DYNAMICAL MODELING AND SIMULATION OF PV-SOLAR PANNELS

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Abstract. *This paper explores a dynamical model of the thermal and electrical behavior of solar photovoltaic module. A detailed heat transfer model is implemented, coupled to an electrical model that takes into account all effects of cell temperature dependence in the variables of a single diode equivalent circuit. Radiation and convection heat transfer are considered, as well as the effect of thermal inertia. Simulations for the unsteady power output are obtained for typical variations of irradiation (ramps and valleys) and other real climatic inputs. A comparison between the dynamical and steady state models is discussed and the main differences for the temperature and power levels have shown the framework of applicability of the proposed model.*

Keywords: *Dynamical model of PV-panels. Heat transfer in solar panel.*

1. INTRODUCTION

The dynamical behavior of the energy conversion in photovoltaic panels is related to the response of the PV cells to the temperature in the module surfaces, given unsteady environmental conditions. The efficiency of the cells is directly related to its temperature that is determined by the heat transfer model, where thermal radiation and convection has to be taken into account. The aim of the present paper is to explore a dynamical thermal model applied to the stand-alone solar panels. Fast changes in environmental conditions, in particular the irradiance levels, are considered.

The dynamical modeling of PV power systems has been explored on the last fifteen years when the applications on solar power plants has need more accuracy in the description of the thermal behavior of the panels. The estimate of the levels of the efficiency and the transient power variations dispatched to the inverters are important key points in the framework of modern system simulation of PV devices (King et al, 20014, Klise and Stein, 2009, Power Analytics, 2011, for instance).

Classically, the thermal problem had been formulated considering an equilibrium steady-state condition in the panel. An algebraic non-linear model for the cell temperature can be obtained by means of an energy balance, which considers the short wave incident radiation, emitted long wave radiation and air convective exchange (Duffie and Beckmann, 1991, Hansen et al., 2000).

More recently, thermal inertia effects have been considered to estimate the temperature of the modules (Jones and Underwood, 2001, Tasai and Tsai, 2012, Lobera and Valkealahti, 2013, Lim and Ye, 2014.). In a thermal point of view, the modules respond dynamically unsynchronized to the quick variations of incident radiation (cloud cover trailing). By consequence, the temperature issued from the classical model, using the steady-state approach that does not considers the thermal inertia, does not represent properly the conversion rate in several situations.

The use of the dynamical thermal model for the PV systems is justified by two main reasons: The first one is due to the importance of the unsteady system variations on time scales in order of seconds. This behavior is important to the inverters control strategy and efficiency and it can directly influence the quality of dispatched energy. The second important key point is related to the use of tracker systems and low concentrating devices. In those situations the variations of direct normal irradiance (DNI) is more influenced by the cloud cover which induces an important temperature variation. Again, for those situations, the dynamical behavior is very relevant.

The present paper is organized as follows: In the second part, the mathematical model for the electrical conversion and the heat transfer is presented. In the third part a discussion about the system response for typical ramp conditions for irradiance will be explored. On the last part, one presents the results associated to the real sunny and cloudy days, evaluating the present proposed model.

2. MATHEMATICAL MODEL FOR PV-PANELS

2.1 Electrical model

In the framework of the present paper, the conversion rate in PV module is modeled considering an equivalent circuit of an array of solar cells, using a single diode approach (Fig. 1). The equation of the for the I-V curve (Villalva et al., 2009, for instance) is classically expressed by:

$$I = I_{PV} - I_0\left[\exp\left(\frac{V+R_sI}{aV_T}\right)-1\right]-\frac{V+R_sI}{R_p} \tag{1}$$

In this equation I and V are the current and the voltage at the photovoltaic panel. I_{PV} and I_0 denote the photovoltaic and saturation currents, a (=1-1.5) is the equivalent diode ideality factor, R_s and R_p are the equivalent series and shunt resistances and V_T is the thermal voltage of the N_s cells connected in series that is given by:

$$V_T = \frac{N_S KT}{q} \tag{2}$$

With K=1.38065 × 10^{-23} J/K (Boltzmann constant) and q=1.60217646 × 10^{-19} C (electron charge). In this equation the temperature has to be expressed in Kelvins.

