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A Three-Dimensional TLM Simulation Method for Thermal Effect in PV-Solar Cells

R. Hocine, A. Boudjemai, A. Amrani, K. Belkacemi

***Abstract*—**Temperature rising is a negative factor in almost all systems. It could cause by self heating or ambient temperature. In solar photovoltaic cells this temperature rising affects on the behavior of cells. The ability of a PV module to withstand the effects of periodic hot-spot heating that occurs when cells are operated under reverse biased conditions is closely related to the properties of the cell semi-conductor material.

In addition, the thermal effect also influences the estimation of the maximum power point (MPP) and electrical parameters for the PV modules, such as maximum output power, maximum conversion efficiency, internal efficiency, reliability, and lifetime. The cells junction temperature is a critical parameter that significantly affects the electrical characteristics of PV modules. For practical applications of PV modules, it is very important to accurately estimate the junction temperature of PV modules and analyze the thermal characteristics of the PV modules. Once the temperature variation is taken into account, we can then acquire a more accurate MPP for the PV modules, and the maximum utilization efficiency of the PV modules can also be further achieved.

In this paper, the three-Dimensional Transmission Line Matrix (3D-TLM) method was used to map the surface temperature distribution of solar cells while in the reverse bias mode. It was observed that some cells exhibited an inhomogeneity of the surface temperature resulting in localized heating (hot-spot). This hot-spot heating causes irreversible destruction of the solar cell structure. Hot spots can have a deleterious impact on the total solar modules if individual solar cells are heated. So, the results show clearly that the solar cells are capable of self-generating considerable amounts of heat that should be dissipated very quickly to increase PV module's lifetime.

***Keywords*—**Thermal effect, Conduction, Heat dissipation, Thermal conductivity, Solar cell, PV module, Nodes, 3D-TLM.

I. Introduction

THE study in depth of the thermal behavior of photovoltaic devices may be considered as a critical aspect in the diffusion of photovoltaic conversion systems. Anomalies in the distribution of the temperature on the cell under operating conditions, may lead to an important decrease of the performances of the cell from an electrical and efficiency point of view. As the efficiency of these devices is low (11-14% for the polycrystalline cells and less than 8% for the a-Silicon ones), its reduction may be detrimental for the performances of the whole conversion plant [1]. Also the electrical parameters are strongly influenced by the temperature increasing: the open circuit voltage (VOC) decreases when temperature increases while the short circuit current (ISC) shows only slight variation [2]. Finally, fill factor and output power of the PV cell are strongly influenced by the temperature variations.

The aim of the paper is to propose the tridimensional model of a photovoltaic cell implemented by Transmission Line Matrix method (TLM). The analysis of the thermal behavior of the implemented model has been conducted to simulate the behavior of the PV module under operating conditions.

The model has been implemented according to the geometrical and physical features of commercial photovoltaic cells and we calculate the junction temperature for a given input power and localises hot spots then visualises the thermal behaviour of the device under power conditions. Two technologies have been considered: poly and amorphous silicon based cells [3]. The implemented model has also been validated from an electrical point of view. Simulation results confirm the goodness of the proposed model for the thermal behavior of PV cells.

II. TLM Technique

The TLM method is intrinsically a discrete approach, which directly models a physical process.

It is based on the telegrapher's equation for a transmission-line [4]:

$$\nabla^2 \Phi = A\, R_d\, C_d \frac{\partial \Phi}{\partial t} + B\, L_d\, C_d \frac{\partial^2 \Phi}{\partial^2 t} \quad (1)$$

where Φ is the potential, R_d, C_d and L_d are distributed resistance, capacitance and inductance, and A and B are dimension constants. If the first time derivative term on the right-hand side of (1) dominates the second term, the network models the diffusion equation described by the known equation:

$$\nabla \left(k_t(T) \quad \nabla T(x,y,z,t)\right) + H(x,y,z,t) = \rho\, c_p \frac{\partial T(x,y,z,t)}{\partial t} \quad (2)$$

R. Hocine is with Department of Electronics Engineering, BP 1505 EL M'Naour, University of Sciences and Technology of Oran Algeria, (e-mail: rak_hocine@yahoo.fr).

A. Boudjemai is with the Centre of Satellite Development (CDS), Space Technology Research Division BP.: 4065 Ibn Rochd USTO Oran, Algeria, (phone: +21341620324; fax: +21341620320; e-mail:a_boudjemai@yahoo.fr).

A.Amrani is with the ECP3M Laboratory Electrical Engineering Department Abdelhamid Ibn Badis University, Mostaganem Algeria. Faculté des Sciences & technologie, Site I, Route de Belahcel BP 300, Mostaganem (phone: + 213 45 26 54 55; fax: +213 45 26 54 52).

K. Belkacemi is with the Centre of Space Techniques, Space instrument Division P.o.Box 13 Arzew 31200, Oran, Algeria, (phone: +21341473919; fax: +21341473665; e-mail: belkacemi.karim10@yahoo.fr).

where T is the temperature, H the heat generation rate per unit volume, Cp is the specific heat, ρ is the density and K_t is the thermal conductivity. Therefore, the material can be replaced by a lumped RLC or transmission-lines network where temperature will be represented by voltage.

Each node of this TLM network, Fig. 1, has the resistors clustered around the node and represents the thermal resistance of the material, while the capacitor/ inductor combination is replaced by a loss-free transmission-line of impedance Z, which connects each node to its neighbours and carry voltage pulses between the nodes in finite time Δt. According to the fundamental transmission line theory [5], the impedance is related to C and L through:

$$Z=\sqrt{\frac{L}{C}}=\frac{3\,\Delta t}{C}=\frac{L}{3\,\Delta t} \qquad (3)$$

Since the capacitor model the heat capacity of the material, the TLM parameters R and Z can be evaluated from:

$$2R=\frac{1}{K_t\,\Delta x} \quad \text{and} \quad Z=\frac{3\Delta t}{\rho c_p \Delta x^3} \qquad (4)$$

where: Δx is the length of the cubic elemental volume representing a node. A TLM solution is obtained by repeatedly considering delta voltage (temperature) pulses to be incident simultaneously on all parts of all nodes. These incident pulses are scattered instantaneously into reflected pulses which, during the time step Δt, travel along link transmission lines to become incident upon neighbouring nodes. The TLM routine operates on the travelling, scattering and connecting of these pulses in the network. The transmission lines in the model act as delay lines, with the node impulse population being the discrete solution at each time step.

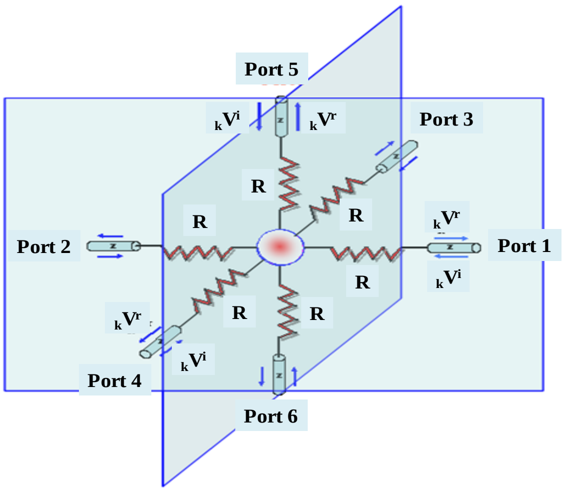

Fig. 1 Equivalent TLM of a node

From TLM modeling [6] the temperature at each node is given by:

$$_kV(N)=\left[\frac{2\left(_kV_1^i+{}_kV_2^i\right)}{R_x+Z}+\frac{2\left(_kV_3^i+{}_kV_4^i\right)}{R_y+Z}+\frac{2\left(_kV_5^i+{}_kV_6^i\right)}{R_z+Z}\right]\frac{1}{Y} \qquad (5)$$

where $Y=\frac{2}{R_x+Z}+\frac{2}{R_y+Z}+\frac{2}{R_z+Z}$ and $_kV_n^i$ are incident pulses, at the K^{ieme} iteration. Reflected pulses are calculated according to:

$$_kV_{1,2}^r=\frac{1}{R_x+Z}\left[Z\ _KV+\left(R_x-Z\right)V_{1,2}^i\right] \qquad (6)$$

$$_kV_{3,4}^r=\frac{1}{R_y+Z}\left[Z\ _KV+\left(R_y-Z\right)V_{3,4}^i\right] \qquad (7)$$

$$_kV_{5,6}^r=\frac{1}{R_z+Z}\left[Z\ _KV+\left(R_z-Z\right)V_{5,6}^i\right] \qquad (8)$$

These pulses travel to adjacent nodes to become, at the (k+1) iteration, incident pulses:

$$_{k+1}V_j^i(x,y,z)=\Gamma_j\ _kV_j^r(x,y,z)+\left(1-\Gamma_j\right)_kV_{j'}^r(u,v,w) \qquad (9)$$

where (x, y, z) are node N co-ordinate. The reflection coefficient in direction (j) is:

$$\Gamma_j=\frac{Z(u,v,w)-Z(x,y,z)}{Z(u,v,w)+Z(x,y,z)} \qquad (10)$$

The corresponding values of j', u, v, w for j=1, 2, … of (9) and (10) are listed in Table I [7].

TABLE I
THE VALUES OF J, J ', U, V, AND W USED

j	j'	u	v	w
1	2	x-1	y	z
2	1	x+1	y	z
3	4	x	y-1	z
4	3	x	y+1	z
5	6	x	y	z-1
6	5	x	y	z+1

Implementing the TLM routine consists solely of repeating (5) to (10) for all nodes for the time of the numerical experiment.

As argued by Kronberg and al. [8], boundary conditions express the interaction of the system in hand with its surroundings. Boundaries are part of the transport model and thus should be consistent with the description of the heat transport inside the medium. For heat sinking the corresponding boundary is an electrical short-circuit S/C or Γ_j =-1. Hence, any incident pulse on the boundary will be returned equal in magnitude but reversed phase. For a heat insulated boundary we use an electrical open-circuit O/C or Γ_j =1 and any incident pulse on the boundary will be returned equal in magnitude and in phase.

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III. The Simulation Models

Two different models have been developed because the amorphous silicon cell structure is obtained through the superposition of more layers with respect to the polycrystalline one. The mono crystalline layer has been replaced with the poly-Si one. Fig. 2 reports the zoom on the thickness of the implemented amorphous Silicon cell.

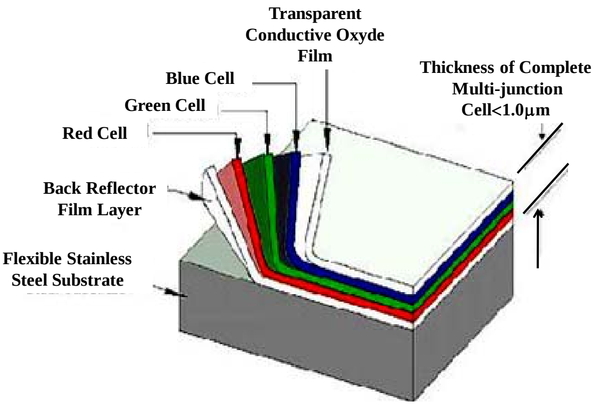

Fig. 2 Zoom on the thicknesses of the a-Si modeled cell

In Fig. 2, the upper layer, the top electrode of the cell has been implemented as to be composed of silver as well as the bottom plate. The PV cells model can be combined and connected together in such a way that they deliver exactly the required power. In this work, each PV panel composed of N series-connected solar cells can be evaluated using TLM method.

Fig. 3 shows example geometry-designs of cooling pipes considered in this work for a PV panel where the fluid inlet of temperature Ta is underneath cell 1 while the fluid outlet of temperature Tb is at backside of the cell N. The fluid serves as both heat sink and solar heat collector [9].

Applying a cooling pipe for each string enhances much more the electrical efficiencies of the PV cells. The best design is the one which keeps the operating temperature of the PV cells as minimum and uniform as possible, resulting in a maximum energy yield of the PV cells.

The thermal analysis has been developed using the TLM method, so to complete the model definition the physical features of each layer have to be set up. The value of thermal conductivity or specific heat has to be set for the thermal analysis. The values of the thermal parameters required in the setting mask for the poly-Si and the a-Si models are reported in Tables II and III, respectively [10], [11].

TABLE II
Thermal Parameters of the Poly-Si Model

Material	K[W/m*°K]	ρ[Kg/m^3]	C_p[J/Kg°K]
Ag	429	10500	235
Poly-Si	34	2320	678
TiO_2	11.7	4156	692

TABLE III
Thermal Parameters of the A-Si Model

Material	K[W/m*°K]	ρ[Kg/m^3]	C_p[J/Kg°K]
Ag	429	10500	235
ITO	87	7120	753
a-Si	$(1.3.10^{-11}(T-900)^3 + 1.3.10^{-9}(T-900)^2 + 1.0.10^{-6}(T-900) + 1.0.10^{-2})$	(0.171 T/1865+0.952)	2260

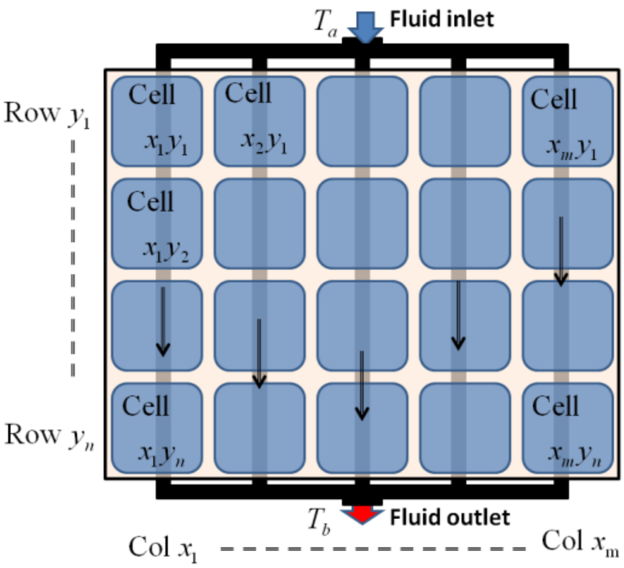

Fig. 3 Example design of a PV panel consisting of N series-connected solar cells

Note that the parameters of the TiO_2 layer (for poly-Si model) and the parameters of a-Si layer (for a-Si model) are defined as a temperature-dependent equation.

The temperature-dependent thermal parameters (typically thermal conductivity k (T)) can be t incorporated conveniently point by point into the TLM routine [12].

Anomalies in the distribution of the temperature on the cell under operating conditions, parameter defined by NOCT (Nominal Operative Cell Temperature) specification, may lead to an important decrease of the performances of the cell from an electrical and efficiency point of view [13], [14], so the values of Tcell and Tenv are defined by the NOCT specification which states that with an incoming flux of 800 W/m^2, a wind speed of 1 m/s and an environmental temperature of 20°C.

Fig. 4 and 5 report the simulation results for temperature distribution on the poly-Si and a-Si cell. We have the cell temperature is 345°C for the poly-Si cell and 350°C for the amorphous one.

The heating of a photovoltaic cell under operative conditions is strongly due to the effect of sun irradiation and the hot-spots are produced when one PV cell (belonging to a module) is partially shaded. The affected cell is forced into reverse bias by starting to dissipate power that increase temperature in consequent.

