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SPATIALLY RESOLVED LEAKAGE CURRENT DENSITY IN PHOTOVOLTAIC MODULES

H. Nagel, M. Glatthaar, D. Philipp, H. D. Neuhaus and S. W. Glunz

Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstraße 2, 79110 Freiburg, Germany
Email: henning.nagel@ise.fraunhofer.de

ABSTRACT: Due to the non-negligible electrical conductivity of module building materials, small leakage currents flow between the grounded module frame and the active cell matrix in photovoltaic (PV) modules under normal operation conditions, which can lead to significant degradation, such as e. g. potential-induced degradation of the shunting type (PID-s). In general, the degradation rate is strongly correlated with the leakage current density, which is highly dependent on the position in large-area modules due to the voltage drop between the frame and the cells. In this work, we present easy-to-use mathematical equations for rapid analytical calculation of the spatial leakage current density distribution in PV modules as a function of distance from the grounded module frame. The validity of the equations is confirmed by numerical simulation of a resistor network. As an application, the leakage current density distribution in a standard c-Si PV module was analytically calculated as a function of temperature and relative humidity, and the width of the circumferential module area threatened by PID-s was predicted under accelerated test conditions.
Keywords: degradation, modelling, module

1 INTRODUCTION

In general, photovoltaic modules consist of the active solar cell matrix and a two-layer system on the front as well as the back side. For crystalline silicon cell arrays, for example, the front side package often consists of a polymer encapsulant (usually ethylene vinyl acetate, EVA) and a glass cover. The back side is made of a polymer encapsulant and a polymer backsheet or glass cover. Due to the high system voltage and the non-negligible conductivity of the materials used and the interfaces formed, leakage currents occur which are the driving force for degradation, e. g. potential-induced degradation of the shunting type [1], potential-induced degradation of the surface passivation [2] or electrochemical corrosion [3].

The total leakage current can be calculated using a circuit model in which the resistances of the individual current paths are combined into a single resistance value [4]. However, this method does not provide information about the lateral distribution of the leakage current density. Therefore, it is not possible to predict a higher degradation rate localised at the perimeter of the module. A systematic approach to predict and understand the main factors for local degradation is to measure the conductivity of the materials and interfaces as a function of temperature and humidity, and then calculate the spatial leakage current density distribution $J_l(x)$. It has been shown before that J_l can be effectively calculated by i) setting up a resistor network and ii) subsequent numerical simulation [5,6]. This method involves some effort, since the resistor network must be built up from several thousand individual resistors to achieve good spatial resolution, and the subsequent numerical simulation can be time consuming. In this work, we present fast and easy-to-use analytical calculations of the leakage current density in large-area PV modules as a function of distance from the grounded module frame.

2 MODEL FOR RESISTOR NETWORK OF PV MODULES

The module package on the front side is electrically described by a two-dimensional resistor network representing a grounded (metal) frame, a laterally conductive glass/air interface, a laterally and vertically conductive glass cover, a laterally conductive glass/encapsulant interface (featuring infinite vertical conductivity because it is very thin), a laterally and vertically conductive encapsulant and a solar cell array to which a uniform module voltage is applied, see schematic drawing in Fig. 1. The formula symbols for the parameters are listed in Table 1 together with a short description of their meaning. For the resistor network, we set up and analytically solved the coupled partial differential equations arising from Kirchhoff's and Ohm's laws. The mathematical derivation of the equations is extensive, but straight forward. A detailed

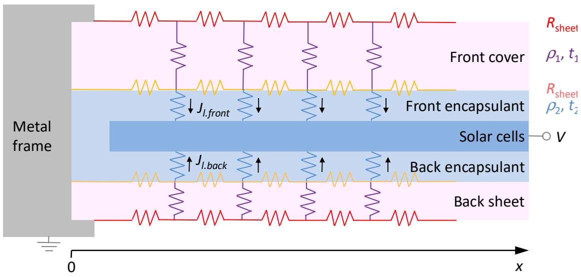

Fig. 1: Schematic drawing of a c-Si PV module cross section showing leakage current paths and electrical material and interface parameters.

Table 1: Parameters for simulation of the resistor network representing the module's front side.

Parameter	Unit	Description
R_{sheet1}	Ω	Sheet resistance of the surface of the front cover
R_{sheet2}	Ω	Lumped sheet resistance of the front cover, front cover/encapsulant interface and encapsulant
ρ_1	Ω cm	Resistivity of the front cover
ρ_2	Ω cm	Resistivity of the front encapsulant
t_1	cm	Thickness of the front cover
t_2	cm	Thickness of the front encapsulant
V	V	Voltage between solar cell and grounded module frame
x	cm	Distance from the module edge
$J_{l.front}$	A/cm²	Leakage current density on the front of the solar cells

description is beyond the scope here and will be published elsewhere. Table 2 shows the result. The obtained equations allow a quick calculation of the leakage current density in PV modules as a function of the distance to the module frame, e. g. using a spreadsheet program such as Microsoft Excel. In the Results section, a verification of an analytically calculated local leakage current density profile is presented by comparison with the profile numerically calculated using the electronic circuit simulator software LTspice XVII [7] and the same device parameters.

