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Experimental investigation and modeling of the thermal behavior of a solar PV module

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ABSTRACT

Photovoltaic (PV) cell/module/array temperature calculations are essential to accurately assess its electrical performance. In this paper, we developed and validated two new models, and then we focused on the comparison of ten theoretical models (including our models) with experimental measurements, based on the ambient temperature, the in-plane array irradiance with/without taking into account the wind speed. These models were used to determine the PV module temperature of a 7.2 kWp standalone photovoltaic power plant installed in Elkaria village (Province of Essaouira, Morocco). The results show that our model without wind yields the highest value of the correlation coefficient R^2 = 96.7% and the lowest value of the root mean square error RMSE = 1.6 °C among the models without wind. On the other hand, our model with wind gives the best statistical coefficients (R^2 = 98.8% and RMSE = 1.1 °C) compared to all models (with/without wind).

1. Introduction

In the development of the photovoltaic industrial market, there is an increasing demand for accurate models forecasting the energy yield. There are several parameters affecting the PV module efficiency. The first of these is the plane of the module irradiance, G_g, and the second one is the PV module temperature, T_m. The latter parameter is:

– in most cases, assumed as being the same as the cell temperature, T_c, [1],
– sometimes considered to be lower than T_c by about 3 °C for an irradiance of 1000 W/m^2, as in the work of King et al. [2], or treated in a different way [3].

The PV module temperature affects negatively its voltage and positively its current. The power temperature coefficient (β_{Pmp}) for crystalline silicon encapsulated solar cells is usually not measured but determined using a calculation procedure according to the IEC 60891 standard, and it is in the range of -−0.52 to −0.37% °C^{-1} [4]. King et al. [2] showed that the efficiency of three PV modules technologies can decrease by up to 10% for the highest module temperatures.

The electrical parameters of PV modules are usually measured by the manufacturers at Standard Test Conditions (STC): an irradiance level of 1000 W/m^2, a cell temperature of 25 °C and an air mass AM = 1.5 spectrum. In fact, these conditions occur rarely on site since solar radiation of 1000 W/m^2 makes it difficult to have a cell temperature of 25 °C [4]. The normal operating cell temperature (NOCT), defined by IEC61215 [5] standard, is measured on an open rack-mounted module with an inclination of 45°, an irradiance level of 800 W/m^2, an ambient temperature of 20 °C and a wind speed of 1 m/s. The effect of different operational conditions (open-circuit, maximal power point, …) on the temperature of a PV module was found not to be negligible and is also dependent on the actual electrical efficiency [6]. The PV module temperature depends on several factors; incident solar radiation, ambient temperature, wind speed and direction, physical properties of the module materials, and mounting structure [2,7,8]. For free-standing modules, in a normal summer day in Germany with an irradiance of 800 W/m^2 and an ambient temperature of 20 °C, the common module temperature is around 42 °C [9], while during cloudy summer days in Central Europe, it can easily reach 60 °C. In extreme conditions, the PV module temperature can exceed 80 °C in Ouarzazate (Morocco) [10], where it is planned to install a 70 MWp photovoltaic power plant in the framework of the Moroccan Solar Plan (Noor IV project). In reference [10], the authors applied a standard NOCT model developed by Nolay [11] which is used in most simulation software to obtain the module temperature from ambient temperature and incident solar radiation, but ignores the effect of the wind. Muller [12] explained why NOCT based models do not explain temperature variations under specific conditions since, for instance, they do not take into account radiation heat losses from the front and rear module surfaces to sky and to ground, respectively. In the Lasnier et al. [13] developed an empirical correlation to obtain the polycrystalline silicon module temperature.

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However, this model does not taking account the effect of wind and the obtained empirical parameters cannot be used for other PV module technologies.

Several authors, such as, King et al. [2], Duffie and Beckman [14], Skoplaki et al. [15], Koehl et al. [16], Kurtz et al. [17], Mattei et al. [1], Barroso et al. [18] and Faiman et al. [7] developed thermal models for PV systems taking into account the wind effect on PV cell/module/array temperature calculations. Koehl et al. [6] reported a wind cooling effect of 15–20 °C for wind speeds of 10 m/s at a solar irradiance of about 1000 W/m^2.

The behavior of the PV module as a thermal mass has been described in the literature [19–23]. For non-steady-state conditions, the thermal time constant of encapsulated solar cells can reach 7 min [22], 15 min [23] or 10.5 min [19], depending on the wind speed.

