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Solar Cell Modeling and Parameter Optimization Using Simulated Annealing

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This paper develops a unique solar cell modeling approach that incorporates search and optimization techniques for the determination of equivalent circuit parameters. In particular, simulated annealing is applied to automate the procedure of finding near-optimal values of the solar cell under various environmental settings. Photocurrents, diode reverse saturation currents, diode ideality factors, series resistances, and shunt resistances involved in the cell structure and parameters can be identified this way for every operating condition in an accurate modeling of the cell behavior. The developed models are evaluated for a set of solar cells, and their accuracy is verified by comparing the I/V curves generated from computer simulations with those provided by the cell manufacturer or determined experimentally. In addition, an algorithm has also been presented to use this model in solar array simulation under varying environmental conditions.

Nomenclature

A	=	diode ideality factor
G	=	illumination intensity at operating conditions, W/m^2
G_o	=	illumination intensity at standard conditions, W/m^2
I	=	current, A
I_{ph}	=	photocurrent, A
I_{sat}	=	diode saturation current, A
K	=	radiation degradation factor
k	=	Boltzmann constant
P	=	power, W
R_p	=	parallel resistance
R_s	=	series resistance
T	=	temperature solar cell at operating conditions, °C
T_K	=	temperature, K
T_o	=	temperature of solar cell at standard test conditions, °C
V	=	voltage, V
V_t	=	thermal voltage, V
λ	=	number of junctions in the solar cell

Subscripts

mpp	=	maximum power point
mppϕ	=	maximum power point under radiation fluence
o	=	standard test condition
oc	=	open circuit
ocϕ	=	open circuit under radiation fluence
sc	=	short circuit
scϕ	=	short circuit under radiation fluence

I. Introduction

SOLAR cell models have long been a source for the analysis of solar cell behaviors. The most common approach to solar cell modeling is the use of a single-diode solar cell equivalent circuit [1], shown in Fig. 1. The current–voltage relation of a solar cell is described by

$$I = I_{ph} - I_{sat}(e^{\frac{V+IR_S}{V_t}} - 1) + \frac{V - IR_s}{R_p} \tag{1}$$

where V_t is given by $V_t = (AkT_K/q)$

Because of the nonlinearity and implicit nature of these equations, the determination of parameters demands significant computational effort. In most cases, the model includes only variations of the photocurrent and diode saturation current whereas the values of other parameters are kept constant or adjusted for better curve fitting [2]. However, it is known that solar cell parameters are affected by temperature and irradiance, both of which further affect solar cell performance curves. Hence, for accurate modeling of a solar cell, it is essential to incorporate these effects. Various analytical methods have been proposed for the determination of junction parameters [3], but applications of these methods are limited to the availability of test data and require significant computational effort. Progress has been reported in [4], in which a genetic algorithm has been implemented for parameter determination, although it requires a set of I/V characteristics as input.

In this paper, we implement a simulated-annealing-based optimization method for the determination of A and R_s for any set of conditions using a set of data at standard test conditions obtained from the manufacturer's data sheet. This eliminates the requirement of having a set of I/V curves of the cell beforehand. Simulated annealing was introduced by Kirkpatrick et al. [5]. It is a global optimization method that can distinguish between different local optima and has the capability of escaping local optima; therefore, it can be used for the optimization of complex nonlinear functions.

As this model is basically developed to simulate the behavior of a solar array over a number of orbit cycles, the primary motivation for this work is to develop a model that can be applied to all major types of solar cells (single and multijunction) in space applications. Thus, the requirement is to design a tool that can automatically update the values of the solar cell parameters if there is any change in environmental conditions. The model is based on a simplified single-diode model to describe the electrical behavior of the solar cell from the cell characteristics given in the cell data sheet. An adapted version of this model, implemented using MATLAB®, is described with the methodology in Sec. II.