The power and efficiency of the module is thus written as:

$$P = VI \quad ; \quad \eta = \frac{VI}{GA} \tag{3}$$

Where G is the income solar radiation and A denotes the area of the module.

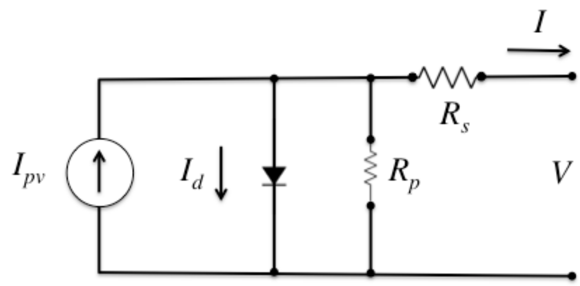


Figure 1- Equivalent circuit for PV-module model

In the Eq. (1), the photovoltaic current is modeled considering a dependence of the I_{PV} to the module temperature T and to the income solar radiation formulated by:

$$I_{PV} = \left(I_{PV,n} + K_I \Delta T\right)\frac{G}{G_n} \tag{4}$$

In this equation $I_{PV,n}$ is the light generated current at nominal conditions (STC), $\Delta T=T-T_n$, G_n is the global incident radiation in STC and K_I is a model constant. All variables with subscript n are related to the STC (G_n=1000 W/m^2 and T_n=25 ^{o}C).

The temperature correction of the saturation current is formulated using the equation proposed by Villalva et al. (2009), which is written as:

$$I_0 = \frac{I_{sc,n} + K_I \Delta T}{\exp\left[\left(V_{oc,n} + K_V \Delta T\right)/aV_T\right]-1} \tag{5}$$

In this equation $I_{sc,n}$ is the short circuit current and $V_{oc,n}$ is the open circuit voltage at STC. Another model constant is introduced, K_V. The Eq. (5) is a better and simpler than the classical correction that uses estimations involving the bandgap energy (Messager and Ventre, 2004). This temperature correction is more accurate in the conditions of high temperature of the module and in the vicinity of the open-circuit condition.

The approaches to obtain all model constants have been explored in many publications (Park et al., 2014, Tian et. al., 2012). The constants $\{I_{PV,n}$,K_I, $I_{sc,n}$,$V_{oc,n}$, $K_v\}$, in the Eq. (4) and Eq. (5), are directly available in manufacturers datasheets (see Tab. 1). Only the values of R_s and R_p have to be determined by an additional approach.

The better strategy to extract the resistance values is to use the Eq. (1) evaluated at some known points of I-V curve at STC. The mathematical problem to find $\{R_s,R_p\}$, has to employ a non-linear searching algorithm, with the I-V curve passing though the points (0, I_{sc}) and (V_{oc},0), with maximum power P_m at V_m, (given also in datasheet). Algorithms using incremental methods (Villalva et al, 2009), power curve derivatives (Tian et al, 2012) or genetic optimization methods (Ismail et al., 2013) have been successfully employed. In the present paper the values of the resistances are obtained using a Particle Swarm Optimization algorithm (PSO) (Brasil Junior, 2015).

In the present paper, the electrical model is simulated using the characteristics of KYOCERA-KC200GT PV-panel with values of resistances of R_s=0.22 Ω and R_p=415.4 Ω (see Fig. 2 for I-V and P-V curves at STC). This commercial module is considered as a reference for the present modeling validations.

Some remarks for the electrical model can be pointed out:

Rem 1: Given the input conditions {G,T,V}, the non-linear equation for I (Eq. (1)) is solved using The intrinsic MATLAB function **fsolve** is employed. A complete MATLAB code was developed for the electrical model of the modules, using the datasheet input parameters, as well as the temperature and irradiance. The results for I-V curve at STC agree with a good accuracy to the experimental measurements as presented in the Fig. 2.

Rem 2: The dependence of the converted power to the module temperature appears in the model equations (1)-(5). Considering that the module will work with a MPPT power control, the converted power P can be obtained from the maximum value of the P-V curve, for input variables {G,T}.

Table 1 - Electrical specifications of some commercial modules.
Conditions of irradiance 1000 W/m^2, cell temperature of 25°C and spectrum AM 1.5.

