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Thermal aspects of c-Si photovoltaic module energy rating

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Abstract

Standard test conditions (STC) of photovoltaic (PV) modules are not representative of field conditions; PV module operating temperature often rises up to 30 °C above STC temperature (25 °C), causing a performance drop of 0.5%/°C for crystalline silicium modules. *Normal operating cell temperature* (NOCT) provides better estimates of PV module temperature rise. It has nevertheless to be measured; moreover NOCT wind speed conditions do not always fit field conditions. The purpose of this work is to model average PV module temperature at given irradiance levels as a function of meteorological parameters and PV module implementation. Thus, no empirical knowledge of PV module thermal behaviour is required for energy rating basing on irradiation distributions over irradiance levels.

Keywords: PV module; Operating temperature; Site profile

1. Introduction

The power rating of photovoltaic (PV) modules at a 1000 W/m^2 irradiance level under spectral irradiance distribution defined by AM 1.5 and junction temperature of 25 °C is not representative of PV modules operating conditions. These conditions nevertheless are, according to IEC standard 61215, the so-called *standard test conditions* (STC), and deliver a reference for PV module peak performance.

But as the irradiance level of 1000 W/m^2 is generally reached during only a few hours around solar noon in the plane of array (POA), and as the PV module temperature often rises up to 40–50 °C rather than 25 °C, neither the peak power nor the efficiency at STC have great chance to be observed under field conditions.

There is hence a great research interest for energy rating of PV modules under field conditions. The first step of energy prediction algorithms often consists in establishing reliable performance correlations, expressed as a relationship between efficiency on the one hand and irradiance and module temperature on the other hand:

$$\eta(G, T_m) = \eta_{STC}(1 + \alpha(T_m - 25) + f(G)) \quad (1)$$

Temperature dependence of efficiency of crystalline silicon modules (c-Si) is in the order of magnitude of $\alpha = -0.5\%/°C$. The function f differs depending on authors; its determination is beyond the scope of this paper.

The second step considers meteorological conditions and PV module implementation specificities: it is necessary to know at what irradiance and temperature levels the PV modules operate. In particular, several approaches have been developed to take into account the performance drop due to PV modules temperature rise. Various thermal models (Fuentes, 1985, Ingersoll, 1986; Krauter, 1993) deliver quite accurate estimates of PV module operating temperature but require irradiance, ambient temperature and wind speed profiles. They might be used in pointwise determination of electrical output (Kenny et al., 2006) or in *I–V* curves translation algorithms (Marion et al., 1999).

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Nomenclature

α	temperature factor of module efficiency (standing alone)
$\tau\alpha$	module transmittance–absorptance factor (–)
ε	emissivity factor (–)
η	module efficiency (–)
κ	clearness index (subscript *cd* stands for *clear day*) (–)
σ	Stefan-Boltzmann constant (S.I.)
Γ	Gamma function (–)
H	solar irradiation (W h)
G	solar global irradiance (W/m^2)
T_m	average module temperature (°C or K)
T_a	ambient temperature (°C or K)
T_0	difference between sky temperature and ambient temperature (K)
T_s	sky temperature (°C or K)
$h(G)$	contribution of irradiance level G to the total irradiation (subscript *cd* stands for *clear day*) 1/(W/m^2)
a, p, k	empirical parameter set for forced convection (S.I.)
v	wind speed (v_w is a parameter of the probability density function of wind speed) (m/s)
h	heat transfer coefficients: h_{cv} for convection (h_{nat} and h_{forc} for natural, resp. for forced convection), h_{IR} for long-wave radiation (W/m^2 K)
STC	standard test condition
(I)NOCT	(installed) nominal operating cell temperature
BIPV	building integrated photovoltaics
POA	plane of array

A way to reduce the number of input parameters is the definition of PV modules *normal operating cell temperature* (NOCT) in the International Standard IEC 61215. It corresponds to open circuit PV modules temperature at POA irradiance level of 800 W/m^2, 20 °C ambient temperature and wind speed of 1 m/s. Thus, the thermal behaviour of PV modules appears to be summed up in only one parameter that has nevertheless to be adjusted depending on the module implementation mode. Fuentes (1985) therefore introduces the concept of *installed nominal operating conditions temperature* (INOCT), which should be determined empirically.

In numerous energy rating methods, PV module temperature T_m is expressed as a function of empirical NOCT or INOCT values as follows (referred to as NOCT *model* in the rest of the paper):

$$T_m = T_a + \left(1 - \frac{\eta}{\tau\alpha}\right)\frac{G}{800}(\text{NOCT} - 20) \tag{2}$$

$T_m(G)$ is possibly used either in explicit models (Kenny et al., 2006), which require empirical (G, T_a) maps, or in the so-called *site profile* approach ((Wheldon et al., 2001), similar to previous works of Siegel, Klein or Evans (Evans, 1981; Klein, 1978; Siegel et al., 1980)), consisting in integrating the efficiency as given in Eq. (1) weighted by the solar irradiation distribution over all possible POA irradiance levels. By definition, $h(G)$ is the contribution of irradiance level G to the overall amount of incoming irradiation. The unit of $h(G)$ is 1/(W/m^2). PV module mean efficiency is eventually given by the following equality:

$$\bar{\eta} = \int_{\Omega_G} \eta(G, \bar{T}_m(G))h(G)\mathrm{d}G \tag{3}$$

As PV modules mean efficiency might be expressed as a linear function of its energy-weighted average temperature (Bücher, 1997; Guérin de Montgareuil, 2003) and as, at a given irradiance level G, taking energy-weighted average is the same as taking the average, the above equation appears to be very interesting in case Eq. (2) delivers a reliable approximation of PV module mean operating temperature for each irradiance level.

Nordmann and Clavadetscher (2003) underline that experimental studies achieved in the framework of Task 2 of the *photovoltaic power system program* (PVPS) on 18 PV systems tend to show that mean PV module temperature at given G is indeed approximately a linear function of irradiance. Some authors anyway point out that the NOCT model is not always the best possible and propose empirical linear regressions for completing thermal aspects of their energy rating method (e.g. $T_m = T_a + 0.031G$ for a *building integrated photovoltaic* (BIPV) system (Mondol et al., 2005)). These approach yields satisfying results but requires knowing *a priori* the thermal behaviour of the modules; these expressions moreover depend on local climate and on the way the modules are mounted (racks, roof-mounted, BIPV, etc.) and may therefore not be used elsewhere without experimental validation. The following semi-empirical approach enables a physical apprehension of the heat transfer phenomena explaining the differences between two sites; it also makes short-term field performance assessments relevant for long-term performance prediction as long as both short-term and long-term site profiles are provided.

This paper hence aims at proposing a convenient way for integrating PV modules thermal behaviour in performance prediction models, without referring explicitly to PV modules temperature measurements. It sets up a thermal model and proposes an empirical validation for determining the average PV module operating temperature at different irradiance levels, as a function of meteorological parameters only.

2. Experimental setup

The aim of the thermal model is to deliver reliable estimates of PV modules mean operating temperature at any