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THEORETICAL MODEL FOR PHOTOVOLTAIC PANEL THERMAL ANALYSIS

BY

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Abstract. The process of energy conversion of incidental solar radiation to useful electric energy in photovoltaic (PV) panels is affected by several external factors, of which panel operational temperature is of utmost importance. The present study attempts to clarify the theoretical components of thermal behaviour of PV panels, by taking into account the detailed structure of thermal resistances of panel layers. The numerical model, developed from the theoretical analysis, shows a good agreement with experimental data provided by manufacturer for the photovoltaic panel Suntech STP280 - 24/Vd.

Keywords: photovoltaic; mathematic model; numeric analysis.

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1. Introduction

The current drive in energy area is to replace the classic sources (from fossil fuels) of energy with renewable ones. Out of the solar, wind, hydropower (both terrestrial and marine), geothermal and biomass renewable sources of energy, solar energy demonstrates the highest potential in availability and the lowest initial financial investment.

The direct conversion of solar energy in thermal and electrical energy is appealing to researchers and technology developers. During the last few decades, the new materials and manufacturing technologies made possible a sharp decrease in photovoltaic (PV) panel prices, to the point where the loss in energy conversion efficiency is overcome by the low cost of implementation and replacement of solar panels.

Analyses performed to date on classic PV panels have documented the influence of various factors on energy conversion efficiency. Besides the obvious geographical location, time of day and weather conditions, the most important factor seems to be the panel operational temperature (Lupu *et al*., 2018). As a result, numerous technologies aim to lower the panel temperature and maintain it within optimal operational range.

2. Theoretical Analysis

In general, for mathematical and numerical modelling of PV panels, the structure taken into account starts with the PV substrate encapsulated (by lamination in vacuum at 150°C) in EVA (ethyl-vinyl-acetate) substrates, conferring mechanical protection and electrical insulation. Because the EVA layers are not resistant to ultraviolet (UV) radiation, the upper part side of the assembly is covered with a protective layer, either low-iron-content glass or transparent PET (poly-ethylene-terephthalate). Similarly, at the back side, non-exposed to incident solar radiation, there is another protection layer from a composite, opaque thin-film of TPT (Tedlar-Polyester-Tedlar). By itself, Tedlar is the commercial product of DuPont Company, designating a film of either PVF (polyvinyl-fluoride) or PET.

Even if these layers (except the upper protective one) are laminated at high temperature, in vacuum and under compression forces, the physical contact between layers is not perfect. Therefore, the proposed model of entire PV cell accounts for all interface thermal contact resistances.

Figures 1 and 2 describe the layers and associated thermal resistances for a typical PV panel design.

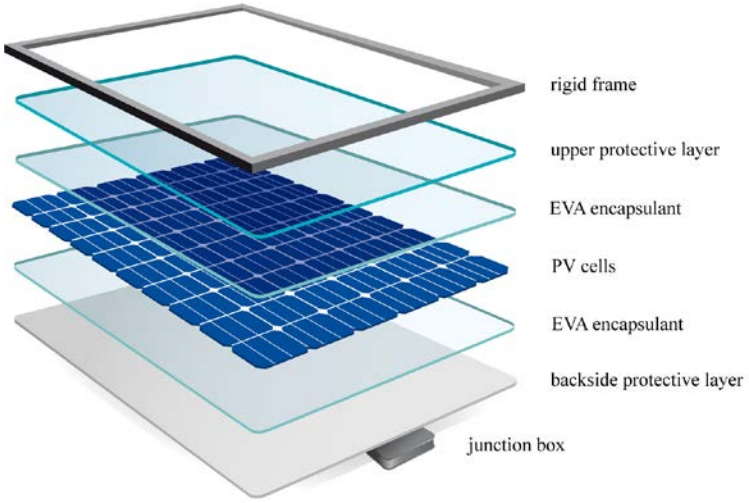


Fig. 1 – Typical structure of a silicon-based photovoltaic panel.