CHARACTERISTIC	YINGLI YL250P-29B	ALTERSA A-250P	KYOCERA KC200GT
Technology	Si Polycrystalline	Si Polycrystalline	Si Polycrystalline
Maximum Power - $P_{max,e}$	250 W	250 W	200 W
Voltage at MPP – V_{mp}	30.4 V	29.53 V	26.3V
Current at MPP – I_{mp}	8.32 A	8.45 A	7.61 A
Open Circuit Voltage - $V_{oc,n}$	38.4 V	37.6 V	32.9 V
Short Circuit Current - $I_{sc,n}$	8.70 A	8.91 A	8.21 A
Number of cells - N_s	60	60	54
Temperature Coefficient for voltage – K_V	- 0.125 V/^{o}C	-0.120 V/^{o}C	-0.123 V/^{o}C
Temperature Coefficient for current - K_I	0.0052 A/^{o}C	0.00356 A/^{o}C	0.00318 A/^{o}C

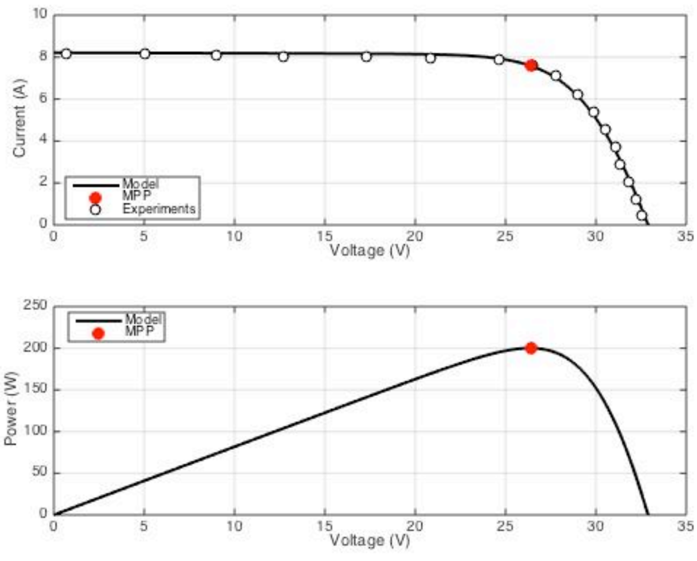


Figure 2- KYOCERA KC200GT PV module I-V and P-V curves (model and experiments at STC)

2.2 Thermal modeling

Let us consider a PV-solar panel that is installed faced to north (for sites in south hemisphere) with a tilted angle of β. The energy exchange from its both sides (upward and downward) involves thermal radiation and convection. The energy conservation can be formulated by:

$$C\frac{dT}{dt} = Q_{r,sw} - Q_{r,lw} - Q_c - P \qquad (6)$$

In this equations C denotes de thermal inertia coefficient and T is the averaged temperature of the panel. The right hand side terms are related to the income radiation ($Q_{r,sw}$), emitted long wave thermal radiation ($Q_{r,lw}$), convection losses (Q_c) and the converted power P (given by the electrical model - Eq. (3)).

The thermal inertia coefficient is calculated by means of a mass weigh summation of the specific heat of each panel component (glass, cells, etc.). Following Jones and Underwood (2001) it can be written as:

$$C = \sum_i m_i c_i \tag{7}$$

Where m_i is the mass of the component and c_i its specific heat.

The income short wave radiation is formulated considering the horizontal measured diffuse and beam components, denoted by I_d and I_b respectively. This term is written as:

$$Q_{r,sw} = (\tau\alpha)_{eff} A\left[\left(\frac{1+\cos\beta}{2}\right) I_d + \left(\frac{\cos\theta}{\cos\theta_z}\right) I_b + \left(\frac{1-\cos\beta}{2}\right) \rho(I_d + I_b)\right] = (\tau\alpha)_{eff} AG \tag{8}$$

In this equation θ denotes the incidence angle of beam radiation and θ_z is the zenith solar angle. The last term is the parcel of income solar radiation reflected by the ground with the reflectivity coefficient denoted by ρ. All those parcels are multiplied by the panel transmissivity-absorptivity coefficient $(\tau\alpha)_{eff}$. For tracked systems the second term is equivalent to the instantaneous DNI.

