.7V
Maximum Power Current (Impp)	6.10A
Open Circuit Voltage (Voc)	20.0V
Short Circuit Current (Isc)	6.79A
*NOCT (Nominal Operating Cell Temperature) :47.9°C	

Fig. 8. Test contained in datasheet.

The open circuit voltage and short circuit current of the datasheet are worth respectively 20 V and 6.79 A, as reported in Figure 8.

For the simulated model the equivalent open-circuit voltage and short circuit current are 20,729 V and 6.7879 A, respectively. Thus the model has an error of only 0.729 V at open circuit voltage, and 0.0021 A in the short circuit current.

5. Visual model

In order to let the photovoltaic panel more accessible to users, were developed a computational visual tool. The Figure 9 shows the model developed in the ATPDraw.

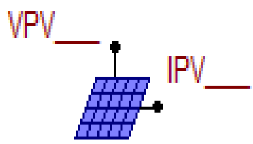

Fig. 9. Visual model.

Where nodes VPV___ and IPV___ are the voltage and current output from the photovoltaic panel, respectively. To configure the dashboard just double click on the template that opens a tab as shown in Figure 10.

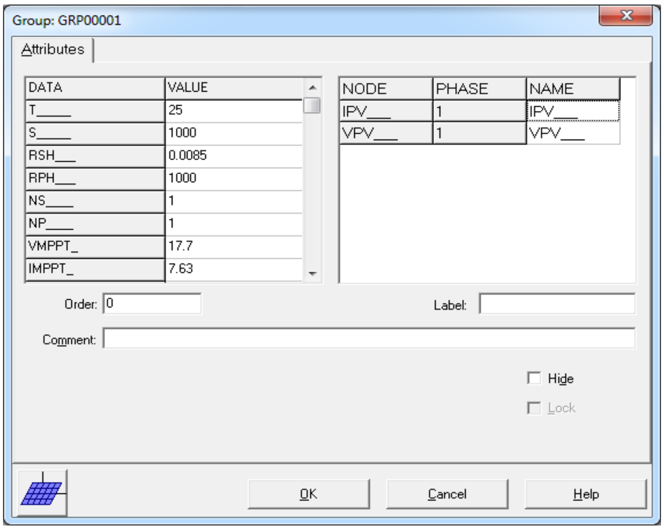

Fig. 10. The visual model configurations.

Where we have the following input parameters:

T_____ - Room temperature.

S_____ - Intensity of solar irradiation of the environment.

RSH___ - Series resistance of the panel.

RPH___ - Shunt resistance of the panel.

NS____ - Number of panels in series.

NP____ - Number of panels in parallel.

VMPPT_ - Maximum output voltage of the panel.

IMPPT_ - Maximum output current of the panel.

VOC___ - Open circuit voltage of the panel.

ISC___ - Short circuit current of the panel.

JO____ - Temperature coefficient of short circuit current.

TREF__ - Reference temperature.

SREF__ - Intensity of solar irradiation of reference.

Q_____ - Elementary electron charge.

K_____ - Boltzmann constant.

EG____ - The forbidden energy band.

N_____ - p-n junction quality factor.

6. Conclusion

According to the results it is observed that modeling responds faithfully to the data provided by the manufacturer's catalog, this fact shows that the computational tool used here, TACS, is adequate and effective when modeling systems, due to resources and processing speed when compared to MODELS in ATP-EMTP.

The tool found here will provide conducting further studies to clarify to the electric sector agents which impacts and benefits may arise from the insertion of this technology in electrical networks. To do so, will require the computational modeling of a complete SFCR. Thus, is in the final development phase the implementation of the boost converter and MPPT in ATP.

Note also that there is a large paradigm to be implemented with regard to the series and parallel resistance of the module, since both vary strongly with temperature. Thus, for future modeling of the module, it is suggested to make use of a model in which the resistance varies according to the values of the instantaneous temperature.

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