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A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting

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ABSTRACT

Following a brief discussion regarding the operating temperature of commercial grade silicon photovoltaic (PV) cells/modules and its effect upon the performance of free-standing one-sun PV installations, a simple semi-empirical explicit correlation for PV cell temperature and the corresponding efficiency form are proposed for modules of arbitrary mounting. To this end, a dimensionless *mounting parameter*, ω, is introduced rendering the correlations suitable for systems like building-integrated photovoltaic (BIPV) array generators. The implications of ignoring radiation and free-convection are quantified and a comparison is made with analogous relations in the literature.

1. Introduction

It is well established that temperature plays a central role in the photovoltaic (PV) conversion process since it affects basic electrical quantities, such as the voltage and the current of the PV generator. As a consequence, the operating temperature, T_c, of a PV device, whether a simple module, a PV/Thermal collector or a building-integrated photovoltaic (BIPV) array, represents a fundamental variable which directly affects the electrical power output of the device and its efficiency. It is only natural, therefore, that in recent years, its prediction and its influence on module/array operation has received considerable attention among the scientific community.

The proposed correlations in the literature normally express T_c as a function of the pertinent weather variables, namely ambient temperature, T_a, and local wind speed, V_w, as well as of the solar radiation flux (or irradiance) incident on the plane of the array, G_T. Generally speaking, T_c is extremely sensitive to wind speed, less so to wind direction, and practically insensitive to the atmospheric temperature [1]. On the other hand, it obviously depends strongly on the "plane-of-array" irradiance. These correlations also include, as parameters, material and system-dependent properties such as glazing-cover transmittance, τ, plate absorptance, α, etc. A large number of correlations can also be found in the literature, which express the negative effect that an operating temperature increase has upon the electrical efficiency, η_c, of a PV cell/module/array.

From the mathematical point of view, the correlations for the PV operating temperature are either explicit in form, i.e. they give T_c directly, or they are implicit, that is they involve variables which themselves depend on T_c. In this last case, an iteration procedure is necessary for the relevant calculation. Most of the correlations usually include a reference state and the values of the pertinent variables at this reference state. It goes without saying that the degree of accuracy with which T_c can be estimated, has a direct bearing on any simulation results and/or relevant calculations which require this temperature as an input.

2. PV cell/module efficiency and power as a function of the operating temperature

The operating temperature effect on the electrical power produced by a PV cell or module can be traced to the temperature's influence upon the current, I, and the voltage, V, as the maximum power is given by

$$P_m = V_m I_m = (FF) V_{oc} I_{sc} \qquad (1)$$

In this expression, which also serves as a definition of the fill factor,[1] FF, subscript m refers to the maximum power point in the module's I–V curve, while subscripts oc and sc denote open circuit and short circuit values, respectively. It turns out that both the

[1] The fill factor is a measure of how much series resistance and how little shunt resistance there is in a solar cell and its circuit. It affects the maximum power voltage change with irradiance and decreases with module age, as the series resistance increases in a degrading PV cell ([2], p. 85). For silicon solar cells, a healthy Fill Factor lies in the range 0.75–0.85.

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Nomenclature

A	cell/module aperture surface area, m^2
FF	fill factor
G_T	irradiance (solar rad'n flux) on module plane, W/m^2
h_{free}	free-convection heat transfer coefficient, W/m^{2}K
h_{rs}	radiation heat transfer coefficient, W/m^{2}K
h_w	wind-convection heat transfer coefficient, W/m^{2}K
I	electrical current
k	Ross coefficient—Eq. (14), Km^2/W
INOCT	installed nominal operating cell temperature, °C
NOCT	nominal operating cell temperature, °C
NTE	nominal terrestrial environment (cf. SRE)
P	electrical power, W
SOC	standard operating conditions
SRC	standard reporting conditions
SRE	standard reference environment (cf. NTE)
TRE	test reference environment
T_a	ambient temperature, K
T_b	back-side cell temperature, K
T_c	cell/module operating temperature, K
T_s	sky temperature, K
U_L	overall thermal loss coefficient, W/m^{2}K
V	voltage, V
V_w	wind speed, m/s