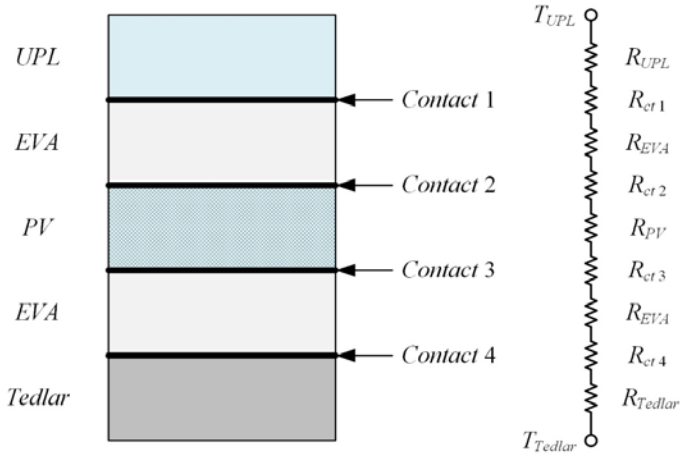


Fig. 2 – Thermal resistances associated with a PV panel layer structure (not at scale).

The mathematical model takes into account the following assumptions:

– on the upper side of the protective layer, the heat losses to the environment are both by convection and radiation;
– the conductive heat transfer through the PV layers is one-dimensional and stationary;
– on the backside of the PV cell, the heat is being removed either by convection or by other cooling devices (*e.g.*, thermal fluid cooling, thermo-electric-generators, etc.).

A solar PV panel reunites several PV cells connected electrically in series and thermally in parallel. From the technical and practical considerations, the PV cells placement on a panel cannot cover its entire surface area. A more accurate model should account for the difference between the total PV panel surface exposed to incidental solar radiation (A_{panel}) and the actual area of PV cells (A_{PV}) used for energy conversion. Depending on the number of PV cells on the panel (N_{cell}) and the surface area of a single cell (A_{cell}), the packing coefficient of the PV panel (β_{PV}) is defined as:

$$\beta_{PV} = \frac{A_{PV}}{A_{panel}} = \frac{N_{cell} \cdot A_{cell}}{A_{panel}} \tag{1}$$

Even though the surface between cells is small compared to the useful PV conversion area (that is, β_{PV} is close to 1), it is important to correctly quantify the heat transfer through the panel to the Tedlar back layer. If the model uses only a single PV cell, then:

$$\alpha_{PV} \cdot \beta_{PV} + \alpha_{Tedlar} \left(1 - \beta_{PV}\right) \cong \alpha_{PV} \tag{2}$$

where α_{PV} and α_{Tedlar} represent the absorptivity of PV material and Tedlar, respectively.

The equivalent electrical circuit accounts for the heat transfer through the PV panel layers and energy exchanges with the environment. The upper protective layer (UPL) partially reflects the incident solar energy, absorbs a fraction, but transfers the most of it to the layers below. Similar processes occur in the PV layer: it partially reflects incidental energy back to the UPL and partially transfers a small fraction through Tedlar back layer to ambient. The absorbed energy is converted to electrical energy.

For UPL, the energy balance is:

$$\dot{E}_{\alpha,UPL} + \dot{Q}_1 = \dot{Q}_{cv} + \dot{Q}_{rad} \tag{3}$$

$$\alpha_{UPL} I_{(t)} A_{panel} + \frac{T_{PV} - T_{UPL}}{R_{ct2} + R_{EVA} + R_{ct1} + R_{UPL}} = \frac{T_{UPL} - T_a}{R_{cv}} + \frac{T_{UPL} - T_{sky}}{R_{rad}} \tag{4}$$

