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Photovoltaic system derived data for determining the solar resource and for modeling the performance of other photovoltaic systems

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ABSTRACT

Using performance data from some of the millions of installed photovoltaic (PV) modules with micro-inverters may afford the opportunity to provide ground-based solar resource data critical for developing PV projects. A method was developed to back-solve for the direct normal irradiance (DNI) and the diffuse horizontal irradiance (DHI) from the measured ac power of south-facing PV module/micro-inverter systems. The method was validated using one year of irradiance and PV performance measurements for five PV systems, each with a different tilt/azimuth orientation, and located in Golden, Colorado. Compared to using a measured global horizontal irradiance for PV performance model input, using the back-solved values of DNI and DHI only increased the range of mean bias deviations from measured values by 0.6% for the modeled annual averages of the global tilt irradiance and ac power for the five PV systems. Correcting for angle-of-incidence effects is an important feature of the method to prevent underestimating the solar resource and for modeling the performance of PV systems with more dissimilar PV module orientations. The results for the method were also shown more favorable than the results when using an existing power projection method for estimating the ac power.

1. Introduction

Ground-based solar resource measurements are critical for developing photovoltaic (PV) projects. Unfortunately, accurate measurements at most locations are lacking due to the cost of solar radiation measurement equipment, which can be more than $40,000 for a first class station. To provide low or no-cost solar resource data traceable to a ground-based physical measurement at a nearby location, we have been developing a method to derive solar resource data from PV performance data such as measured by Enphase Energy Inc. micro-inverters, which have been deployed with millions of PV modules and have been providing reliable data with a 5-min temporal resolution since 2011—and for some early systems since 2007.

This work uses PV performance data to back-solve for the unknown direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI). It required the development of two key methods: (1) determining the global tilted irradiance (GTI), otherwise known as the plane-of-array (POA) irradiance, from the ac power (P_{ac}), and (2) determining the DNI and DHI from the GTI. The DNI and DHI values, or their global horizontal irradiance (GHI) equivalent, may then be used with conventional modeling software, such as PVsyst, Helioscope, and the National Renewable Energy Laboratory's (NREL's) System Advisor Model (SAM), to estimate the performance of PV systems of any size, or PV array tilt and azimuth orientation, including tracking.

We recently published a method to determine the DNI and DHI from the GTI when measured with pyranometers (Marion, 2015). It is a modification of the DIRINT model by Perez et al. (1992), which separates input values of GHI into their DNI and DHI components. The modification substitutes GTI for GHI, and adds an iterative procedure to adjust the global clearness index to improve the derived values of DNI and DHI. The resulting model is referred to as the GTI-DIRINT model. The GTI-DIRINT model was validated using GTI values measured with Kipp & Zonen CMP11 and CMP22 pyranometers for three climatically diverse locations: Cocoa, Florida; Eugene, Oregon; and Golden, Colorado. For the GTI measured at a small tilt angle from the horizontal (10°) and south-facing, the deviations between the measured DNI and DHI and the GTI-DIRINT modeled DNI and DHI were essentially the same as those for the DIRINT model when using the GHI for model input. For larger tilt angles from horizontal, the deviations between modeled and measured values were larger, but still reasonable. Results were least favorable for GTIs measured with a pyranometer tilt angle

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Nomenclature

A, B, C	quadratic equation constants
AOI	angle-of-incidence (°)
D	GTI subtracted from GTI_m
DHI	diffuse horizontal irradiance (W/m^2)
DNI	direct normal irradiance (W/m^2)
F	AOI correction factor for diffuse irradiance
F_b	AOI correction factor for beam and circumsolar irradiance
F_{sky}	AOI correction factor for diffuse sky irradiance
F_{hor}	AOI correction factor for horizon diffuse irradiance
F_{grd}	AOI correction factor for ground-reflected diffuse irradiance
F_1	Perez model circumsolar anisotropy coefficient
F_2	Perez model horizon/zenith anisotropy coefficient
GHI	global horizontal irradiance (W/m^2)
GTI	global tilt irradiance (W/m^2)
GTI_0	GTI at STC, 1000 W/m^2
GTI_m	modeled GTI corrected for AOI losses (W/m^2)
MBD	mean bias deviation (%)
P_{ac}	AC power (W)
P_{aco}	AC power rating of inverter (W)
P_{ac0}	AC power at STC (W)
P_{dc}	DC power (W)
P_{dco}	DC power rating of inverter (W)
P_{dc0}	DC power at STC (W)
P_{so}	self-consumption of inverter (W)
R	range of ω
RMSD	root-mean-square deviation (%)
STC	standard test conditions
T	PV cell temperature (°C)
T_0	T at STC, 25 °C
T_a	ambient dry bulb temperature (°C)
ΔT_c	difference between the cell temperature and the back surface of the PV module when GTI equals GTI_0 (°C)
WS	wind speed at a 10 m height (m/s)
a_0–a_5	polynomial coefficients for AOI correction factors
a,b	empirical Sandia temperature coefficients depending on the PV module construction and mounting configuration
c_0–c_6	coefficients for the Killinger method
c	max(0, cosine of AOI)
d	max(0.087, cosine of solar zenith angle)
n	refractive index
m	number of measured or modeled values
x_i	the ith measured value
y_i	the ith modeled value
β	PV module tilt angle from the horizontal (°)
γ	power correction factor for temperature (°C^{-1})
ρ	albedo of the ground
ω	solid angle of the incident diffuse irradiance