In most PV systems, measured PV module temperature is not available. Hence, it is desirable to model physical relations between the PV module temperature, incoming irradiance, ambient temperature and, when available, wind speed. Even with a small impact for slow winds, the latter remains a pertinent factor that, when available, should be taken into account to calculate PV module temperatures. However, due to the difficulty of predicting winds, more accurate models ignoring wind speeds are necessary to forecast future PV systems yield within the framework of the Moroccan Solar Plan (MSP) [23,24]. For this reason, we decided to evaluate the accuracy of the module temperature models from onsite measurements:

– ignoring wind, considering plane of array irradiance, Gg and ambient temperature, Ta,
– considering the wind speed v.
– The objective of the present work is to:
– propose and validate two new models that calculate the PV module temperature with/without wind,
– compare the results of our models and of eight existing models (with/without wind), with onsite measurements.

Results of this paper are indented to be used in the framework of the "*Propre.ma*" project whose main goal consists on constructing grid-connected photovoltaic yield maps for all Morocco with ground calibration using identical plants installed in partner institutions located in 20 different Moroccan cities.

2. Experimental setup

2.1. Description of the photovoltaic plant

The PV power plant is situated in a coastal area nearby to the city of Essaouira (Region of Marrakesh-Safi, Morocco) located at 31.52°N, 9.27°W. With average wind speed reaching 7–8 m/s [25]. This area is known as a windy place but has also a reasonably important level of solar irradiation. Its exposure to the Atlantic Ocean moderates the temperature amplitudes compared to inland regions. The meteorological station is installed on the roof of the technical room, located approximately 5 m to the south of the PV plant. All the PV modules are mounted on a galvanized steel support with an inclination of 35° and are oriented to the south, as shown in Fig. 1 (A & B).

The PV field is composed of 32 monocrystalline silicon panels with a peak power of 225 W_p (1559 × 798 × 46 mm with 72 solar cells) from Sun-power (SPR-225-WHT) covered with a 3.2 mm-thick tempered glass and a back polymer sheet.

2.2. Monitoring system

The PV power plant and its meteorological station are fitted up with several sensors to monitor irradiance, wind speed as well as ambient and module temperatures. The monitoring of this PV plant provides useful information about the PV system. With a 5 min time step, the meteorological parameters are recorded by a Sunny Boy Control Plus (SMA) data logger which communicates with the Sunny Sensor Box (SMA) to record the data (see Fig. 1 A & B):

– incident irradiation on a reference cell,
– ambient temperature,
– module temperature provided by a Pt100 sensor installed in the back of one of the PV modules,
– wind speed measured by an anemometer installed at 3 m above the ground just near this PV module.

3. Theoretical models

3.1. PV module temperature calculation models

In addition to the solar radiation, the performance of a PV module depends on its temperature. The latter is determined by an energy balance on a unit area where the absorbed solar energy that is not converted into electricity ($[(\tau\alpha)-\eta_{PV}]$. Gg) is transformed into heat, which is in part dissipated to the surroundings ($U_L(T_m-T_a)$), as shown in Fig. 2. As the PV module efficiency depends essentially on the solar irradiance and the cell temperature [[26–30]], the following hypothesis are assumed for our calculations:

– Layers parallel to the plane of area are isothermal [1] and under steady-state conditions.
– Environment of the PV module is always at ambient temperature.
– Wind speed and direction are assumed to be the same on all the sides of the module.
– Module materials properties are assumed to be independent of temperature, of the incident solar radiation wavelength and angle of incidence.
– Transmittance-absorptance product is in the range of 0.9 [3,9,14,15,31,32].
– Due to thermal inertia, disturbances caused by wind direction and clouds in transit are random and produce a fluctuation around the stationary model.

The heat loss coefficient, U_L, includes losses by convection and radiation from the front and rear surfaces of the PV module to the environment at ambient temperature. Heat losses are almost equally shared between convection and radiation [33] and U_L is a linear function of wind speed ($U_L = U_{L0} + U_{L1}.v$) [7]. However, King et al. [2] used an exponential behavior with wind.

The energy balance for a PV module is given by:

$$[(\tau\alpha) - \eta_{PV}]G_g = U_L(T_m - T_a) = U_{L0}(T_m - T_a) + U_{L1}v(T_m - T_a) \tag{1}$$

The most known nonlinear model for photovoltaic module efficiency is given by the following equation:

$$\eta_{PV} = \eta_{STC}\left[1 + \beta_{P_{mp}}(T_m - T_{ref})\right]\left[1 + \gamma_{P_{mp}}Ln\left(\frac{G_g}{G_0}\right)\right] \tag{2}$$

Where η_{STC} and β_{Pmp} are the module efficiency and the temperature coefficient of maximum power, respectively, at Standard Test Conditions (18.1% and −0.39%/°C, respectively, are given by the manufacturer of m-Si SPR-225-WHT modules). T_{ref} and G_0 are the reference temperature and reference solar irradiance (25 °C and 1000 W/m^2, respectively). γ_{Pmp} is a dimensionless coefficient which is between 0.03 and 0.12 for single crystalline silicon [26–30], and we choose 0.04 in this study.

The steady-state energy balance leads to the following module temperature Tm, based on solar irradiance, ambient temperature and wind speed: