Electro-thermal circuit models of PhotoVoltaic cells subjected to optical degradation phenomena

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The occurrence of hot spots in PhotoVoltaic (PV) systems is a detrimental phenomenon characterised by non-uniform temperature distribution across PV modules or even among individual cells within a single module [1]. These localized temperature anomalies can reach values of several hundred Celsius degrees. The most immediate and critical impact of hot spot formation is the degradation of the energy yield of PV systems. In addition to reduced power generation efficiency, the presence of hot spots accelerates the aging process of PV modules and may, ultimately, lead to thermal failure or combustion. Furthermore, the spatial non-uniformity of temperature introduces a complex interplay between cause and effect: while mismatches in electrical characteristics typically initiate hot spots, the reverse can also occur—wherein hot spots exacerbate or even induce mismatches. This bidirectional interaction reveals a closed-loop relationship between mismatching and aging, with temperature acting as the central mediating factor [2]. This revised design paradigm suggests that the maximization of extracted power should not be pursued at the expense of inducing severe thermal stresses, since. such an approach may compromise long-term system reliability and performance. In light of these findings, there is an evident necessity for the development of a sophisticated modelling framework capable of taking into account the coupled electro-thermal dynamics of PV modules in case of temperature-dependent degradation. The development of such a model would support the creation of proper control strategies and system architectures able to enhance energy efficiency and extend module lifespan, particularly under mismatching scenarios. In this context, the present work introduces an enhanced formulation of the conventional one-diode PV model. The proposed model integrates a thermal feedback mechanism that establishes a dynamic link between mismatching conditions and aging processes. Specific emphasis is placed on the temperature dependence of transmittance and/or reflectance, which drives the closed-loop link between mismatching and optical degradation in PV systems.

METHODOLOGY

Thermal stresses induced by mismatching operating conditions exerts a substantial influence on transmittance and or reflectance, manifesting in two distinct temporal domains: firstly, as a reversible optical behavior, and secondly, as a result of material degradation over an extended timeframe. In the short term, transmittance can vary with temperature due to changes in material refractive index and thermal expansion. Hereafter, when exposed to elevated temperatures for an extended period (severe mismatching conditions), materials undergo chemical and structural changes that result in a permanent reduction in transmittance. This, in turn, leads to a decrease in the amount of light reaching the photovoltaic cell, thereby directly reducing the photogenerated current and energy yield. A direct consequence of the thermal-induced optical degradation is the worsening of mismatching conditions and hence the major occurrence of further thermal stresses (Figure 1). A schematic model for a PV cell, which illustrates the aforementioned closed-loop correlation between mismatching and optical degradation is shown in Figure 2. Such a model represents an enhancement of the precise electro-thermal model outlined in [3]. The primary distinction between the two models lies in the formulation of photogenerated current I_{ph} (Block A), as a function of irradiance G, and cell temperature T_{cell}. In particular, the formulation adopted for I_{ph} is:

$$I_{ph}(G, T_{cell}) = \frac{J_{sc}(T_{cell}) \cdot S \cdot G}{1000} \quad (1)$$

Where J_{sc} is the short circuit current density in A/ cm^2, S is the PV cell area in cm^{-2}, G is the incident irradiance in W m^{-2}. The equation uses the Standard Test Conditions (STC), (AM1.5 spectrum, temperature at 25°C, and irradiance at 1000 W m^{-2}). The idea is to use an analytical semiconductor model to express the short circuit current density as a function of the reflectance and/or transmittance which are dependent on PV cell temperature (the closed-loop control is driven by the temperature dependence of the transmittance and/or reflectance). In particular:

$$J_{sc}(T_{cell}) = \int_0^{\infty} [J_{scE}(\lambda, T_{cell}) + J_{scB}(\lambda, T_{cell})] \, d\lambda \quad (2)$$

where J_{scE} (J_{scB}) is the Emitter (Base) short circuit spectral current density whose values are calculated using the following equations:

$$J_{scE}(\lambda, T_{cell}) = q \cdot \alpha \cdot \phi \cdot [1 - R(T_{cell})] \cdot \frac{L_p}{(\alpha \cdot L_p)^2 - 1} \cdot \eta_{ccE} \quad (3)$$

$$J_{scB}(\lambda, T_{cell}) = q \cdot \alpha \cdot \phi' \cdot [1 - R(T_{cell})] \cdot \frac{L_n}{(\alpha \cdot L_n)^2 - 1} \cdot \eta_{ccB} \quad (4)$$

where q is the elementary charge (1.602 10^{-19} C), ϕ is the photon spectral flux at the emitter surface (photons/cm^2 s µm), ϕ' is photon spectral flux at the base surface (photons/cm^2 s µm), R is the reflectance of the front surface, L_p is the hole diffusion length in the emitter layer (cm), L_n is the electron diffusion length in the base layer (cm) and η_{ccE} (η_{ccB}) is the carrier Emitter (Base) term.

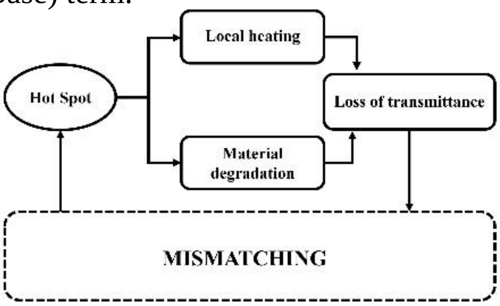

Figure 1: Closed-loop link between mismatching and optical degradation in PV systems

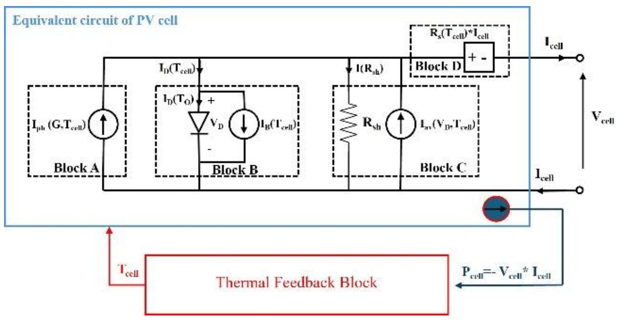

Figure 2. Schematic model for a PV cell showing the closed-loop link mismatching and optical degradation.

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