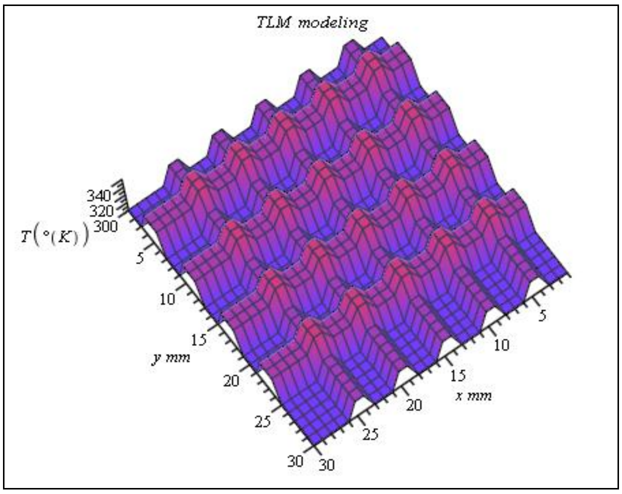

Fig. 4 Temperature distributions on poly-Si cell

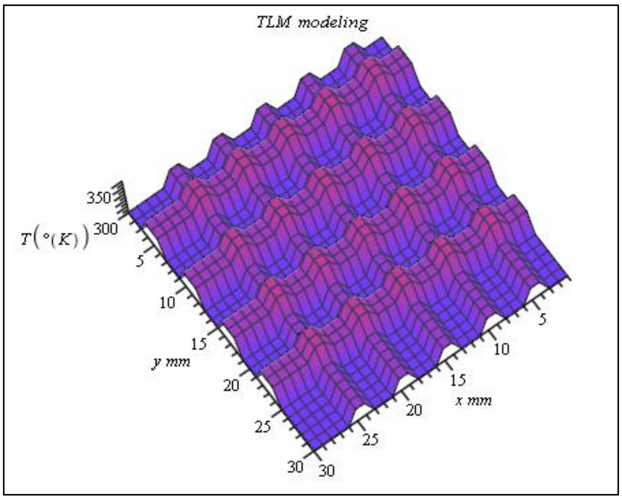

Fig. 5 Front face temperature distributions for the a_Si cell

The simulations results confirm the goodness of the proposed model that shows a temperature distribution quite similar to the real operating case.

Fig. 6 shows the vertical profile heat diffusion in cells.

A three-dimensional TLM analysis has been presented in this paper to investigate the effect of self-heating in solar cell as unit element of PV module.

The results show clearly that each of unit cells are capable to self-generating amount of heat, which needs to be removed efficiently to avoid ample thermal cycles, which strongly reduce the PV lifetime. Therefore, this study introduced a more accurate evaluation of the PV modules performance implemented with cooling pipes underneath each PV string.

The best design is the one which keeps the operating temperature of the PV cells as minimum and uniform as possible, resulting in a maximum energy yield of the PV cells.

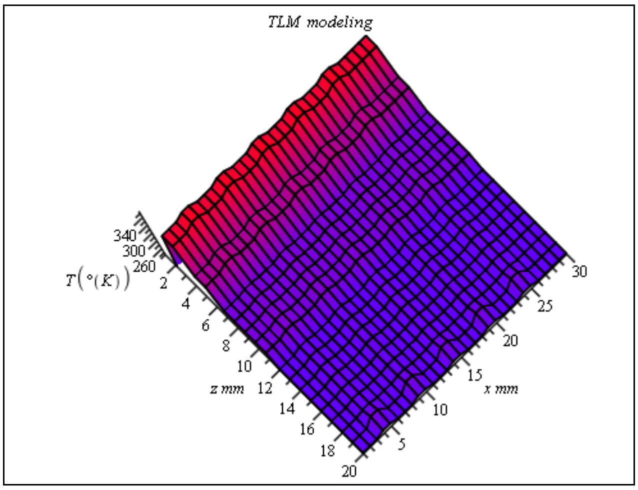

Fig. 6 Vertical profile temperature distribution on the cells

IV. Conclusion

The paper proposes the 3-D TLM model for a PV-cell in operating condition. The proposed model of a well-operating PV-cell can be useful for implementing typical defects usually pointed out by means of thermography.

The TLM method was applied to study self-heating in solar cell. The method is easy to program and gives insights on temperature distribution throughout the cells. It allows a better understanding of heat behavior and management at each layer that forms the structure. Localized absolute temperature determination and precise hot sources is important in PV module.

The TLM can be a good alternative design tool, since it allows the evaluation of temperature at any point of the structure. We believe that the unconditionally stable nature of the method and the ease with which complex geometry can be handled good with the TLM technique. So a comprehensive thermal analysis is possible for different solar cells with complex geometry and fabricated with many different materials.

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