The model also makes use of an additional diode factor feature for multijunction solar cells, making it suitable for all major types of space solar cells, that is, single and multijunction, with almost the same accuracy. Another attractive feature of this model is that it makes use of a data-based approach, that is, the data set of current and voltage values of the solar cell at any standard environmental

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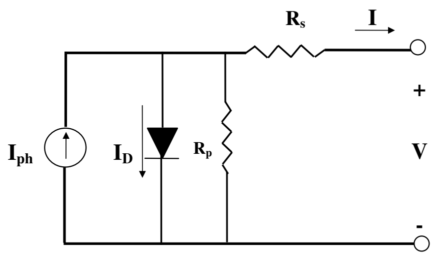

Fig. 1 Solar cell equivalent circuit.

condition will be enough for the model to work for any environmental condition.

The model developed herein is applied in Sec. III to generate the I/V curves for a set of solar cells at different illumination and temperature conditions. The accuracy of this model is verified by comparing the I/V curves generated from computer simulation to the ones provided by the cell manufacturer. The application of the model for the determination of I/V characteristics of the solar cell after degradation under radiation fluence has been described in Sec. III.A. In addition, an algorithm has also been presented in Sec. III.B to use this model in solar array simulation under varying environmental conditions.

II. Methodology

A. Solar Cell Equivalent Circuit Model Equations

Most of the modeling applications make use of a simplified solar cell model [2]. This model ignores the effect of leakage currents, eliminating the last term of Eq. (1). In addition, for multijunction cells, the concept of considering multijunction solar cell as series connected diodes is used. These series connected diodes are replaced by a single equivalent diode, using an additional factor λ, representing the number of junctions in the solar cell [6]. And so Eq. (1) can be rewritten as follows:

$$I = I_{\mathrm{ph}} - I_{\mathrm{sat}}(e^{\frac{V+IR_s}{V_t}} - 1) \tag{2}$$

where V_t is given by $V_t = \lambda(AkT_K/q)$

The current model needs the following four parameters, V_{oc} (open circuit voltage), I_{sc} (short circuit current), I_{mpp} (current at maximum power point), and V_{mpp} (voltage at maximum power point), along with their respective temperature coefficients, which are represented by dV_{oc}, dI_{sc}, dI_{mpp}, and dV_{mpp}. The effect of variations in temperature and illumination on different operating conditions is given as follows.

1. Short Circuit Condition

$$I_{\mathrm{ph}} = I_{\mathrm{sco}}(G/G_o) + dI_{\mathrm{sc}}(T - T_o) \tag{3}$$

2. Open Circuit Condition

$$I_{\mathrm{sat}}(G,T) = \frac{I_{\mathrm{ph}}(G,T)}{(e^{\frac{V_{\mathrm{oc}}(T)}{V_t(T)}} - 1)} \tag{4}$$

$$V_{\mathrm{oc}} = V_{\mathrm{oc}o} + V_t \ln(G/G_o) + dV_{\mathrm{oc}}(T - T_o) \tag{5}$$

which is generally true for illumination intensity less than 100 $\mathrm{W/m^2}$. For illumination intensity greater than 100 $\mathrm{W/m^2}$, the following relationship is used:

$$V_{\mathrm{oc}} = V_{\mathrm{oc}o} + V_t \ln(G/100)\ln(G/G_o) + dV_{\mathrm{oc}}(T - T_o) \tag{6}$$

3. Peak Power Point

$$I_{\mathrm{mpp}}(G,T) = I_{\mathrm{mpp}s}(G/G_o)(1 + dI_{\mathrm{mpp}}(T - T_o)) \tag{7}$$

$$V_{\mathrm{mpp}} = \begin{cases} V_{\mathrm{mpp}o} + V_t \ln(G/100)\ln(G/G_o) + dV_{\mathrm{mpp}}(T - T_o) & \text{if } G \geq 100\ \mathrm{W/m^2} \\ V_{\mathrm{mpp}o} + V_t \ln(G/G_o) + dV_{\mathrm{mpp}}(T - T_o) & \text{if } G < 100\ \mathrm{W/m^2} \end{cases} \tag{8}$$

B. Simulated-Annealing-Based Parameter Prediction

Equations (3–8) represent the change in solar cell parameters with regard to temperature and irradiance. The coefficients of temperature for current and voltage are usually provided in the manufacturer's data sheet. Therefore, the change in value of I_{ph} and I_{sat} can be determined linearly if an accurate value of A and R_s is known. The main effect of A and R_s is on the shape of the curve around the maximum power point and, hence, on the determination of the maximum power point under that operating condition. Because of this reason, in most of the cases, the values of these parameters are usually obtained from I/V curves.

