Investigation of the effects of Joule heating on the performance of photovoltaic modules:

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Abstract:

This paper aims to study the effect of resistive heating (Joule heating) on the PV devices in forward and reverse bias modes through a steady-state, electro-thermal model using a detailed thermal network approach. The paper will present a preliminary analysis of the impact of internally generated heat on the efficiency of a PV device. The model will analyse the problem of resistive heating in PV devices when bypass diodes are not used or damaged by considering ideal and worst case scenarios. The created model will be simulated using the Finite Element Analysis (FEA) package Ansys Workbench and validation will be performed using data recorded by a commercial PV panel.

1. Introduction:

It is commonly known that solar cells are negatively impacted with increase in temperature which affects their power yield. The ambient temperature is one of the external conditions and is the principal trigger of heating in a PV panel. In the literature, several researchers discussed the possible correlation of ambient temperature, solar radiation and efficiency under different scenarios in order to calculate the optimal value of efficiency according to ambient temperature (Skoplaki and Palyvos, 2009). The use of a temperature-dependant electrical model is not usually appropriate as the effects of heating extend from the decrease of power output to more irreversible damages such as thermal stress caused by hotspots (Giaffreda et al. 2011). The problem of hotspot occurs frequently when the panels are partially shaded, result in modules operating in reverse bias mode. Local overheating is mainly considered a structural problem, leading to material damage at the level of the cells or the encapsulant. In short term, and depending on external operating conditions, exposure to hotspots in a PV panel decreases the efficiency. Resistive/ohmic (Joule) heating is often overlooked in literature, only tackled in papers oriented to material analysis at microlevel. When considering thermal effects, a decrease in performance of PV modules has been shown in both simulation and experimental studies such that in normal conditions (i.e. air mass=1.5, clear sky irradiance G=1000W/m2, T_{amb}=25°C), changes in ambient temperature can negatively affect the direct power output by 0.05% for each degree Celsius (Masters 2004). Approaches to the analysis of the problem of heat transfer based on Finite Element Analysis (FEA) express the thermal model and represent thermal losses resulting in PV modules (Lee et al.2012; Siddiqui et al. 2012**).** Resistive heating (Joule heating), it is often referred to as hybrid PV/T analysis and a few number of papers discuss the aforementioned phenomenon and its impact on solar PV (Peter et al.2015).

2. Problem Description:

The use of equivalent thermal models of PV panels is aimed at investigating the behaviour of the modules under various operating thermal conditions (Fuentes 1984; Jones and Underwood 2001; Armstrong and Hurley 2015). In this case, thermal resistance networks are used to take into account the thermal and material properties of the PV module. The principle consists of reproducing the structure of the commercial PV panel used as a thermal resistance circuit using

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an electrical analogy. In a steady state study, each layer is represented by a thermal resistance. The purpose of the proposed model is to calculate the temperature distribution across the PV panel and evaluate the effects of generated heat during partially shaded conditions. The module featured in this paper is a 5-layer Mono Cr-Si (Crystalline-Silicon)PV panel, with dimensions of 1490mm x 670mm x 35mm with maximum power P_{max}=150W as described in the manufacturing data sheet of the commercial PV panel from Solar Technology International. The following figure shows the layered structure of the PV panel considered for this paper.

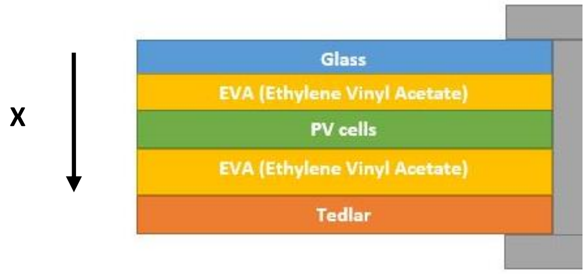

Fig.1. Layered structure of PV laminates with frame

The creation of a thermal equivalent model is performed according to the following assumptions:

- It consists of a one dimensional steady state analysis
- All material properties and heat transfer coefficients are linear according to temperature changes and materials are isotropic
- PV module is mounted according to a given tilt angle.
- The module is exposed to free air convection on the front and back surfaces.
- Wind speed is assumed as v=5m/s
- Contact resistances between layers is negligible.
- 80% of the applied solar irradiance is converted into heat.

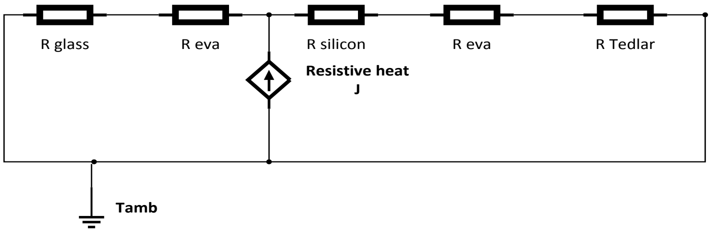

Fig.2. Equivalent Thermal Resistance Network of solar PV

The layers properties are displayed below in Table 1:

Table 1. PV layers characteristics

Layer	Thickness (mm)	Thermal conductivity (W/m K)
Glass	3.2	1.8
Silicon	5	148
EVA	1.5	0.35
Tedlar	1	0.2

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3- Governing equations:

3.1- Thermal Analysis:

PV panels exchange heat with external environment following heat transfer laws. To build the thermal model, it is necessary to define the nature of the thermal analysis, the boundary conditions, the linearity of the heat transfer coefficients and material properties. Temperature distribution depends on materials properties and since modules are composed of different materials, they absorb heat according to physical properties.

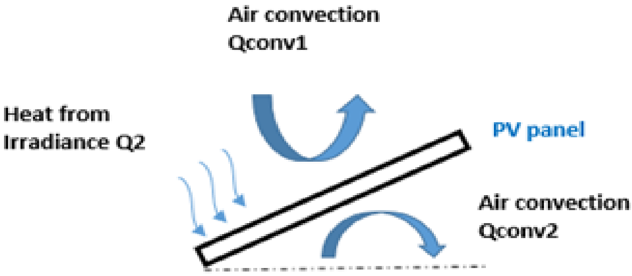

Fig. 3. Heat Exchange Modes at the Surfaces of PV Panel

Heat transfer across the PV panel is assumed one-dimensional. Heat diffusion equation in steady state conditions using Fourier's Law is:

$$KA\frac{d^2T}{dx^2} = 0 \qquad \text{Eq. (1)}$$

with conduction resistance calculated as follows:

$$R_{cond} = \frac{L}{KA} \qquad \text{Eq. (2)}$$

where Q is the heat flux at a given node through conduction (W/m^2); K is the thermal conductivity of the material (W/ (m. K)); A is the surface area of the element (m^2); T_1 is the input temperature of the element (°C); T_2 is the output temperature of the element (°C) and L is the thickness of the layer (m). Convection can be expressed by Newton's law of cooling:

$$Q = hA(T_{fluid} - T_{surface}) \qquad \text{Eq. (3)}$$

with convection resistance is calculated as follows:

$$R_{conv} = \frac{1}{hA} \qquad \text{Eq. (4)}$$

where Q is the heat flux at a given node through convection (W/m^2); h is the heat transfer coefficient of air (W/m^2. K); T_{fluid} is the temperature of fluid (air) (°C) and $T_{surface}$ is the temperature of the surface exposed to convection (°C). The convective heat transfer coefficient of air can be determined using the following expression (Lee et al. 2012):

$$h = 2.8 + 3.0v \qquad \text{Eq. (5)}$$

where V is the wind speed (m/s).

In this study, the PV panel is considered subject to the following boundary conditions in relation to the ambient temperature and the heat flow across the front face of the panel:

$$T_{amb} = 25°\text{C}; \quad -KA\left.\frac{dT}{dx}\right|_{x=12.2cm} = hA(T_{amb} - T_{front}) \qquad \text{Eq. (6)}$$

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Fig.1 illustrates a simplified version of the PV panel which is represented through five elements and six nodes. The heat equation (1) can be solved for each node for the five elements using the Finite Elements Method (FEM) and so it can be written as the following matrix equation:

$$\boldsymbol{KT} = \boldsymbol{Q} \qquad \text{Eq. (7)}$$

where $\boldsymbol{K}$ is the global thermal conductance matrix (W/ (m.K)); $\boldsymbol{T}$ is the vector of the nodal temperatures (°C) and $\boldsymbol{Q}$ is the vector of the thermal loads applied (W).

The use of Finite Element Method allows to discretize the solution domain by dividing the system into elements and nodes. Each element is associated with a matrix and a set of linear equations in order to determine the nodal temperature of each node. Elemental Matrix has the following form:

For glass sheet (element 1):

$$[K]^{(1)} = \frac{kA}{L}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & kA \end{bmatrix} \quad \text{and } [Q]^{(1)} = \begin{bmatrix} hAT_{air\ 1} \\ 0 \end{bmatrix} \qquad \text{Eq. (8)}$$

The same process is followed to create the elemental matrices for each of the other elements and then assemble them into a global matrix.

3.2- Electrical Analysis:

The electrical model considered is based on a five-parameter model of the PV module (Tian et al. 2012). It allows the calculation of the resistances of a single PV module and the currents circulating in them. The following lines discuss the electrical parameters involved to calculate the resistive heat (Joule heat) according to the one diode electrical model of solar cell. The PV module used for this study is a commercial PV module by Solar Technology, mono -crystalline silicone, composed of 72 solar cells connected in series. Table 2. shows the specifications of the module:

Table 2. Commercial PV panel electrical characteristics

PV module	Solar Technology
Nominal Power P_N (W)	150
Open Circuit Voltage V_{oc} (V)	21.6
Short circuit Current I_{sc} (A)	9.72
Maximum Power Voltage V_{mp} (V)	17.2
Maximum Power Current I_{mp} (A)	8.72
Reference Efficiency	17%
Number of cells in series N_s	72

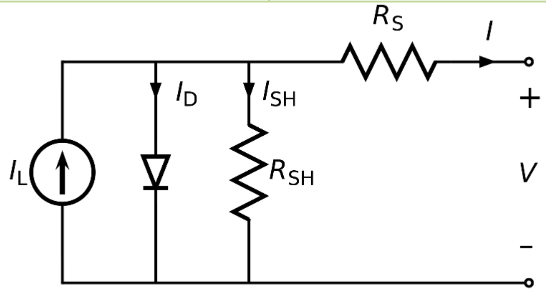

Fig. 4. Equivalent electrical model of solar cell

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3.2.1- Forward Bias Electrical model of one PV panel:

The electrical model used in this paper is the NREL model (Tian et al. 2012) in forward bias mode. Referring to Fig.4, the output current I is calculated as follows:

$$I = I_L - I_d - I_s \quad \text{Eq. (9)}$$

$$I_{sh} = \frac{V + IN_sR_s}{N_sR_{sh}} \quad \text{Eq. (10)}$$

$$I_d = I_0\left(exp\left(\frac{q(V + IN_sR_s)}{nN_sKT_c}\right) - 1\right) \quad \text{Eq. (11)}$$

where I is the output current of the PV panel [A]; V is the output voltage (V); I_{sh} is the shunt current (A); I_d is the diode current (A); I_L is the light current (A); I_0 is the diode saturation current (A); R_s is the series resistance of the panel (Ω); R_{sh} is the shunt resistance of the panel (Ω); q is the electron charge (C); n is the diode ideality factor; K is Boltzmann constant and T_c is the cell temperature (°C). The value of the shunt and series resistances R_{sh} and R_s are not usually provided by the manufacturer but they are approximated by the following expressions (ECEN 2060, 2008)

$$R_{sh} = 100(V_{oc-cell}/I_{sc}) \quad \text{and} \quad R_s = (V_{oc-cell} - V_{mp-cell})/I_{mp} \quad \text{Eq.(12)}$$

where V_{oc_cell} is the cell open circuit voltage (V); V_{mp_cell} is the cell maximum power point voltage (V) and I_{mp} is the maximum power point current (A).

3.2.2- Reverse Bias Electrical model:

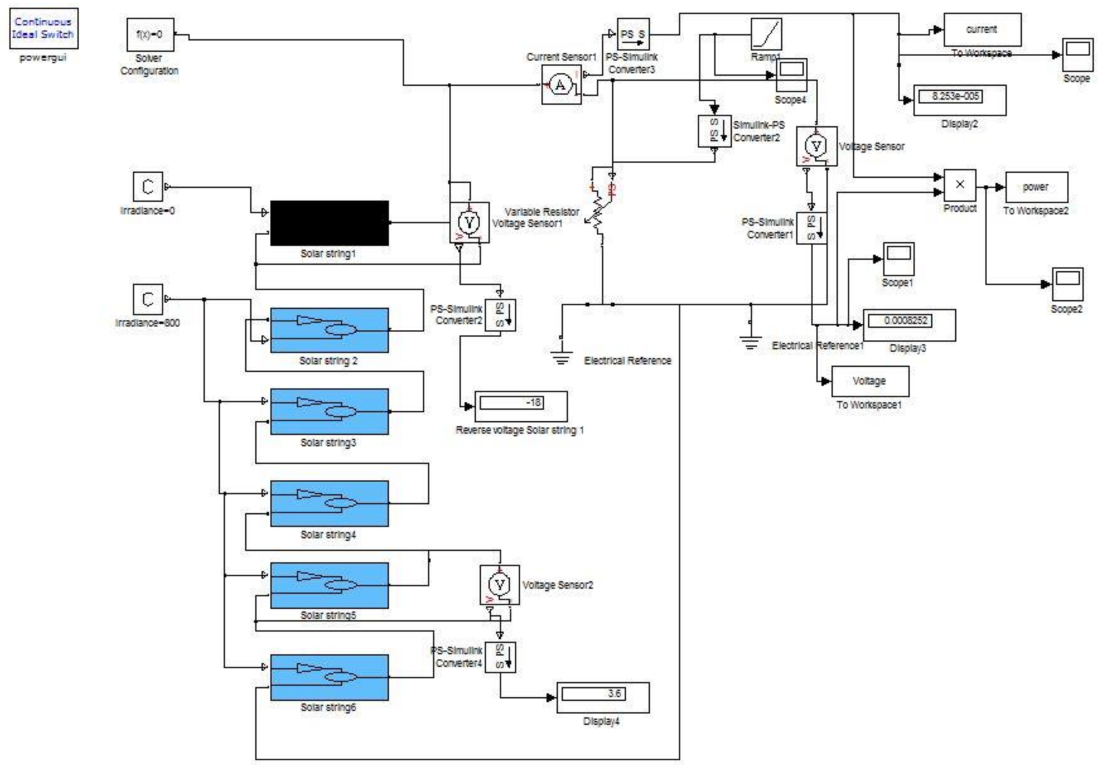

Fig.5. Partially Shaded Simulink model of PV Panel

Under partial shading, PV modules operate in reverse bias mode. It results in an electrical mismatch in the solar cell string or a string of multiple PV panels mounted in series. The problem could be at the level of one module or at the level of full PV array. This mode is

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characterized by the appearance of reverse saturation current I_R and a return voltage V_R. This mode can arise when solar cells or PV panels mounted in series are not identical in performance as the voltage of the entire string will be injected into the shaded cell or shaded panel. Fig. 5. illustrates a Matlab/Simulink model of such mismatching condition. The reverse voltage of solar_cell_string1 (black) when solar irradiance G=0 is equal to V_R= -18V.

4. Resistive heating:

The circulation of current in the PV panel as described above causes Joule effect at the level of series and shunt resistances of the PV panel. Resistive heating or Joule heating is considered a parasitic effect and is governed by the following equation:

$$Q_J = I^2 R \qquad \text{Eq. (13)}$$

For calculating Joule heat in reverse bias conditions, shunt and series resistance are considered for the study. The approximation of R_{sh} provided in eq. (12) will be used to estimate its value and thus calculate the corresponding Joule heat. The values used in this study are R_s = 0.008 **Ω** and R_{sh} = 3.086 **Ω**. Heat generated through the Joule Effect is given by:

$$Q_{sh} = I_{sh}^2 R_{sh} = {V^2}/{R_{sh}} \quad \text{and} \quad Q_s = I_s^2 R_s \qquad \text{Eq. (14)}$$

When the panel is partially shaded as in Fig.5, and the irradiance G at Solar_String_1 = 0, the voltage present in the string is the return voltage V_R. In the absence of bypass diodes, the shaded string is dark and is subjected to the sum of the voltages of the other operating strings. At the maximum power operating point in forward bias conditions, $I=I_{mpref}$ and $V=V_{mpref}$ and therefore Q_s = 0.60W and Q_{sh} = 0.03W. For the shaded string as shown in Fig.5, V_R=-18V and Q_{sh} = 104.99W.

5. Implementation of the simulation model into Ansys Workbench:

5.1- Geometry

The geometry used is a simplified version of the Mono Cr-Si PV panel and consists of 72 solar cells connected in series. The dimension of a single solar cell is 125mm x 125mm with a 2mm gap between neighbouring cells. The frame thickness is 35mm and the thickness of each layer is displayed in Table 1. Each solar cell has two copper busbars that ensure the conduction of electrical current through the entire cell and thus the entire panel.

5.2- FEA model:

Simulation work consists in using the geometry created in Fig. 6. and Fig.7. with specified boundary conditions and applying the external loads including heat from radiation and air convection . The computational model will evaluate the behaviour and temperature distribution in two cases: under normal conditions and under normal conditions with resistive heat when the panel is reversed biased, using the electrical characteristics corresponding to each case. After meshing the model, the loads and constraints are incorporated into the model.

5.2.1-Case.1: Simulation under normal conditions

The error of simulation between the actual model provided by the manufacturer's data sheet and the simulated result below Fig. 7 is estimated at 2.53% since the Nominal Operating Cell Temperature (NOCT) of the commercial PV panel considered is 48°C.

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Table 3. Simulation parameters

Ambient Temperature T_{amb} (°C)	25
Air Convection on the front (W/m^2. K)	17.8
Air Convection on the edges (W/m^2. K)	17.8
Air Convection on the back (W/m^2. K)	17.8
Heat applied through radiation on the front (W/m^2)	800

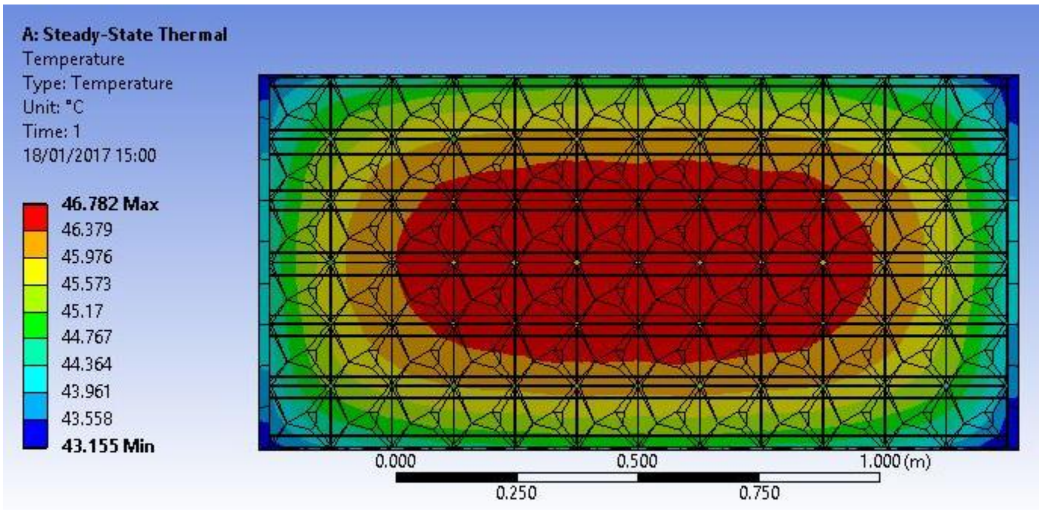

Fig. 6. Temperature distribution through a single PV panel under normal conditions