The outcome long wave radiation term is formulated by the Stefan-Boltzmann equation, taken into account the parcels from upward and downward surfaces, considering its respectively view factors. This term is formulated by:

$$\begin{aligned} Q_{r,lw} \quad = \quad & \sigma\varepsilon A\left(\frac{1+\cos\beta}{2}\right)\left(T^4 - T_{sky}^4\right) + \sigma\varepsilon A\left(\frac{1-\cos\beta}{2}\right)\left(T^4 - T_\infty^4\right) + \\ & \sigma\varepsilon A\left(\frac{1+\cos(\pi-\beta)}{2}\right)\left(T^4 - T_{sky}^4\right) + \sigma\varepsilon A\left(\frac{1-\cos(\pi-\beta)}{2}\right)\left(T^4 - T_\infty^4\right) \end{aligned} \tag{9}$$

In the Eq. (9) ε and σ denote respectively the emissivity of the module (close to 1.0) and Stefan-Boltzmann constant (5.6704×10^{-8} W.m^{-2}.K^4). The temperature T_∞ and T_{sky} are the ambient temperature (air=ground) and sky temperature, considered here as (Swinbank, 1963):

$$T_{sky} = 0.0552 T_\infty^{1.5} \tag{10}$$

At last, classically the convection heat transfer in the module can be expressed by means of Newton cooling law as:

$$Q_c = 2hA(T - T_\infty) \tag{11}$$

Where h is the heat transfer coefficient computed by a empirical relation for the *Nusselt* number, Nu, expressed by:

$$Nu = Nu(Re, Ra, Pr) \equiv \frac{hL}{k} \tag{12}$$

Which involves the *Reynolds*, *Rayleight* and *Prandtl* dimensioless numbers, denoted respectively by Re, Ra and Pr , which are defined by:

$$Re \equiv \frac{\rho L U_\infty}{\mu}\,;\, Ra \equiv \frac{g\beta_T (T - T_\infty) L^3}{\nu^2}\,;\, Pr \equiv \frac{\mu C_p}{k} \tag{13}$$

In the Eq. (13) all air properties $\{\rho, \nu, \mu, C_p, k, \beta_T\}$ (density, viscosity, specific heat, thermal conductivity and thermal expansion coefficient) are evaluated at film temperature. In this equation U_∞ is the wind velocity and L is the length of the panel.

Empirical relations for forced and natural convection can be employed. For no wind conditions (free convection) the following expression for inclined plates (Churchill and Chu, 1975) is used:

$$Nu_{free} = \left[0.825 + \frac{0.387(Ra\sin\beta)^{1/6}}{\left[1 + \left(0.492/\mathrm{Pr}\right)^{9/16}\right]^{8/27}}\right]^2 \tag{14}$$

For forced convection on a flat plate with laminar to turbulent transition, the Nusselt number is given by:

$$Nu_{forced} = 0.68 Re^{1/2} Pr^{1/3} \tag{15}$$

In most of the real situations, the forced and free convection effects are observed, in a regime of mixed convection. Taken it into account, the final expression for the Nusselt number using Eq. (14) and (15) is:

$$Nu = \left(Nu_{forced}^{n} + Nu_{free}^{n} \right)^{1/n} \tag{16}$$

In the present paper $n=3$ is used.

Rem 3: The dynamical model (Eq. (6)) expresses the time history of the temperature of the module. Given an initial condition for the temperature, an incremental algorithm using Euler backward method is employed using time steps of order of 0.5 second.

Rem 4: A steady-state thermal equilibrium model can be also considered, using the Eq. (6) to Eq. (16), with $C=0$. Using a non-linear equation solver (MATLAB **fsolve**), the temperature of the module can be obtained after the Eq. (6).

Rem 5: Classically, the temperature of the module is determined by the NOCT model (Duffie and Beckman, 1991). It is a very simple steady-state model, which the temperature of the module is determined by:

$$T = T_{\infty} - (T_{NOCT} - 20)\frac{G}{G_{NOCT}} \tag{17}$$

In this equation T_{NOCT} is the Nominal Operating Cell Temperature, which is in general available in panel datasheets. This expression is calibrated for the conditions of wind speed less than 1 m/s and G_{NOCT} equal to 800 W/m^2 (reference income solar radiation). Of coarse its is very simple model that do not represents precisely the complex heat transfer model presented in Eq. (6)-(11). On the other hand, the practical Eq. (17) has been extensively employed in the design of solar systems and some standard references of IEC 61215 and IEC 61646 explore the use of this formulation.