In [7], it was shown that the value of A and R_s are best when the difference between the value of $\frac{\mathrm{d}I}{\mathrm{d}V}$ at the maximum power point and $\frac{I_{\mathrm{mpp}}}{V_{\mathrm{mpp}}}$ is minimal. Using this as our objective function, we have defined a search and optimization problem for the determination of the optimal values of A and R_s. Adaptive simulated annealing (ASA) is implemented for the objective minimization optimization problem in which the objective function is defined as follows:

$$J = -\frac{\mathrm{d}I}{\mathrm{d}V}\bigg|_{V=V_{\mathrm{mpp}}} + \frac{I_{\mathrm{mpp}}}{V_{\mathrm{mpp}}} \tag{9}$$

where

$$\frac{\mathrm{d}I}{\mathrm{d}V}\bigg|_{V=V_{\mathrm{mpp}}} = \frac{\frac{I_{\mathrm{sat}}}{V_t} e^{(\frac{V_{\mathrm{mpp}}+IR_s}{V_t})}}{1 + \frac{I_{\mathrm{sat}}R_s}{V_t} e^{(\frac{V_{\mathrm{mpp}}+IR_s}{V_t})}}$$

The model presented in this paper consists of mainly two parts: 1) a simulated-annealing-based optimizer, and 2) a single-diode-based cell modeler. Both of these have access to the set of basic parameters (V_{oc}, I_{sc}, I_{mpp}, and V_{mpp}) at standard test conditions along with their respective temperature coefficients for different types of cells. This set of data can be upgraded to accommodate any type of cell. The model is called for a specific cell type with environmental conditions. Upon the call, both the modules (optimizer and modeler) are loaded with the specific cell data. Then the optimizer calculates the optimal (near optimal) values of A and R_s using the cell data and environmental conditions (temperature and illumination intensity). These values are then given to the modeler, who generates the I/V curves for the cell or array, whatever the case may be.

III. Results

A MATLAB®/Simulink-based model is used to demonstrate the performance of the modeling process and has been tested for various types of cells. Figures 2–4 show the result of the simulation of I/V curves for Si, $GaInP_2/GaAs/Ge$ dual junction (DJ) and ultra, or advanced, triple junction (ATJ) solar cells, respectively, at standard conditions, as well as a comparison with the data points taken from the I/V curve given in the manufacturer's data sheet. Along with this, the model has been checked for its performance at various environmental conditions. The effect of illumination on the I/V curve of the advanced triple junction solar cells is demonstrated in Fig. 5. These cells are used in the NPSAT1 satellite. The results in Fig. 5 show very close resemblance to those from the experiment [8]. The effects of temperature variation on single junction GaAs/Ge cells are presented in Fig. 6. Here, the results are compared with the points taken from [9]. An analysis of simulation results for the values of A and R_s under different illumination conditions for Si solar cell is given in Table 1. Here we can see that the error varies between 0.1–10%. As stated in the previous section, the main effect of A and R_s is on the shape of curve around maximum power point; thus, the simulation results are also compared in terms of voltage and power at the maximum power point with the measurement data given by the manufacturer. The comparison for Si and ATJ solar cells over a range of temperatures is given in Fig. 7. Here we can see that error between the simulated and measured values is limited to a maximum value of less than 3%. A possible reason for the very high error percentage in cases of A and R_s can be attributed to the fact that the values taken from the literature [10] may only be approximate and do not represent the accurately measured data.

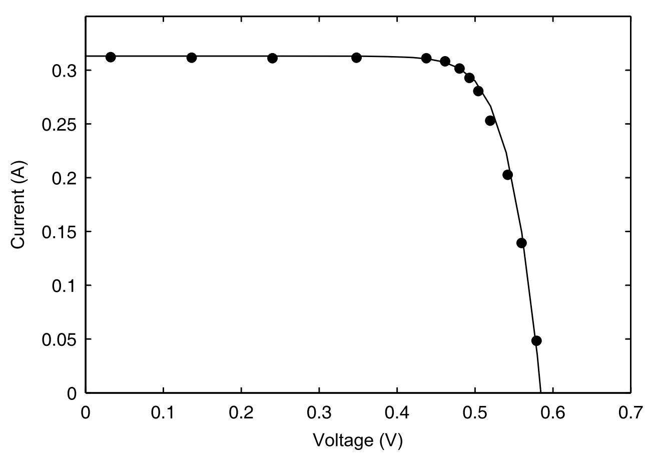

Fig. 2 Simulated I/V curve for the Si solar cell compared with the discrete points taken from the manufacturer's data sheet.

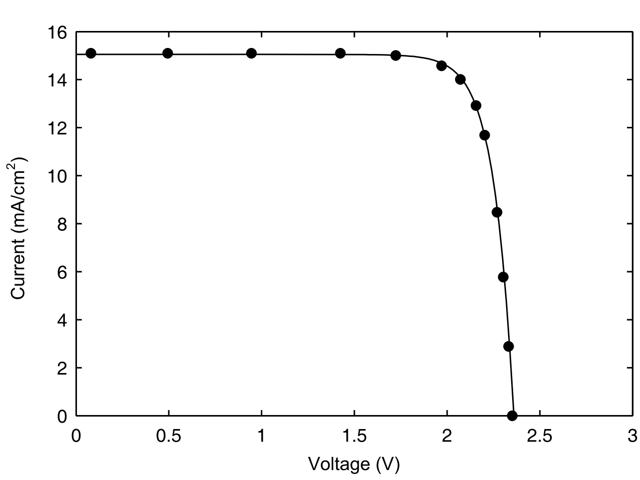

Fig. 3 Simulated I/V curve for the DJ solar cell compared with the discrete points taken from the manufacturer's data sheet.

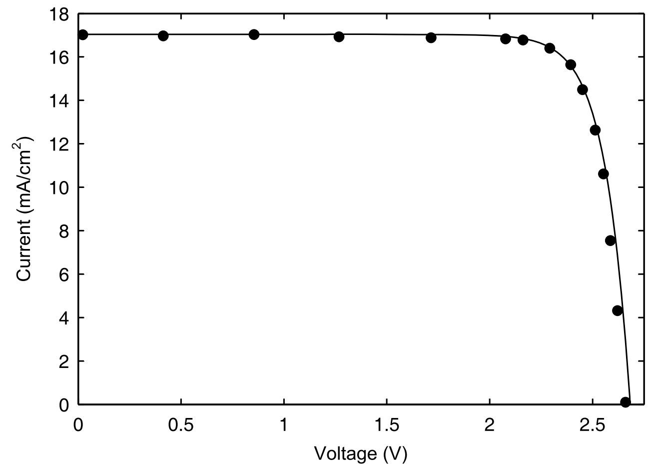

Fig. 4 Simulated I/V curve for the ATJ solar cell compared with the discrete points taken from the manufacturer's data sheet.

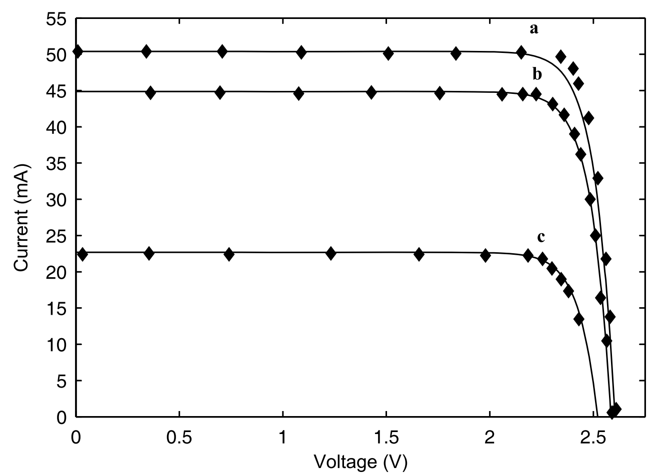

Fig. 5 Simulated I/V curves for the ATJ solar cell for the illumination intensity of I/V and various incident angles: a) 0, b) 30, and c) 60 deg. The discrete points shown are taken from [8].