Unless otherwise stated, in this work the outer solar cells of the cell matrix are assumed to be close to (without direct electrical contact with) the grounded metal frame. This model can be extended to include an additional distance L between the cells and the module frame by introducing a voltage U_{offset} that drops at the circumferential edge of the module across encapsulants, covers and interfaces. In [5], it was shown by two-dimensional finite element based numerical solution of Maxwell's equations that in the case of high sheet resistance of the module surface and for standard sodalime cover glass, EVA encapsulant, and Tedlar-Polyester-Tedlar backsheet, the electrical field in the region between the cell and the frame is directed horizontally towards the frame. Then, a simple one-dimensional model can account for a voltage offset

$$U_{offset} = R_{sheet3} L \frac{I}{w}$$

which reduces the voltage between the cell matrix and the grounded module frame. I and w are the total leakage current through the perimeter of the module and the length of the perimeter, respectively. R_{sheet3} is a lumped sheet resistance given by

$$R_{sheet3} = \left(\frac{1}{R_{sheet.front\_surface}} + \frac{1}{R_{sheet.front\_cover}} + \frac{1}{R_{sheet.interface.front\_cover/front\_encapsulant}} + \frac{1}{R_{sheet.front\_encapsulant}} + \frac{1}{R_{sheet.back\_surface}} + \frac{1}{R_{sheet.back\_cover}} + \frac{1}{R_{sheet.interface.back\_cover/back\_encapsulant}} + \frac{1}{R_{sheet.back\_encapsulant}} + \frac{1}{R_{sheet.interface.front\_encapsulant/back\_encapsulant}} \right)^{-1}.$$

Table 2: Equations for analytical calculation of the local leakage current density.

$$J_{l.front} = \frac{V}{\rho_2 t_2} \left(\left(\frac{R_{sheet1} c_1}{p_1} - c_1 p_1 \rho_1 t_1 \right) exp^{-p_1 x} + \left(\frac{R_{sheet1} c_2}{p_2} - c_2 p_2 \rho_1 t_1 \right) exp^{-p_2 x} \right) \quad (1)$$

$$c_1 = - \frac{p_1 p_2^2}{(p_1^2 - p_2^2) R_{sheet1}} \quad (2)$$

$$c_2 = \frac{p_1^2 p_2}{(p_1^2 - p_2^2) R_{sheet1}} \quad (3)$$

$$p_{1,2} = \sqrt{ \frac{R_{sheet1} + R_{sheet2}}{2 \rho_1 t_1} + \frac{R_{sheet2}}{2 \rho_2 t_2} \pm \sqrt{ \left(\frac{R_{sheet1} + R_{sheet2}}{2 \rho_1 t_1} + \frac{R_{sheet2}}{2 \rho_2 t_2} \right)^2 - \frac{R_{sheet1} R_{sheet2}}{\rho_1 t_1 \rho_2 t_2} } },$$

'+' applies to p_1, '-' to p_2 (4)

$$R_{sheet2} = \left(\frac{1}{R_{sheet.front\_cover}} + \frac{1}{R_{sheet.interface.front\_cover/front\_encapsulant}} + \frac{1}{R_{sheet.front\_encapsulant}} \right)^{-1} \quad (5)$$

Outside the distance L at the module edge, the front and back sides of the module are electrically decoupled by the intermediate solar cell matrix, so the local leakage current density on each side can be calculated separately using the equations in Table 2 but different electrical material und interface parameters. In this work, we focus on the calculation of the local leakage current density on the front side of the solar cells to obtain information about the width of the module edge affected by PID-s. PID-s takes place in the emitter of the cells, which is generally located on the front side of the PV module.

It should be noted that it is not directly the leakage current density, but the area-related cumulated charge density that is decisive for the local degradation. It is simply the local leakage current density on the solar cell times the duration of the current flow. In the case of fluctuating leakage current densities, e. g. due to changes in electrical resistivity caused by temperature fluctuations, the leakage current density is integrated over time.

3 RESULTS

3.1 Validation of the analytical calculation

Fig. 2 shows a comparison of analytically and numerically calculated leakage current density as a function of the distance to the module frame. 1000 V were applied between the cell matrix and the frame. The simulated cross-sectional module layout was 3.2 mm sodalime glass/0.42 mm EVA/cell matrix. The electrical material parameters were taken from [6] for a module temperature of 60 °C and a relative humidity (RH) of 45 % (which affects the conductivity of the front surface). The obtained sheet resistances are listed in Table 3.

In the numerical simulation, we varied the node spacing of the resistor network between 1 and 0.1 cm. It can be seen from Fig. 2 that the resulting leakage current curves converge with that determined analytically and show very good agreement at a node spacing of 0.1 mm. Since the spatial resolution of the numerical simulation increases with finer node spacing, we conclude that the analytical calculation is well confirmed.

