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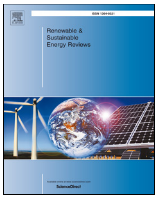

Modeling of photovoltaic cell temperature losses: A review and a practice case in South Spain

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ABSTRACT

To determine temperature losses in a photovoltaic (PV) installation, the operating temperature of the cells in the PV panels must be known. This temperature cannot be directly measured because the cells are not accessible from the outside, as they are inside the panels, with other layers of material surrounding them. Therefore, the parameter to which direct access exists by means of measuring is the temperature of the outer surfaces of the modules. However, the cell junction temperatures are typically 1–3 °C higher than the temperature measured on the module's rear surface, depending on the module construction. Some methods exist for determining the cell temperature, including measuring the open-circuit voltage of the panels, but because this is difficult to do with an on-site PV installation, normally this temperature is determined by using models. Numerous models appear in the literature for determining the cell temperature, so in this paper, a recompilation of twenty models is taken into account for determining the temperature and miscellaneous losses of a PV installation located in South Spain in a year's time. These models have different relations between the value of the cell temperature and some environmental parameters, considering or not the value of the wind speed and the form in which the panels are installed. A maximum difference in annual temperature losses found using the twenty models was 90.4 h/year. This non-negligible quantity indicates the importance of an appropriate choice of model and the correct conditions for applying it to make a precise estimation of the capture temperature losses. Moreover, it would be interesting to reach an agreement on the best procedure for determining this type of losses, especially for correctly performing comparisons of these losses in different PV plants in operation, which can reach very significant values in locations with high temperature registers.

1. Introduction

Temperature plays a central role in the photovoltaic (PV) conversion process, due to an operating temperature increase of above 25 °C has a negative effect on the electrical efficiency of PV modules, whose rate of change can be expressed in the function of this parameter by means of a large number of correlations that can be found in the literature [1–9].

Mainly in scenarios that feed-in tariffs do not protect, having an accurate understanding of the operating temperature of PV modules in each location is fundamental for achieving a more precise forecast of the production of these types of installations, which is a basic requirement for determining their profitability [10]. Knowing the temperature is also important for estimating the thermal stress on the materials and thus for quantifying the degradation of the PV modules [11], which is essential for predicting the service life of the PV modules in an installation.

However, once a PV plant is estimated to be profitable and is installed, operation and maintenance interventions must be carried out to optimize its production. For this purpose, some parameters of the plant are usually monitored, as this provides information about how its components perform, thus quantifying the different loss mechanisms. If the solar energy that the modules receive, the energy they produce and the energy at the exit of the inverters are recorded, it is possible, by means of the balance of these energies, to quantify the losses that take place in the capture system (L_c), that is, in the PV field, and the losses occurring in the inverter (L_s) [12–16]. The losses in the PV modules are considered the sum of two different groups of losses. On the one hand, there are temperature losses (L_{ct}) due to the already-indicated loss of efficiency of the modules via the increase of this magnitude above 25 °C, that can reach values of up to 0.4, 0.5 or 0.9 h/d in locations such as South Italy, India or South Spain [16–18]. On the other hand, the denominated miscellaneous capture losses (L_{cm}) are grouped together. This last group includes all of the different types of losses that may occur in the capture system, excluding those due to temperature, that may be associated with the joule effect in the wiring, diodes losses,