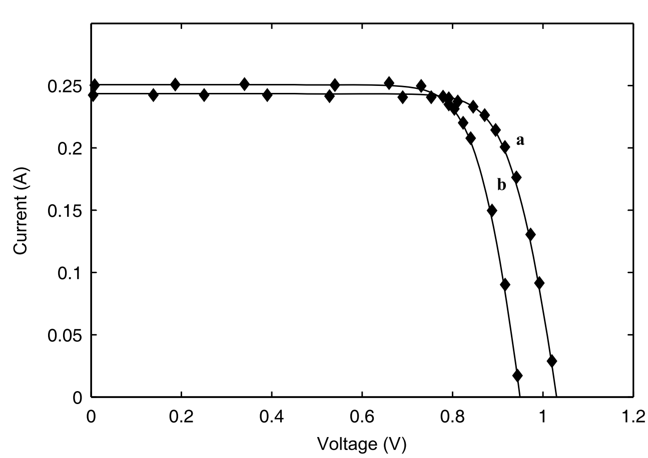

Fig. 6 Simulated I/V curves for the single junction GaAs/Ge cell at various temperatures: a) 25, and b) 70°C. The discrete points shown are taken from [9].

Table 1 Simulation results error analysis

Condition	Data taken from literature	Simulation results	Relative error, %
Temperature = 27°C	$A = 1.130$	$A = 1.1278$	0.19
Insolation = 1353 W/m^2	$R_s = 0.0432$	$R_s = 0.0392$	9.25
Temperature = 27°C	$A = 1.0$	$A = 1.103$	9.33
Insolation = 1070 W/m^2	$R_s = 0.0113$	$R_s = 0.0117$	3.41

A. Solar Cell Performance Evaluation After Degradation

In the previous section, we discussed and evaluated the model for varying temperature and illumination. For spacecraft applications, the users are more interested in end of life (EOL) rather beginning of life (BOL) characteristics. The model presented here can also be equally useful in predicting EOL characteristics after radiation degradation. In a space environment, radiations of different types are the main environmental degradation factor. For theoretical and experimental purposes, the radiation effect due to electron and proton fluxes are integrated into an equivalent 1 MeV electron flux (fluence). The equivalent fluence for a particular mission depends on solar cell and solar array type along with orbit parameters and mission duration. Let the radiation degradation factors for V_{oc}, V_{mpp}, I_{sc}, and I_{mpp} under a given equivalent fluence (ϕ) be $K_{v\mathrm{oc}}$, $K_{v\mathrm{mpp}}$, $K_{I\mathrm{sc}}$, and $K_{I\mathrm{mpp}}$ respectively. The temperature coefficients of the solar cell in this case are given as $V_{\mathrm{oc}\phi}$, $V_{\mathrm{mpp}\phi}$, $I_{\mathrm{sc}\phi}$, and $I_{\mathrm{mpp}\phi}$. These factors can be determined from the manufacturer's data sheet for the given set of fluences or can be calculated by interpolating the given data. The solar array characteristics are then determined by modifying Eqs. (3–8) as follows:

$$I_{\mathrm{ph}} = I_{\mathrm{sc}o} K_{I\mathrm{sc}}(G/G_o) + dI_{\mathrm{sc}\phi}(T - T_o) \tag{10}$$

$$V_{\mathrm{oc}} = V_{\mathrm{oc}o} K_{v\mathrm{oc}} + V_t \ln(G/G_o) + dV_{\mathrm{oc}\phi}(T - T_o) \tag{11}$$

$$V_{\mathrm{oc}} = V_{\mathrm{oc}o} K_{v\mathrm{oc}} + V_t \ln(G/100) \ln(G/G_o) + dV_{\mathrm{oc}\phi}(T - T_o) \tag{12}$$

$$I_{\mathrm{sat}}(G,T) = \frac{I_{\mathrm{ph}}(G,T)}{(e^{\frac{V_{\mathrm{oc}}(T)}{V_t(T)}} - 1)} \tag{13}$$

$$I_{\mathrm{mpp}}(G,T) = I_{\mathrm{mpp}s} K_{I\mathrm{mpp}}(G/G_o)(1 + dI_{\mathrm{mpp}\phi}(T - T_o)) \tag{14}$$

$$V_{\mathrm{mpp}} = \begin{cases} V_{\mathrm{mpp}o} K_{v\mathrm{mpp}} + V_t \ln(G/100) \ln(G/G_o) + dV_{\mathrm{mpp}\phi}(T - T_o) & \text{if } G \geq 100\ \mathrm{W/m^2} \\ V_{\mathrm{mpp}o} K_{v\mathrm{mpp}} + V_t \ln(G/G_o) + dV_{\mathrm{mpp}\phi}(T - T_o) & \text{if } G < 100\ \mathrm{W/m^2} \end{cases} \tag{15}$$

The effect of radiation fluence on Si solar cell characteristics under standard temperature and illumination conditions is given in Fig. 8. To establish the accuracy of this approach, the simulation results for the BOL and EOL of triple junction solar cells are compared with the experimentally measured results [11] in Fig. 9. The simulated characteristics show a very close resemblance to the ones determined experimentally. This verifies that the presented model can predict the solar cell characteristics at EOL with a high level of accuracy.

B. Solar Array Performance Calculation in a Varying Environment

The solar array consists of a number of solar modules composed of a series parallel combination of cells. Consider an array consisting of M number of modules, each module consisting of N_p number of parallel strings, and each string consisting of N_s cells connected in series. Assuming that all cells are identical, the current–voltage relationship is given as follows:

$$I(V) = M[N_p I_{\mathrm{ph}} - N_p I_{\mathrm{sat}}(e^{\frac{V/N_s + IR_s/N_p}{V_t}} - 1)] \tag{16}$$

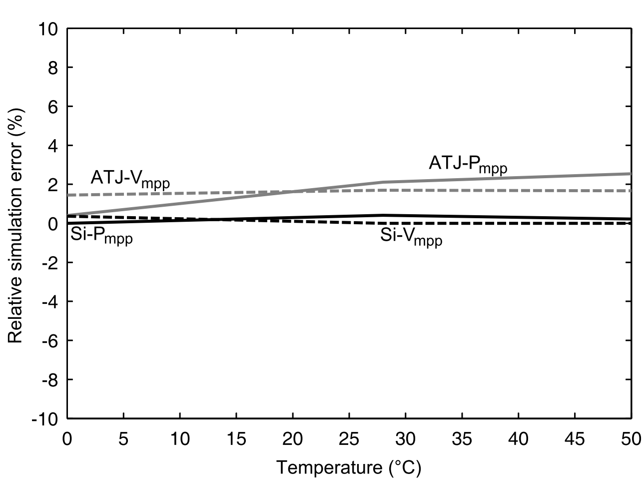

Fig. 7 Relative simulation error with temperature variation.

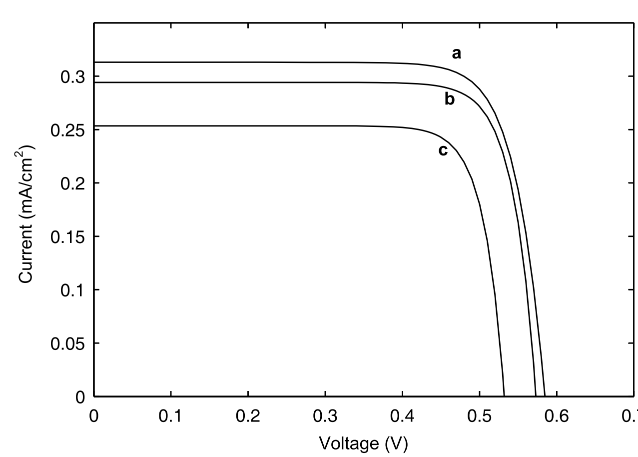

Fig. 8 Simulated I/V curves for the Si solar cell: a) BOL, b) EOL at a fluence of 1×10^{14} e/cm^2, and c) EOL at a fluence of 1×10^{15} e/cm^2.

