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Experimental validation of the electro-thermal model of a PV panel

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Abstract

The use of solar energy to generate electricity by photovoltaic (PV) cells is increasing, in response to the world energy needs and environmental constraints. However, most of the incident radiation on conventional PV cells is not converted into electricity being wasted through heat dissipation and responsable for rising the cells temperature and lowering even more the already low efficiency of photovoltaic energy converters. A way to maintain the efficiency higher is to control the temperature of the cells. To understand the variation of PV efficiency, specific models are needed, that incorporate electric, thermal and climatic parameters. This paper presents a dynamic model of a PV cell and evaluates its thermal and electrical performance. Simulation and experimental results are presented and compared to validate the model.

Key Words: Photovoltaic Cells, Modelling, Efficiency.

1. Introduction

The conversion of solar energy into electricity is mainly obtained through the use of photovoltaic cells based on crystalline technology. The efficiency conversion hardly reaches 20% and unfortunately decreases with temperature. This situation is critical during the summer when more solar radiation is available, but also the ambient temperature is higher. To decrease cell's temperature, maintaining the higher efficiency possible, the external cooling of the cells is necessary. A solution to reach this goal is through a hybrid collector known as a Photovoltaic/Thermal collector (PV/T), integrating a PV panel with a thermal collector, generating electricity and heat, which can be also used. In this way, the overall efficiency, per unit area, for the PV/T, is higher than the addition of a PV and thermal collector efficiencies when operating independently. Studies regarding numerical models that represent the behaviour of the PV, thermal and hybrid PV/T panels are available in the literature [1-3]. These models can have different levels of complexity, mainly in the thermal part with 1D, 2D or 3D structures, although for normal operating conditions the simpler 1D model seems to be sufficient to represent the panels behaviour. This work presents the development of a 1D mathematical model for a PV panel and its numerical implementation in Matlab/Simulink in order to analyse its electrical and thermal behaviour and validate it with experimental tests. Climatic models regarding the daily solar radiation, temperature and wind speed are also used to define the inputs for the PV, creating a more realistic condition for the panel simulation.

2. Mathematical Model

The electrical models for PV cells are derived from the general equation of diodes resulting in the equation for the PV output current:

$$I = I_{cc} - I_o \left(e^{\frac{qU}{AKT}} - 1\right) \tag{1}$$

where q is the electrical charge, Icc is the short circuit current, Io is the diode's reverse saturation current, K is Boltzman's constant and A is the diode ideality factor. Depending on the precision of the model, a one or two-diode model is used, but the simpler one is mostly used and is retained in our simulation [4].

The development of the thermal model is based on the balance of energy transfer between the cells and the environment, which is hard to represent because, besides the PV, it depends on conditions not controllable like the weather and surroundings [5]. Anyway, using the energy balance the following equations can be obtained:

$$Q_{store,ph} = Q_{ph} + Q_{conv,a-ph} + Q_{rad,e-ph} - Q_e \tag{2}$$

where $Q_{store,ph}$ is the amount of energy stored in the photovoltaic component, Q_{ph}. the solar energy absorbed by the PV panel, $Q_{conv,a\text{-}ph}$ the energy transfer from panel and air by convection, $Q_{rad,e\text{-}ph}$ the energy transfer from sky by radiation and Q_e the electric energy produced by the PV panel.This equation can further be developed in the form:

$$m_{ph} c_{ph} \frac{dT_{ph}}{dt} = \alpha_{ph}\, G\, S + h_{c,a-ph} S(T_a - T_{ph}) + h_{r,e-ph} S(T_a - T_{ph}) - UI \tag{3}$$

where, G is total solar radiation, S the surface area of the panel, α_{ph} is the absorptance of the PV module, m_{ph} and c_{ph} are the mass and specific heat of PV panel, respectively;T_{ph} and T_a are the temperatures of the PV cells and external air temperature, respectively; $h_{c,a\text{-}ph}$ is the convective heat transfer coefficient between air ambient and the PV panel $h_{r,e\text{-}ph}$ is the radiative heat transfer coefficient between ambient air and the PV panel.