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Nomenclature

α	Absorption coefficient of the cells
a'	Empirical parameter used in Model 20
A	PV module area associated to each inverter
A'	Empirical parameter used in Model 17
b	Empirical parameter used in Model 16
b'	Empirical parameter used in Model 20
B'	Empirical parameter used in Model 17
β	Power temperature coefficient of PV modules
d	Empirical parameter used in Model 19
ΔT	Empirical parameter used in Models 6, 16 and 17, whose value depends on the module materials and the type of assembly
e	Empirical parameter used in Model 19
E_{DC}	Net DC energy generated in PV modules
E_G	Tilted irradiation received in the PV modules
E_r	Reference solar energy received by the PV modules
f	Empirical parameter used in Model 19
G	In-plane irradiance
γ	Irradiance coefficient of PV modules
G_{NTE}	Irradiance at nominal terrestrial environmental conditions
G_{STC}	Irradiance at Standard Test Conditions
η	PV panel efficiency
H	Overall heat transfer coefficient of a PV module
h	Convective heat transfer coefficient of a PV module
H_{NTE}	Overall heat transfer coefficient of a PV module at nominal terrestrial environmental conditions
I_{DC}	Direct current from PV modules
I_{pm}	Maximum power current of a PV module
I_{sc}	Short circuit current of a PV module
k	Ross parameter
$k_{free\text{-}standing\text{-}array}$	Ross parameter k for the free-standing case
$k_{integration\text{-}category}$	Ross parameter k for each specific mounting situation
L_c	Capture losses
L_{cm}	Miscellaneous capture losses
L_{ct}	Thermal capture losses
MPP	Maximum power point
NTE	Nominal terrestrial environmental conditions
P_{STC}	PV nominal power under Standard Test Conditions
P_{Tc}	Power generated in a PV panel under general conditions of T_c
STC	Standard Test Conditions
τ	Transmittance of the module cover system for a beam and diffuse radiation
t	Monitoring time interval
T_a	Ambient temperature
$T_{a,NTE}$	Ambient temperature at nominal terrestrial environmental conditions
$T_{a,STC}$	Ambient temperature at Standard Test Conditions
T_c	Cell temperature
T_m	Module temperature
T_{INOCT}	Installed Normal Operating Cell Temperature
T_{NOCT}	Normal Operating Cell Temperature
U_0	Ordinate in the origin in the linear relation between H and v. It describes the effect of the Solar radiation on the module temperature
U_1	Slope in the linear relation between H and v. It describes the cooling effect of the module due to wind speed
v	Free stream wind speed
v_{NTE}	Wind speed at nominal terrestrial environmental conditions
V_{DC}	Direct voltage from PV modules
V_{mpp}	Maximum power voltage of a PV module
V_{oc}	Open-circuit voltage of a PV module
Y_A	Array yield
ω	Parameter named mounting coefficient, used in Model 15
Yr	Reference yield
Y_T	Reference yield corrected by the effect of the temperature

shading effect, mismatch losses, low irradiance, dirt accumulation, snow covering or losses due to the non-ideal maximum power point tracking [12,16].

Temperature losses cannot be directly measured but instead are calculated using models that indicate the variation of the efficiency of the modules as a function of the temperature, whose value must be previously known [1–9]. Once these temperature losses are determined, the miscellaneous losses are calculated by subtracting the temperature losses from the global losses in the capture system that have been obtained by measuring ($L_{cm} = L_c\text{-}L_t$). Therefore, to adequately estimate the miscellaneous losses, whose correct evaluation can help with amending deviations in the design or operation of these types of renewable installations, it is necessary to properly know the value of the temperature losses, and for this, it is necessary to previously know the value of the temperature at which the cells that make up the PV modules operate.

The value of this temperature, which would correspond to the average temperature of the electronic junctions of their cells (standard IEC 60904-5:2011 [19]), cannot be immediately known. The PV cells are not accessible from the outside, as they are inside the panels, with other layers of material surrounding them. Cells are covered directly by an encapsulating material (commonly ethylene-vinyl-acetate (EVA)), coated with a layer of tempered glass on the upper surface, and the back side covered with another layer of glass or with a layer of plastic material—in many cases, Tedlar (polyvinyl fluoride, PVF) [20–23]. Therefore, the temperature of the PV cells cannot be directly measured, unless during the manufacture of the modules a series of thermal sensors were integrated into their different layers, as was done in the works of Mattei et al. [20] and Huang et al. [24], or were integrated manipulating the modules, such as in some of the measures made in the work of Kuitche et al. [25]. Hence, the parameter to which direct access exists by means of measuring in a PV installation is the temperature of the outer surfaces of the PV module.

The standard IEC 60904-5:2011 [19] presents a procedure for determining, in an indirect way through the open-circuit voltage of each panel, the value of the equivalent temperature of the cells. This standard indicates that this is the most accurate method for determining this parameter. However, the difficulty of this method arises when carrying out these measurements in a group of PV modules in operation. Thus, this method would require the use of an additional reference module not connected to the PV array, only for temperature measurement purposes [26]. Moreover, according to the standard IEC 60904–5:2011 [19], the fact that the modules are exposed to an open circuit for the determination of this magnitude would lead to a higher cell temperature [27] because the electrical power is not extracted but rather is converted into heat. For this reason, some authors, such as Koehl et al., have proposed avoiding the characterization of the temperature cells in open-circuit conditions [11]. Other authors, such as Huang et al. [24], have presented a method for determining the cell temperature that involves measuring the irradiance and the open-circuit voltage of the solar PV module (V_{oc}). However, to use this procedure in an on-site application, it is necessary to disconnect the solar PV module for a short period of time (10 ms for each register) to measure V_{oc}. Although the results are good, the disconnection of the power generation circuit implies extra energy loss in the PV installation, together with the requirement of incorporating a circuit that allows for