The energy balance for the PV layer is:

$$\dot{E}_{\tau,UPL} = \dot{E}_{\alpha,PV} = \dot{E}_{el,PV} + \dot{Q}_1 + \dot{Q}_2 \tag{5}$$

$$\tau_{UPL} I_{(t)} A_{panel} = P_{el,PV} + \frac{T_{PV} - T_{UPL}}{R_{ct2} + R_{EVA} + R_{ct1} + R_{UPL}} + \ldots + \ldots + \frac{T_{PV} - T_a}{R_{PV} + R_{ct3} + R_{EVA} + R_{ct4} + R_{Ted} + R_{cv}} \quad (6)$$

In the above equations, the temperatures and resistances have the same significance as in Figs. 2 and 3. Also, α_{UPL} and τ_{UPL} are the absorptivity and transmissivity of the UPL, respectively, while subscripts "α" and "τ" represent the corresponding absorbed and transmitted fractions of incidental solar energy. $I_{(t)}$ represents the intensity of incidental solar radiation, which is time dependent.

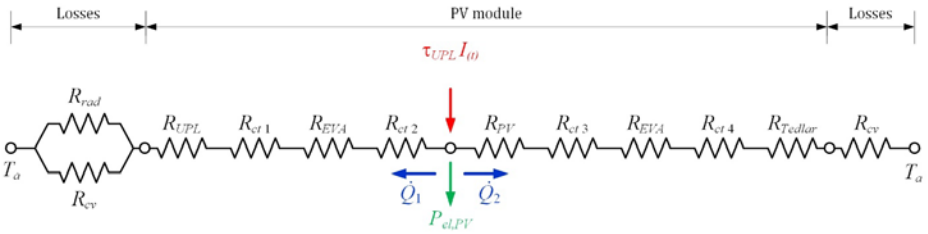


Fig. 3 – Thermal resistances and energy fluxes in a PV panel.

The convective resistance at both upper and lower sides is:

$$R_{cv} = \frac{1}{h_{cv} A_{panel}} \quad (7)$$

In most cases, the convective heat transfer coefficient accounts for the wind speed ($0 < u_w < 7$ [m·s^{-1}]), (Watmuff *et al.*, 1977):

$$h_{cv} = 2.8 + 3.0 \times u_w \quad (8)$$

In some particular cases, the convection and radiation effects are quantified using a combined heat transfer coefficient ($0 < u_w < 5$ [m·s^{-1}]):

$$h_{cv+rad} = 5.7 + 3.8 \times u_w \quad (9)$$

Here, the reference temperature for the radiation losses is considered the same as ambient temperature ($T_{sky} = T_a$), although this hypothesis may introduce some errors (Kalogirou *et al.*, 2016; Sharhaddi *et al.*, 2010).

If computed separately, the radiation thermal resistance is:

$$R_{rad} = \frac{1}{h_{rad} A_{panel}} \tag{10}$$

with an equivalent heat transfer coefficient:

$$h_{rad} = \varepsilon_{UPL} \sigma \left(T_{UPL}^2 + T_a^2 \right) \left(T_{UPL} + T_a \right) \tag{11}$$

where ε_{UPL} represents UPL emissivity and σ is the Stefan-Boltzmann constant.

The contact thermal resistances consider the temperature jump at layers' interface due to imperfect contact between solid surfaces. Experimental studies conducted at temperatures close to environmental ones show that thickness and conductivity of adhesive layers have major influence on thermal resistance characteristics, while pressure applied to the layers exhibits minimal effects, (Mirmira *et al*., 1997).

The electrical energy from the PV module is:

$$\dot{E}_{el,PV} = P_{el,PV} = \eta_{PV} \left(\tau_{UPL} I_{(t)} \right) A_{PV} = \eta_{PV} \left(\tau_{UPL} I_{(t)} \right) \left(\beta_{PV} A_{panel} \right) \tag{12}$$

where η_{PV} represents the PV module conversion efficiency, which is dependent of solar cell temperature (Evans, 1981; Skoplaki and Palyvos, 2009):

$$\eta_{PV} = \eta_0 \left[1 - \beta_0 \left(T_{PV} - T_0 \right) \right] \tag{13}$$

The subscript "0" refers to Standard Test Conditions (STC), defined as incident radiant solar energy of $G_{ref} = I_{(t)} = 1000$ [W·m^{-2}], reference temperature $T_{ref} = 25$°C, and air-mass index AM = 1.5.