Greek symbols

α	solar absorptance of PV layer
α	I_{sc} correction coefficient for temperature (°C^{-1})
$\beta(G_T)$	V_{oc} correction coefficient for temperature (°C^{-1})
β_{ref}	efficiency correction coefficient for temperature (°C^{-1})
γ	efficiency correction coefficient for irradiance
$\delta(T)$	V_{oc} correction coefficient for irradiance
Δ	$= T_c – T_a$
ε_g	PV glazing emmissivity
η_c	cell/module electrical efficiency
$\eta_{T_{ref}}$	electrical efficiency at temperature T_{ref}
σ	Stefan–Boltzmann constant (5.6697×10^{-8} W/m^{2}K^4)
τ	transmittance of glazing
ω	mounting coefficient—Eq. (24)

Subscripts

a	ambient
b	back side
c	cell/module
f	free-stream
L	thermal loss
m	at maximum power point
NOCT	at NOCT conditions
NTE	at NTE conditions
oc	open circuit
ref	at reference conditions
s	sky
sc	short circuit
T	on module's tilted plane
w	wind induced

open circuit voltage and the fill factor decrease substantially with temperature (as the thermally excited electrons begin to dominate the electrical properties of the semi-conductor), while the short-circuit current increases slightly [3].

The same argument holds for the effect of temperature on the electrical efficiency of the PV cell/module, which is defined as $\eta_c = P_m/AG$, with A the cell's area or the module's aperture area. For this definition to hold, the maximum power must be measured under the so-called Standard Reporting Conditions[2] (SRC).

Equations for the short-circuit current and the open-circuit voltage as functions of the PV operating temperature can be found in the literature, based on various proposed electrical models (cf. [5] and references therein). Such expressions include temperature coefficients that provide the rate of change with respect to temperature of PV performance parameters such as I_{sc}, V_{oc}, I_{mp}, V_{mp}, but also FF, and η_c. Recent standard testing methods [4] address two of these parameters, one for current and one for voltage, although outdoor characterization of module performance studies have suggested that all four current and voltage parameters listed above are needed for accurate predictions under various operating conditions [6].

Among the relevant expressions, those used in the NREL's Module Energy Rating (MER) procedure [7] are

$$\mathrm{SC} = \frac{G_T}{G_{T_0}} I_{SC_0}[1 + \alpha(T_c - T_0)] \tag{2}$$

and

$$V_{OC} = V_{OC_0}[1 + \beta(G_{T_0})(T_c - T_0)][1 + \delta(T_c)\ln(G_T/G_{T_0})] \tag{3}$$

in which α is the I_{sc} correction coefficient for temperature, $\beta(G_T)$ is the V_{oc} correction coefficient for temperature as a function of irradiance, $\delta(T)$ is the V_{oc} correction coefficient for solar radiation flux as a function of the module temperature, and the subscript zero refers to SRC. If Eqs. (2) and (3) are introduced into Eq. (1) and combined with the definition of the efficiency, they can produce an expression for the latter. In view of the fact that the correction coefficients are small (α is of order 10^{-4}, β is of order 10^{-3}, and δ is of order 10^{-2}), products of coefficients can be dropped, and after a little algebra a linear relation for η_c emerges, similar in form with the well known equation proposed by Evans [8]:

$$\eta_c = \eta T_{ref}[1 - \beta_{ref}(T_c - T_{ref}) + \gamma \log_{10} G_T] \tag{4}$$

In this expression, $\eta_{T_{ref}}$ is the module's electrical efficiency at temperature T_{ref} and at solar radiation flux of 1000 W/m^2. The efficiency correction coefficient for temperature, β_{ref}, and the efficiency correction coefficient for solar irradiance, γ, are mainly material properties, having average values of about 0.0045 K^{-1} and 0.12, respectively, for silicon modules [9]. The latter, however, is usually taken as zero [8], so that Eq. (4) reduces to

$$\eta_c = \eta_{T_{ref}}[1 - \beta_{ref}(T_c - T_{ref})] \tag{5}$$

which represents the traditional simple linear expression for the PV electrical efficiency [10].

The quantities $\eta_{T_{ref}}$ and β_{ref} are usually given by the PV module manufacturers, but they can be also obtained from flash tests, in which the module's electrical output is measured at two different temperatures for a given solar radiation flux [11]. The value of the efficiency correction coefficient for temperature, on the other hand, depends not only on the PV material but also on T_{ref}. It is

[2] 1000 W/m^2 total irradiance, G 159 spectral irradiance, 25 °C [4]