3. RESULTS AND DISCUSSIONS

3.1 Steady-state conditions

Firstly, the thermal model presented in the part 4 is employed without the thermal inertia term, to obtain the temperature of the module given the climatic conditions of income radiation, ambient temperature and wind speed. The KYOCERA 200GT module is simulated for different conditions using both the complete model (Eq. (6)-(16)) and the NOCT model (Eq. (17)). The results are summarized on the Tab. 2-4 and in the Fig. 3.

Table 2 – Module temperature for complete and NOCT models

	Income radiation G (in W/m^2)			
	200	**500**	**800**	**1000**
T **(°C) – Complete model**	28.6	38.9	48.5	54.5
T **(°C) – NOCT model**	31.9	41.9	52.0	58.9

Table 3 – Power for complete and NOCT models

	Income radiation G (in W/m^2)			
	200	**500**	**800**	**1000**
P **(W) – Complete model**	35.8	90.8	140.9	171.4
P **(W) – NOCT model**	35.2	89.4	138.2	167.3

Table 4 – Efficiency for complete and NOCT models

	Income radiation G (in W/m^2)			
	200	**500**	**800**	**1000**
η (%) – Complete model	12.7	12.9	12.5	12.1
η (%) – NOCT model	12.5	12.7	12.2	11.7

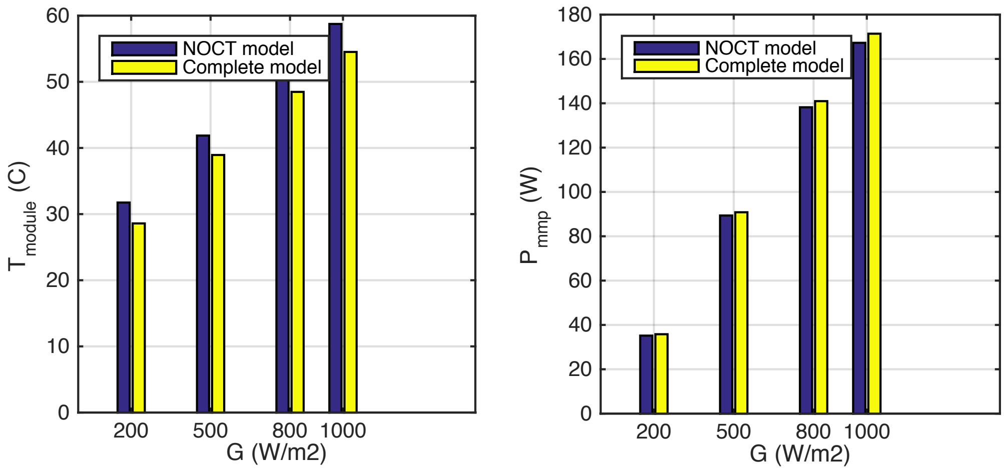


Figure 3- Comparisons for module temperature and power for complete and NOCT models

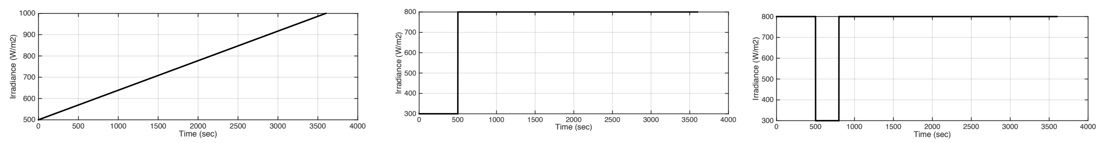
The difference of the temperature obtained in the two models is up to five degrees and are higher for values of income radiation greater than 800 W/m^2. The complete model represents more precisely the heat transfer on the module surfaces and the values and shown that the NOCT model overestimate the level of the temperature. The use of the NOCT model is simplest to be implemented often it do not need the use of a nonlinear solver. This simple model is extensively used in the simulations codes and some had hoc corrections can be implemented to consider different conditions of wind speed.