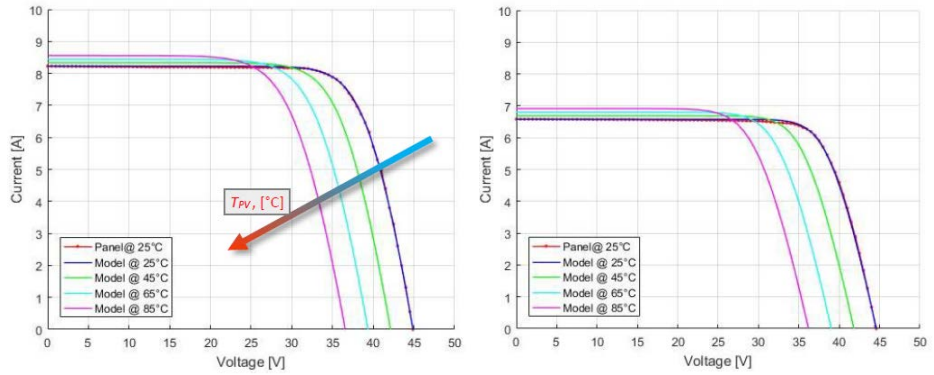
Occasionally, manufacturers specify PV panel electrical characteristics at Nominal Operating Cell Temperature (NOCT), that considers incident solar radiation G_{ref} = 800 [W·m^{-2}], ambient temperature T_{amb} = 20°C, and wind velocity 1 [m·s^{-1}].

3. Numerical Results

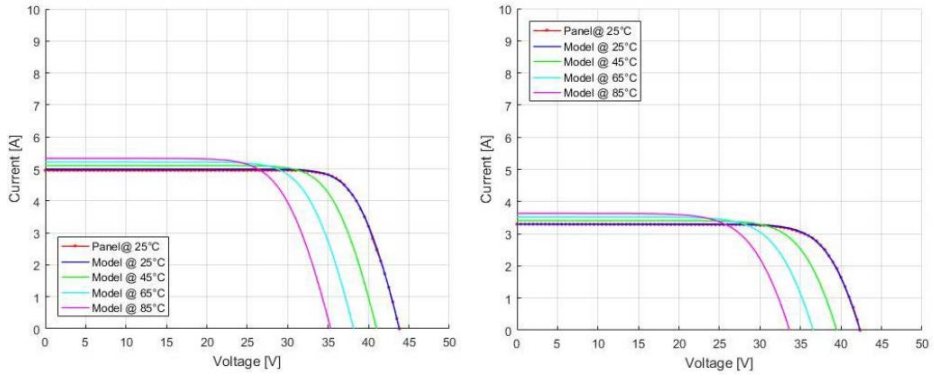
In order to compare results and validate the proposed numerical model, data provided by the manufacturer of solar PV panel Suntech STP280-24/Vd were digitized for several intensities of incidental solar radiation.

For a regular silicon-based solar PV panel, the current – voltage (I-V) and power – voltage (P-V) characteristics reveal that the open circuit voltage, and subsequently, the electrical power supplied decreases significantly with the increase in panel temperature. Even if the panel exhibits an increase in current, the decrease in voltage is much larger and hence, the decrease in power.