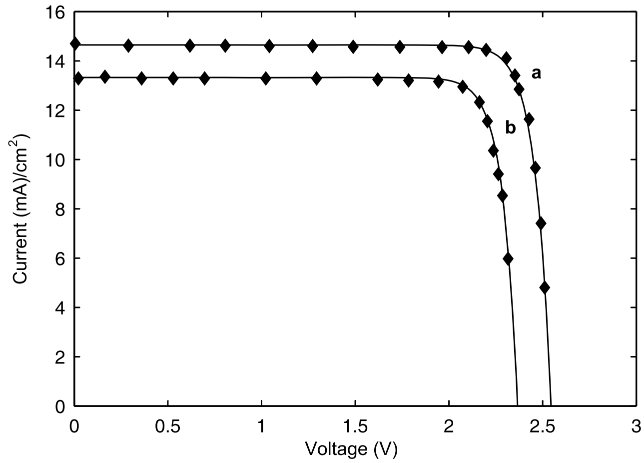

Fig. 9 Simulated I/V curves for the triple junction solar cell: a) BOL, and b) EOL at a fluence of 5×10^{14} e/cm^2. The discrete points shown are taken from [11].

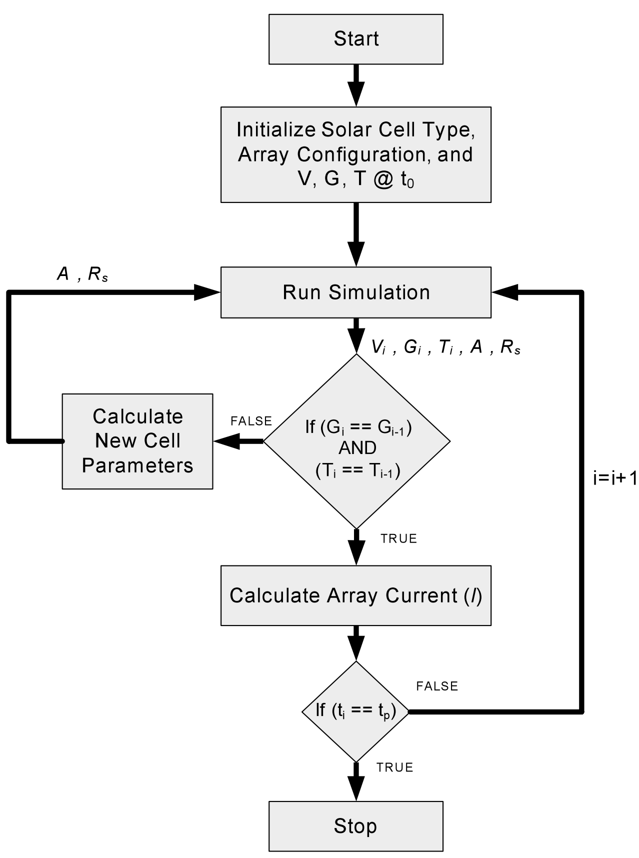

Fig. 10 Algorithm for the solar array analysis.

This model has the capability to calculate the current–voltage relation in an environment in which illumination and temperature are varying, as in the case of the spacecraft solar array. An algorithm to demonstrate its application to solar array analysis over a simulation period of t_p is described in Fig. 10.

IV. Conclusions

The application of simulated annealing to determine optimal values of series resistance and diode ideality factors has been developed for the accurate and fast simulation of solar cell characteristics. The model needs only basic data of the cell characteristics, which are available in the solar cell data sheet. The application of optimization-based modeling is demonstrated for various types of solar cells for standard test conditions and varying temperature and illumination, as well as after degradation. The results presented here are well within the acceptable error range, especially when the simulation results are compared with the data from the manufacturer. The results show that the approach used in this paper performs very well for almost every type of cell and, hence, can be used in a tool for the automated generation of solar cell or array performance.

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