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Brief Note

Numerical method for angle-of-incidence correction factors for diffuse radiation incident photovoltaic modules

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ABSTRACT

A numerical method is provided for solving the integral equation for the angle-of-incidence (AOI) correction factor for diffuse radiation incident photovoltaic (PV) modules. The types of diffuse radiation considered include sky, circumsolar, horizon, and ground-reflected. The method permits PV module AOI characteristics to be addressed when calculating AOI losses associated with diffuse radiation. Pseudo code is provided to aid users in the implementation, and results are shown for PV modules with tilt angles from 0° to 90°. Diffuse AOI losses are greatest for small PV module tilt angles. Including AOI losses associated with the diffuse irradiance will improve predictions of PV system performance.

1. Introduction

The angle-of-incidence (AOI) is the angle between the normal to the photovoltaic (PV) module surface and the vector of the incoming radiation. When the AOI is increased, an increased percentage of the in-plane irradiance is reflected from the surface of a PV module. This reduces the in-plane irradiance reaching the PV cells that generates electricity. To account for this reduction when modeling PV performance, the in-plane irradiance is multiplied by an AOI correction factor (from 0 to 1). The AOI correction factor is the in-plane irradiance reaching the PV cells divided by the in-plane irradiance reaching the PV cells when the AOI is normal to the PV module surface. Other terms for the AOI correction factor include: transmittance for diffuse radiation (Brandemuehl and Beckman, 1980), relative transmittance (Sjerps-Koomen et al., 1996), angular factor (Martin and Ruiz, 2001, 2013), incidence angle modifier (De Soto et al., 2006), and relative light transmission into the module (IEC, 2016).

The AOI correction factor may be represented by a function, $F(\mathrm{AOI})$, that provides a relationship with the AOI. The function may be based on indoor or outdoor tests where the short-circuit current output of the PV module or one of its cells is measured over a range of AOIs. Eq. (1) is the Sandia function as formulated by King et al. (2004) as a 5th-order polynomial where the a values are the polynomial curve-fit coefficients:

$$F(\mathrm{AOI}) = a_0 + a_1 \cdot \mathrm{AOI} + a_2 \cdot \mathrm{AOI}^2 + a_3 \cdot \mathrm{AOI}^3 + a_4 \cdot \mathrm{AOI}^4 + a_5 \cdot \mathrm{AOI}^5. \tag{1}$$

Eq. (2) is the function as formulated by Martin and Ruiz (2001, 2013) using exponentials where a_r is the angular loss coefficient determined from a best fit of the measured data. This formulation is used in the International Electrochemical Commission (IEC) standard 61853-2 (IEC, 2016):

$$F(\mathrm{AOI}) = [1 - \exp(-\cos(\mathrm{AOI})/a_r)]/[1 - \exp(-1/a_r)]. \tag{2}$$

For PV modules with a flat glass surface, the IEC standard 61853-2 also allows an air-glass model, such as developed by Sjerps-Koomen et al. (1996), to be used in place of measurements. The air-glass model resulted from studies that showed that the air-glass interface dominates the transmittance of radiation relative to normal incidence. Snell's law is used to determine the angle of refraction in the glass and Fresnel equations are used to determine the reflection from the glass surface. From Duffie and Beckman (1991), the reflectance at normal incidence, r_0, is defined by Eq. (3):

$$r_0 = [(n-1)/(n+1)]^2, \tag{3}$$

where n is the index of refraction of the PV module cover material. (For glass, $n = 1.526$ and r_0 becomes 0.0434.) For values of AOI other than for normal incidence, the angle of refraction, AOI_r, is determined using Eq. (4) and then the reflectance, r_{AOI}, is determined using Eq. (5):

$$\mathrm{AOI}_r = \sin^{-1}(\sin(\mathrm{AOI})/n), \tag{4}$$

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$$r_{AOI} = 1/2 \cdot [(\sin^2(AOI_r - AOI)/\sin^2(AOI_r + AOI)) + (\tan^2(AOI_r - AOI)/\tan^2(AOI_r + AOI))]. \quad (5)$$

Finally, Eq. (6) represents the function, $F(AOI)$, when using the air-glass model to determine AOI correction factors:

$$F(AOI) = (1 - r_{AOI})/(1 - r_0). \quad (6)$$

Both the direct beam and diffuse irradiance may be corrected for the AOI, with the diffuse irradiance classified by its type: (1) sky—radiation from the sky dome, (2) circumsolar—radiation from the region of the sky near the sun, (3) horizon—radiation from the region of the sky near the horizon, and (4) ground-reflected—radia tion reflected from the ground. This classification of the diffuse irradiances is consistent with the popular Perez transposition model where the sky-dome irradiance distribution has an isotropic background with enhanced circumsolar and horizon regions (Perez et al., 1990). Other transposition models use similar classifications for diffuse irradiances. Yang (2016) provides a recent summary of available transposition models and their features.

The circumsolar diffuse irradiance is considered to have the same AOI as the beam irradiance; consequently, their values of $F(AOI)$ are the same. Their AOI is calculated based on the sun's position and the PV module's azimuth and tilt from horizontal. For the other classifications of diffuse irradiance, the PV module receives radiation from angles within its 180° field of view. If the radiation is considered isotropic—meaning that the radiation intensity is the same and independent of direction—then radiation from directions with large AOIs contribute less to the in-plane irradiance because the cosine of the AOI is less. A smaller amount of radiation will also reach the PV cells because the value of $F(AOI)$ is also less. Based on the work of Brandemuehl and Beckman (1980), Eq. (7) integrates the effect of the AOI for all angles within the field of view to provide an overall AOI correction factor for the diffuse radiation, F_d:

$$F_d = \frac{\int_A F(AOI) \cdot \cos(AOI)d\omega}{\int_A \cos(AOI)d\omega}, \quad (7)$$

where ω is the solid angle of the incident diffuse irradiance and A is the range of ω. The radiation's $F(AOI)$ is weighted by its contribution to the in-plane irradiance.

This work provides a method for numerically integrating Eq. (7) to obtain overall AOI correction factors for the sky, horizon, and ground-reflected diffuse irradiance components. To aid users in the implementation of the method, pseudo code is provided in Section 3, and example results for a PV module are provided in Section 4.

2. Numerical method

By definition, the solid angle subtended by an object is the area projected onto the surface of the unit sphere, radius of one, with the vertex of the solid angle located at the center of the unit sphere. The dimensionless unit of the solid angle is the steradian. About a point, the total solid angle is 4π, which is the same as the surface area of a sphere with a radius of one.

In Fig. 1, an elemental surface area, dA, of the sky viewed by the PV module is projected onto the surface of the unit sphere. The resulting projected surface area, dA_s, equals the solid angle $d\omega$. To facilitate calculating values of dA_s, the ϕ–ψ coordinate system shown in Fig. 2 is used to define dA_s, where ϕ is the angle between the zenith and a line from the center of the sphere to the dA_s and ψ is the angle from north for a line from the center of the sphere to the vertical projection of the dA_s in the horizontal plane. From elementary geometry, the surface area of dA_s may be calculated using Eq. (8):

$$dA_s = (\psi_2 - \psi_1) \cdot [\cos(\phi_1) - \cos(\phi_2)], \quad (8)$$

where ψ is in radians and the subscripts define the range of angles, with a subscript of one corresponding to the minimum angle and a subscript of two corresponding to the maximum angle. Using the average values of ϕ and ψ to represent the center of the dA_s and recognizing that the coordinate system is the same as that used for the sun's position in the sky, an equation from Iqbal (1983) provides the AOI:

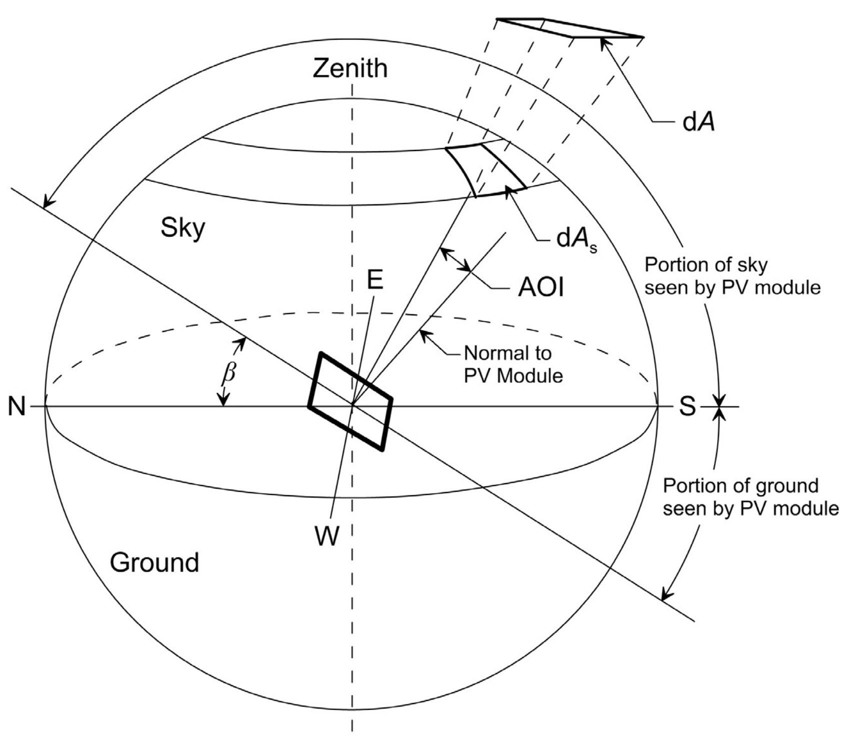

Fig. 1. PV module located at the center of the unit sphere showing the regions of the sky and ground within the PV module's field of view, the elemental area, dA, projected onto the unit sphere, and the resulting angle of incidence, AOI, between the projected elemental area, dA_s and the normal to the PV module.