Besides the silicon cells, a PV incorporates also on the front a low-iron glass, a polymer insulator (EVA - ethylene vinyl acetate), and on the backs the same EVA with tedlar (another polymer). From those components the glass is the one that plays the major role in the heat transfer, because it is heavier and thicker.

The instantaneous electrical efficiency is defined in terms of power as:

$$E_e = \frac{U\, I}{G\, S} \tag{4}$$

being U and I the external voltage and current of the PV, respectively.

2.1 Heat transfer coefficients

The heat transfer coefficients are fundamental to characterize the thermal behaviour of the PV [6-7]. The convective heat transfer coefficient due to the wind (h_{wind}=$h_{c,a\text{-}ph}$) is given by :

$$h_{wind} = 2{,}8 + 3{,}0\, v_{wind} \tag{5}$$

and is a function of wind velocity, v_{wind}.

The radiation heat transfer coefficient between sky (assuming that the temperature of air and environment are equal) and the PV module, $h_{r,e\text{-}ph}$, is given by:

$$h_{r,e-ph} = \sigma\, \epsilon_{ph} (T_{ph}^2 + T_e^2)(T_{ph} + T_e) \tag{6}$$

where σ and ϵ_{ph} are the Stefan-Boltzman constant and the photovoltaic cell emissivity, respectively.

2.2. Climatic Inputs

To simulate the PV behaviour one needs to define the inputs for the model, namely, radiation, wind speed and ambient temperature. For a clear sky the incident radiation on a PV panel with a tilted surface can be defined as previously with little error. The major error arrive from the wind speed which is mainly random and can influence the ambient

temperature also. For simulations purposes the wind speed is defined randomly with maximum and minimum values according with statistical data avaiable for the local where the experimentals tests will be performed. A similar approach was done for the maximum ambient temperature and solar radiation.

3. Simulation results

The numerical development of the model is implemented in Matlab/Simulink using a PV panel with the following mechanical and electrical characteristics (at STC - Standard Test Conditions).

Table 1 - PV data.

Maximum power	200 W
Maximum power voltage	26.3 V
Maximum power current	7.31 A
Number of cells	54
Width	1425 mm
Lenght	990 mm

The daily evolution of ambient temperature (Tamb) and wind speed (Vwind) for a typical summer day in July at Guarda Portugal, are presented in Fig. 1, toghether with the medium temperature of photovoltaic cells (Tmed):

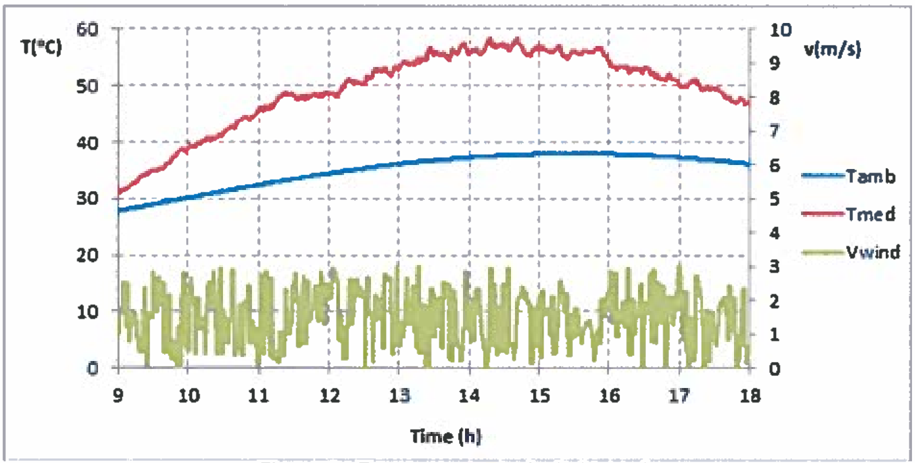

Figure 1 - Temperatures and wind speed.

The solar (Ps) and the eletrical (Pr) powers obtained in a constant passive load defined for the maximum power for STC conditions, are presented in Fig. 2.

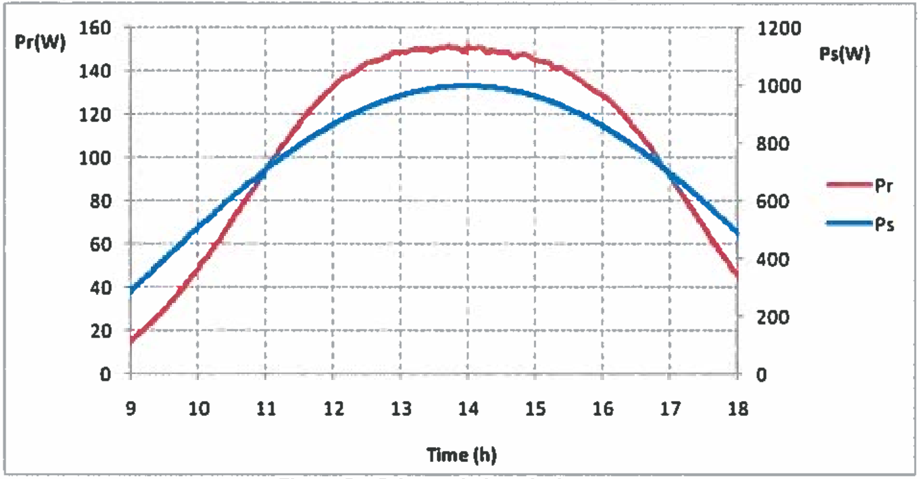

Figure 2 - Solar and electrical power.

The instantaneous power efficiency Ee is presented in Fig 3.

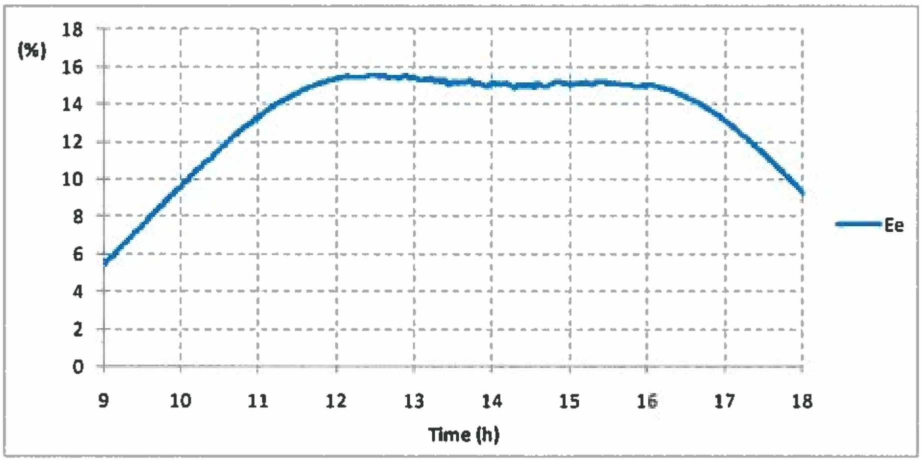

Figure 3 - Conversion efficiency.

The simulation results are comparable with those from other studies, showing the decrease in the efficiency of the panel when the temperature is higher.

4. Experimental results

The experimental results are obtained using sensors and a data acquistion system which measures the radiation, wind speed, ambient temperature, panel temperature and electrical power with a 15s sampling time. The equivalent results for Fig.1 to 3 are presented in Figs. 4 to 6, respectively.

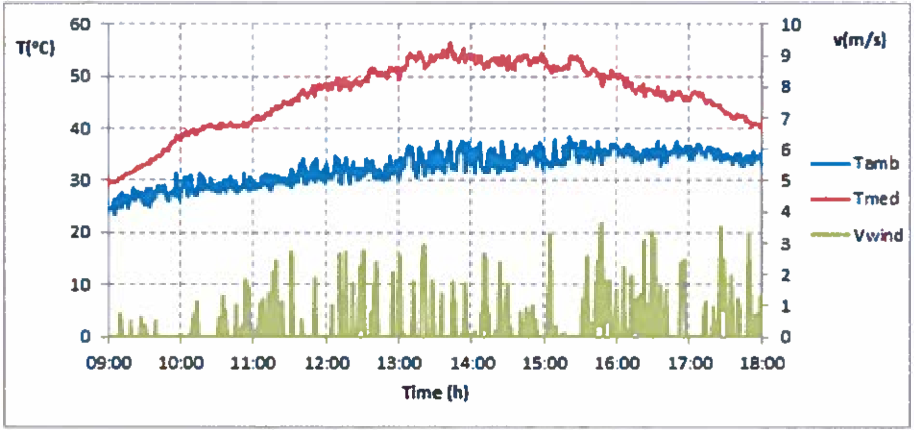

Figure 4 - Temperatures and wind speed.

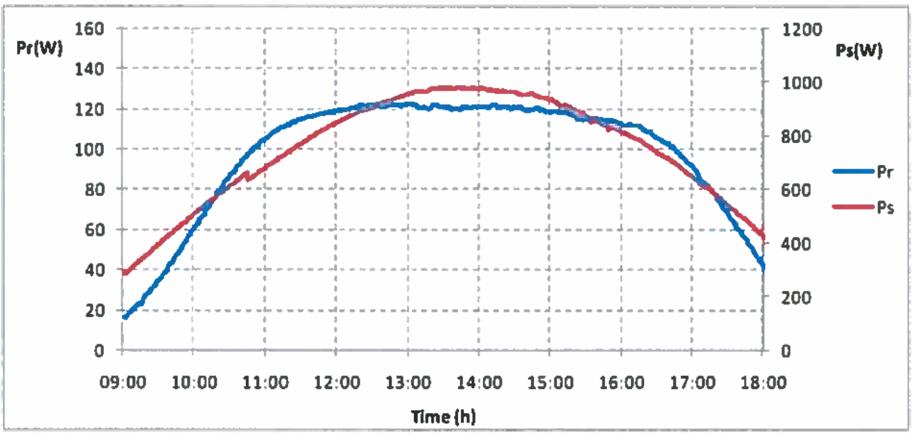

Figure 5 - Solar and electrical power.

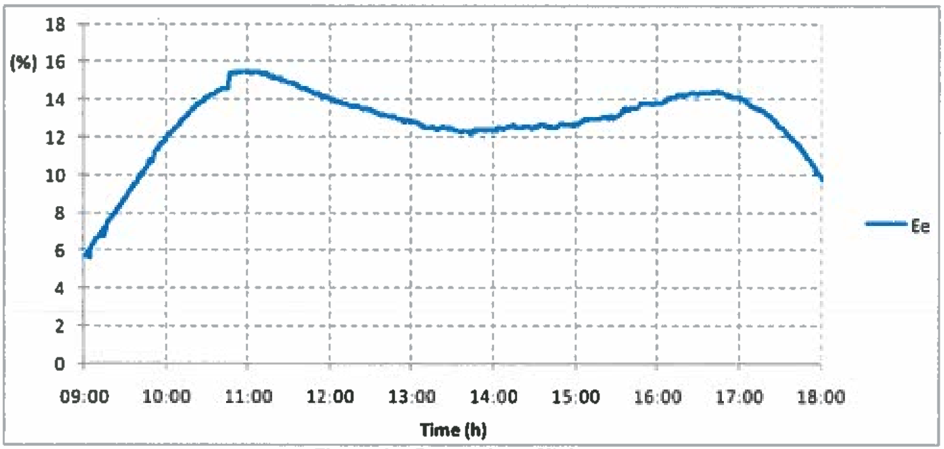

Figure 6 - Conversion efficiency.

5. Discussion

The experimental results have the same pattern of the simulation ones, but some diferences can be noticed. Some of them are expected, because they depend on the exact matching of climatic data, namely the maximum values, which in reality had been lower than expected. Besides the wind, one source of error is present in the measurement of the radiation power. In simulation it was considered both direct and difuse radiation, but the sensor is mainly sensible to the direct component. However, the main divergence is observed on the efficiency which seems to be lower than predicted and expected due to the lower cells temperatures.

6. Conclusions

From the results the negative effects imposed by the temperature on the behaviour of PV panels are confirmed. This justify the need to develop further studies regarding the behaviour of PV panel and photovoltaic energy conversion, namely by introducing cooling capacities in PV panels leading to hybrid PV/T structures.

However the results also reinforce the importance of the models to predict with more precision the expected results in order to define and validate more efficient systems.

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