Table 3: Sheet resistances of the layers in the simulated module at 60 °C and 45 % RH.

Layer	R_{sheet} (Ω/sq)
Glass surface	$6.93 \cdot 10^{11}$
Glass	$3.09 \cdot 10^{11}$
Interface between glass and EVA	$1.06 \cdot 10^{11}$
EVA	$2.33 \cdot 10^{13}$

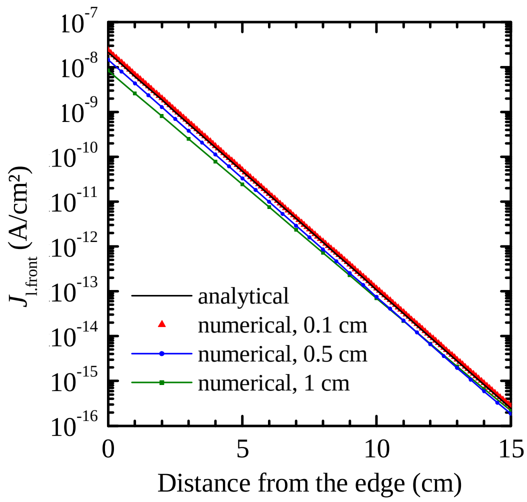

Fig. 2: Comparison of analytically and numerically calculated leakage current density through the front side of a PV module. The numbers in the legend indicate the node distances in the numerical simulation.

3.2 Application of the analytical calculation: variation of temperature and relative humidity

The equations presented in Table 2, together with the electrical parameters of materials used for module fabrication, provide the means to calculate the effects of environmental conditions on the local leakage current density. We again assumed the cross-sectional module layout 3.2 mm sodalime glass/0.42 mm EVA/cell matrix, a voltage of 1000 V applied between the cell matrix and module frame, and used the previously measured electrical parameters as a function of temperature and RH [6]. Fig. 3 shows the result for two different relative humidities of 45 and 85 % and a module temperature ranging from 40 to 70 °C. From the figure, it can be seen that the influence of RH on the leakage current density at a certain distance from the module edge is even greater than the influence of the increased conductivity of materials and interfaces due to the increase in module temperature. Obviously, the increase of the conductivity of the surface of the front glass with higher RH has a great effect.

The grey line in Fig. 3 marks a current density of 1×10^{-10} A/cm², which results in a charge density of 6×10^{-5} C/cm² deposited on the front of the encapsulated solar cells after 6.9 days. In case of PID-s prone cells, this charge density leads to a 90 % power drop [8]. It can be seen from the figure that at 70 °C and 85 % RH, a complete 6inch solar cell at the module edge is at risk by this degree of degradation.

It is interesting to note that the analytical solution for the local leakage current density described in Section 2 is a linear superposition of two exponential functions, see Equation (1). From Fig. 3 it can be seen that it can often be approximated by a single

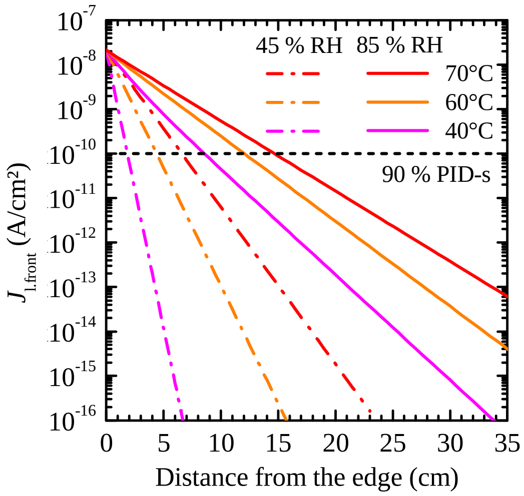

Fig. 3: Analytically calculated local leakage current density through the front side of a PV module with the cross-sectional layout 3.2 mm glass/0.42 mm EVA/cell array. The bias voltage between cell array and grounded module is 1000 V. The dashed black line indicates the expected local 90 % power degradation of PID-s prone c-Si solar cells after 6.9 days.

exponential function. Whether this is a good approximation depends on the ratio of the sheet resistance of the glass surface R_{sheet1} and the lumped sheet resistance R_{sheet2} of the front cover, front cover/encapsulant interface and encapsulant.

4 SUMMARY

Easy-to-use equations for analytical calculation of leakage current density in PV modules as a function of distance from the grounded module frame were presented. The result was compared with that obtained from numerical simulations of a resistor network. By varying the node spacing in the resistor network, it was found that the numerical solution approaches the analytical solution for a small node spacing of 0.1 mm, showing i) the validity of the analytical solution and ii) the need for a very fine resistor network for accurate numerical simulation, which can thus become quite time consuming. As an application, the effect of temperature and relative humidity on local leakage current density in a standard c-Si PV module was calculated analytically using the equations in a spreadsheet software along with previously measured material parameters. In combination with climate data and degradation rates as a function of area-related charge density, it may be possible to rapidly predict local degradation of PV modules due to leakage current as a function of exposure time in different climates.

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