5.2.2-Case.2: Simulation under partially shaded conditions

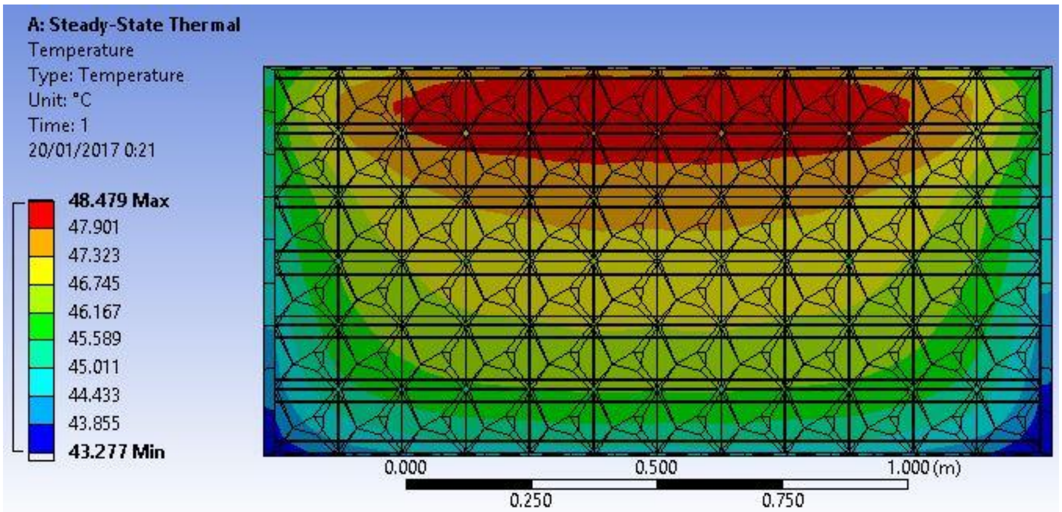

Fig. 7. Temperature distribution through a single PV panel under partial shading with generated joule heat in the shaded string

6. Results and Discussion:

The silicon sheet was partitioned according to the materials existing in the PV panel, each section was meshed in order to discretize the model and calculate loads and temperatures at nodes. Then Joule heating calculated separately in a previous section of this paper was incorporated into the model as internal heat generation. After simulation, it is observed that the maximum temperatures in each case depends on the resistances values. Fig. 6 serves as a reference to compare normal conditions and the effect of internal heat generated. For Case 1, maximum temperature has reached 46.782°C and the minimal temperature through the panel

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is 43.15°C and for Case 2, maximum and minimum temperatures are 48.47°C and 43.27°C respectively. High temperatures are localized mostly in the centre of the shaded area while the edges and connections experience lower temperatures in Case 2.

Table.4. comparison between simulated and reference temperatures

Temperature under normal conditions (°C)	**Simulated temperature with Joule effect (°C)**	**Difference (°C)**
46.782	48.479	1.69

6. Conclusion:

In this paper, a simple model is presented to evaluate resistive losses in a PV module using the approximation of the internal series and shunt resistance of the module. It is aimed as an indicator for evaluating the effect of internally generated heat through Joule effect on the solar cells , which proved to be minimal as observed at the temperature distribution of case2. The simulation was performed under standard ambient temperature T_{amb}=25°C and considering normal irradiance and partial shaded conditions .It represents the best case scenario where parameters remain unchanged through time. In real conditions, PV modules experience irradiance fluctuation on a frequent basis which expose them to stronger thermal effects caused by high currents and overvoltage, leading to local overheating known as hotspots (He et al.2015). Bypass diodes are always used to avoid mismatching in PV circuit caused by partial shading but they became faulty due to harsh external conditions.

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