from horizontal of 40° and an azimuth angle from north of 210°, with deviations between modeled and measured values of DNI almost twice as great as for the south-facing GTIs.

More recently, Gostein et al. (2016) successfully applied the GTI-DIRINT model for use with one-axis tracking PV modules with the axis horizontal and oriented north-south. This orientation results in the PV module being tilted at small angles during mid-day, a favorable condition because the GTI-DIRINT model is functionally the same as the DIRINT model if the tilt is horizontal and the GTI equals the GHI.

This work developed and validated a method to derive the GTI from the P_{ac} for south-facing PV modules, the optimal orientation based on our previous work, and then to use the GTI-DIRINT model to determine the DNI and DHI. Results are presented for implementing the overall procedure to derive the DNI and DHI from the P_{ac}, and for then using the derived values of DNI and DHI to model the GTI and P_{ac} for various tilted orientations, including non-south-facing and tracking.

Recent work of a related nature includes that of da Costa et al. (2014), where irradiance and temperature are both derived from operating points on the PV module current-voltage curve, but at the expense of interrupting the operation the PV module at its maximum power. The GTI-DIRINT model uses a method similar to that of Yang et al. (2013, 2014), but the iteration procedure uses the anisotropic transposition model of Perez et al. (1990) in place of an isotropic transposition model.

Killinger et al. (2016) provides a power projection method for estimating the performance of one PV system from that of another, which is quite similar to our method. They use the GTI-DIRINT model for one of their variants, and we have adopted their technique of using a quadratic solution to determine the GTI from the P_{ac}, but have added provisions to account for the effect of wind speed on PV module temperature, inverter efficiency as a function of load, and increased reflection losses due to the angle-of-incidence (AOI) of direct and diffuse solar radiation.

Another power projection method uses a "clear sky index for PV" (Engerer and Mills, 2014). The index is determined by dividing the measured PV power by that calculated for clear-sky conditions. To estimate the performance of a nearby PV system, the PV power calculated for the nearby PV system for clear-sky conditions is multiplied by the index. Lonij et al. (2012) uses a similar index to forecast the power output of PV systems. For best results when using these types of indices, the orientation of the PV systems should be similar because the contributions of the direct and diffuse solar radiation are not treated separately. To address this concern, Engerer and Xu (2015) later developed a method to estimate the diffuse fraction from the "clear sky index for PV."

The following sections discuss the method for determining the DNI and DHI from the P_{ac}, data used for validating the method, implementation of the method, results and their analysis, summary and conclusions from the key outcomes, and future work.

2. Method description

The following sections describe the method's two key elements: (1) deriving the GTI from the ac power, and (2) deriving the DNI and DHI from the GTI using the GTI-DIRINT model.

2.1. Deriving the GTI from the ac power

The solution for deriving the GTI from the ac power is a two-step process where the dc power (P_{dc}) is first derived from the P_{ac} and then the GTI is derived from the P_{dc}. This is opposite to the normal modeling chain of PV performance software; consequently, inverted PV performance equations are used based on conventional equations for P_{ac} and P_{dc} and PV cell temperature (T). Eq. (1) represents the equation for P_{ac} from the Sandia inverter performance model when using the default values of zero for the Sandia empirical coefficients (King et al., 2007).

$$P_{ac} = P_{aco} \cdot (P_{dc} - P_{so})/(P_{dco} - P_{so}), \tag{1}$$