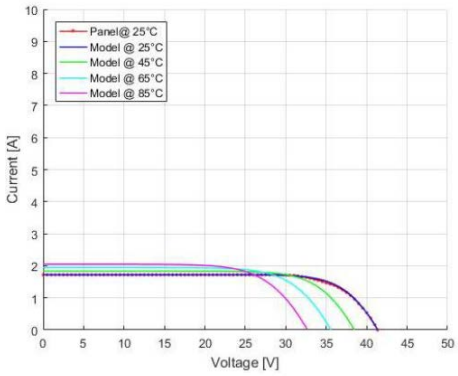
The proposed numerical model evaluates the PV panel thermal response for different values of solar radiation intensity in the range 200 – 1000 [W·m^{-2}]. The panel temperature varied in 20°C increments between 25 – 85°C, values that cover the STC and NOCT values, as well as manufacturer data, for direct comparison and model validation. The temperature increments may be chosen larger or smaller, depending on the analysis requirements. The numerical model is based on the single diode non-linear equivalent electrical circuit.



a) b)

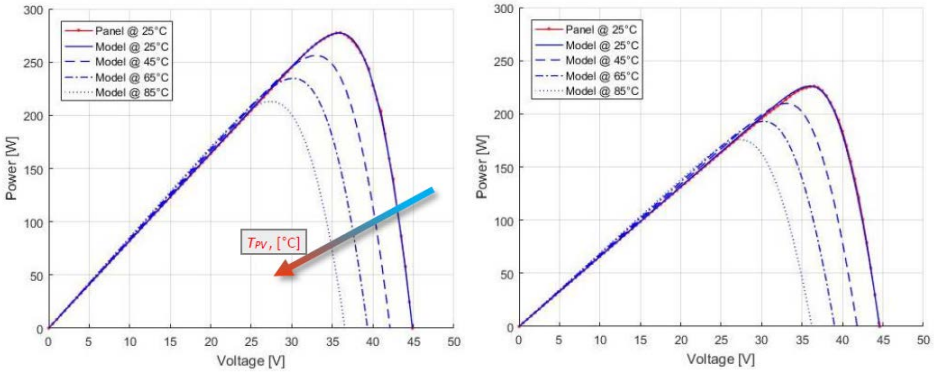


c) d)

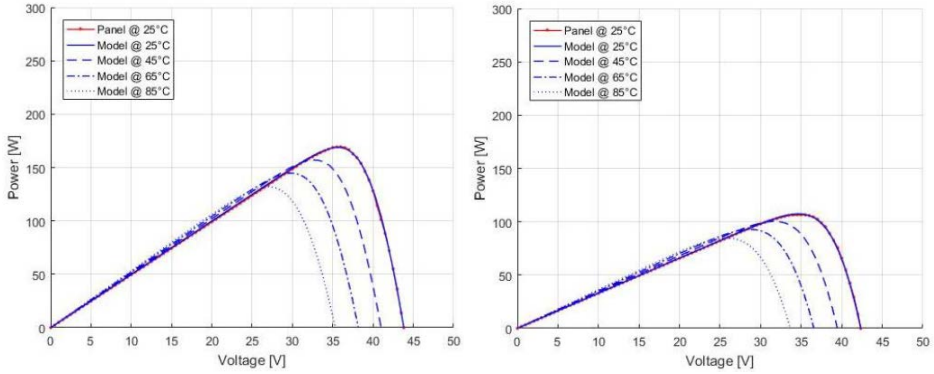


e)

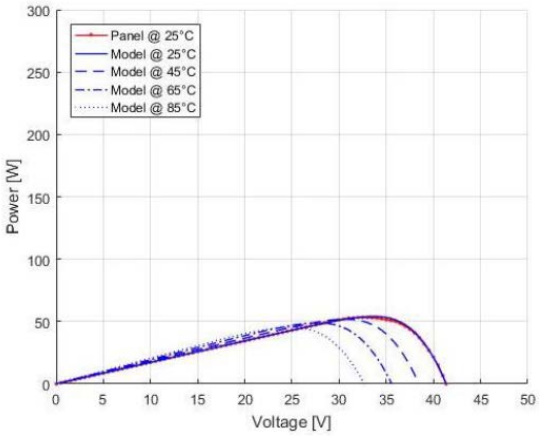
Fig. 4 – The I-V characteristic depending on temperature, for Suntech STP280 - 24/Vd at: a) G = 1000 [W·m^{-2}], b) G = 800 [W·m^{-2}], c) G = 600 [W·m^{-2}], d) G = 400 [W·m^{-2}] and e) G = 200 [W·m^{-2}].



a) b)



c) d)



e)

Fig. 5 – The P-V characteristic depending on temperature, for Suntech STP280 - 24/Vd at: a) G = 1000 [W·m^{-2}], b) G = 800 [W·m^{-2}], c) G = 600 [W·m^{-2}], d) G = 400 [W·m^{-2}] and e) G = 200 [W·m^{-2}].