The few degrees of difference between the thermal models induce the difference in the power limited to 8 W (which correspond to 5 % of module maximum power). It is related to a difference of few percentage of the module efficiency. Taken into account that our operational condition uses a MPPT approach to operate the module in different income radiation conditions, that compensates the influence of the module temperature.

3.2 Unsteady idealized input conditions

The dynamical simulations of the module response to different unsteady input conditions are performed for ramp, step and valley variation of the income radiation. In those test cases, the ambient temperature and wind speed are constant and equal to 25 ^{o}C and 1 m/s respectively. The income radiation variations for three different unsteady conditions are shown in Fig. 4. All conditions have the maximum time of 1 hour (3600 sec) and the time step for the dynamical simulations are 0.5 sec. For the ramp condition the slope is 500 W/m^2-h. In the step case the radiation grows suddenly from 300-800 W/m^2. At least, the valley condition the radiation varies between 800-300 W/m^2 and maintain the low level during 500 sec.

The results presented for the unsteady condition shown an important difference in the module temperature level in the 15 minutes observed interval. Those differences represent few watts in the difference of the power converted by the module in MPPT approach. In the cases of the step and valley, it can be observed that the thermal response time of the module is around 1200 sec. Another important point that can be observed is related to the small difference between the steady-state module and the dynamical model in the interval of 15 min (900 sec), in particular for the converted power estimates.



(a) (b) (c)

Figure 4- Unsteady input conditions – (a) Ramp, (b) step and (c) valley test cases.

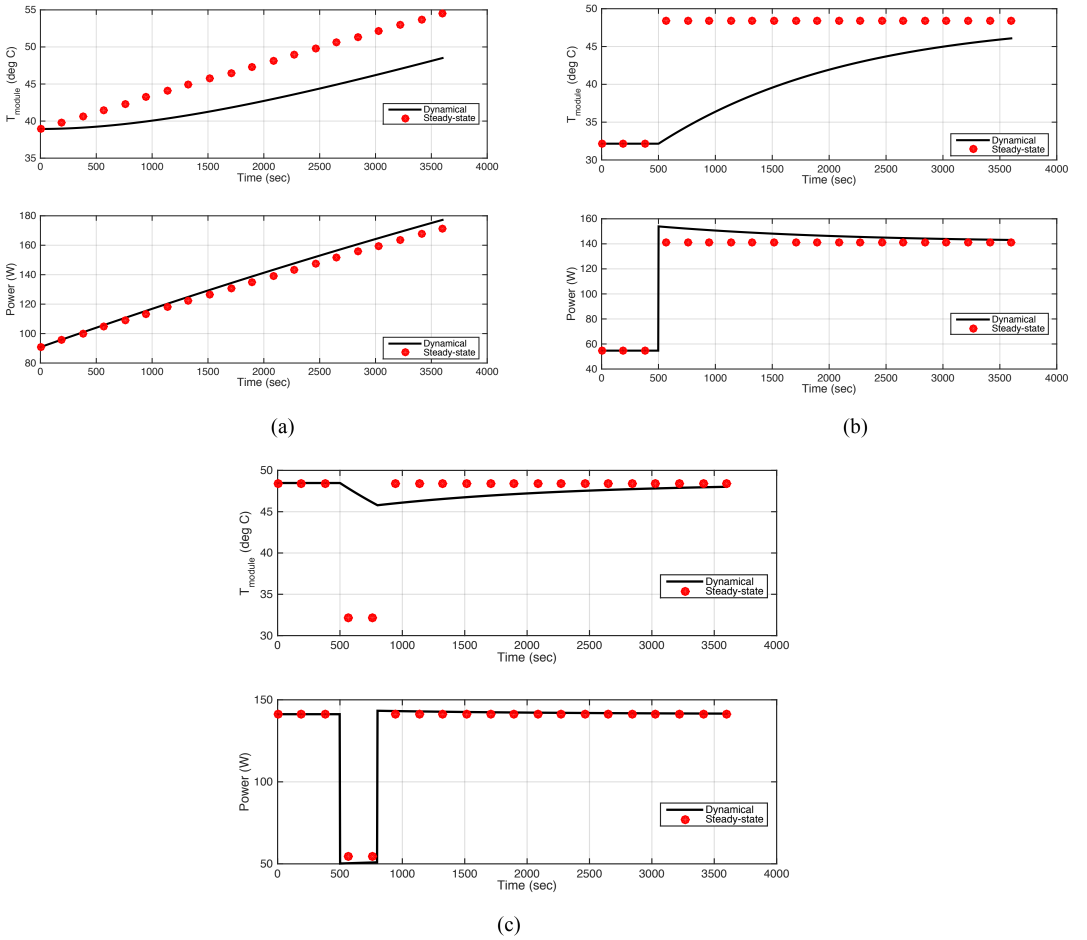


Figure 5- Unsteady system response – (a) Ramp, (b) step and (c) valley test cases.

3.3 Unsteady real input ambient conditions

The dynamical simulation of the thermal and electrical model is performed for real conditions of a cloudy day in the city of Brasilia-Brazil (S15°45'38"; W47°52'27"). The 15 minutes register of ambient temperature, wind speed and income radiation (DNI and diffuse) are used as input variables for a KYOCERA 200GT module with tracker. The data for 25-may-2014 is shown in the Fig. 6. The results for simulation of module temperature and converted electrical power are shown in the right side of the same figure.

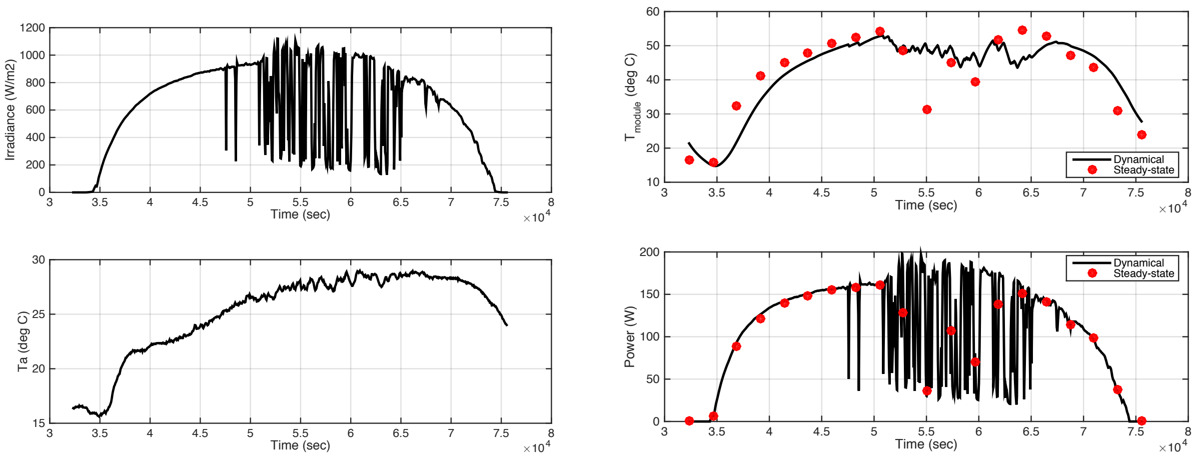


Figure 6- Unsteady real situations (Partially cloudy day in Brasilia – 25-may-2014)

The results for partially cloudy day have shown the same behavior of the idealized inputs previously presented. For slightly ramp condition, with slow variation late in the morning and clos to the sunset, the results for the complete model for the steady-state results and for dynamical model are equivalent. In those conditions the module temperature and the power do not have any important difference. On the other hand, close to the solar moon, when the cloud cover is important and the income radiation is strongly influenced by the cloud traveling, the temperature of the module and the electrical power have important variation, and on those condition the dynamical model presents a gain in the accuracy of the results. The difference for the power considering 15 minutes intervals of averaging for converted energy do not justify the use of the more expensive dynamical model – the difference in the integral of the energy in one hour, for instance, is not too important. It is mainly justify by the strategy to the use of MPPT electronics control that minimize the difference between the power converted on different levels of module temperature, with differences up to 5 degrees. On the other hand, if the fast variations have to be used to determine the control strategy of the modules (and the strings), the dynamical approach has to be considered, in order to guarantee a good accuracy in the electrical power.

Acknowledgments

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