The results presented in Figs. 4 and 5 exhibit a very good agreement with manufacturer data, with a minor exception for the case G = 200 [W·m^{-2}], where the approximations from digitization procedure become relatively large in comparison to measured data.

For each 20-degrees temperature increment there is a minute increase in current (about 1.3%), but the sharp decrease of 8% in voltage triggers a power decrease of roughly 7.6%. For a better visual comparison, the coordinate axes maintained same limits, showing the decrease in power with both increase in temperature and decrease in incidental solar radiative energy.

4. Conclusions

Strong temperature dependence of conversion efficiency of solar energy into electrical energy in PV panels has triggered, during last decades, significant experimental researches. Theoretical and numerical analyses developed in this paper detail the PV panel layers and associated thermal resistances, including the imperfect contacts between layers. The numerical model based on single diode non-linear equivalent circuit, delivers both I-V and P-V output electrical characteristics, accounting for PV panel specifications (packing configuration, operational and maximum electrical values, temperature characteristics, module efficiency). For the case of PV panel type Suntech STP280-24/Vd numerical results exhibit a very good agreement with manufacturer data.

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REFERENCES

Evans D.L., *Simplified Method for Predicting Photovoltaic Array Output*, Solar Energy, **27**, 555-560, 1981.

Kalogirou S.A, Karellas S., Braimakis K., Stanciu C., Bădescu V., *Exergy Analysis of Solar Thermal Collectors and Processes*, Progress in Energy and Combustion Science, **56**, 106-137, 2016.

Lupu A.G., Homutescu V.M., Bălănescu D.T., Popescu A., *A Review of Solar Photovoltaic Systems Cooling Technologies*, IOP Conference Series: Materials Science and Engineering, **444**, 082016, 2018.

Mirmira S., Marotta E., Fletcher L., *Thermal Contact Conductance of Adhesives for Microelectronic Systems*, Journal of Thermophysics and Heat Transfer, **11**, 141-145 (1997).

Sarhaddi F., Farahat S., Ajam H., Behzadmehr A., *Exergetic Performance Evaluation of a Solar Photovoltaic (PV) Array*, Australian Journal of Basic and Applied Sciences, **4**, *3*, 502-519 (2010).

Watmuff J.H., Charters W.W., Proctor D., *Solar and Wind Induced External Coefficients for Solar Collectors*, Revue Internationale d'Heliotechnique, **2**, 56, 1977.

Skoplaki E., Palyvos J.A., *On the Temperature Dependence of Photovoltaic Module Electrical Performance: A Review of Efficiency/Power Correlations*, Solar Energy, **83**, *5*, 614-624, 2009.

MODEL TEORETIC PENTRU ANALIZA TERMICĂ A PANOURILOR FOTOVOLTAICE

(Rezumat)

Procesul de conversie energetică a radiaţiei solare incidente în energie electrică utilă, cu ajutorul panourilor fotovoltaice (PV), este afectat şi de câţiva factori externi, dintre care o importanţă majoră o are temperatura de operare a panoului. Această lucrare propune clarificarea elementelor teoretice ale răspunsului termic al panourilor PV, prin considerarea structurii detaliate ale straturilor panoului, inclusiv a resistenţelor termice asociate acestora. Modelul numeric propus, dezvoltat din această analiză teoretică, arată o bună concordanţă cu datele experimentale furnizate de producător pentru PV Suntech STP280 – 24Vd.