GOALI Report Section on: Irradiance Estimation for a Smart PV Array

Andreas Spanias, PI
Cihan Tepedelenlioglu and Devarajan Srinivasan, Co-PIs

August 31, 2015

This section of the GOALI report describes the method of irradiance estimation for the PV array. The UW-Madison PV performance model, together with measurements from SMDs, may be used to characterize the performance of individual modules. This model is clearly accurate when V, I, M, and T_c are perfectly known and the model perfectly matches the behavior of the device. However, none of these conditions holds true in practice: measurements are always noisy and the UW-Madison model is only an approximation of device behavior. Furthermore, cell temperature T_C in our implementation is estimated from module back-surface temperature. King gives a model [1] for estimating the temperature difference between cell and module back surface temperatures, but this is of course not perfectly accurate. Finally, Air mass M is typically calculated based on the solar zenith angle [2] but these functions are unlikely to be accurate under partial shading conditions. The source and intensity of shade (e.g. clouds vs. buildings) will affect air mass in ways that cannot be feasibly predicted by any method we are aware of. This section examines the effects of several potential sources of error on the accuracy of estimated irradiance S, and maximum power current, voltage, and power I_{MP}, V_{MP}, P_{MP}.

1 Measurement Noise

The relationship between noise in model inputs and error in output is extremely important, but the complex and non-linear input/output relationship makes evaluating these effects non-trivial. We examine this important relationship between input noise and output error using the widely used first-order propagation of error equation. Assuming statistical independence between sources of error, this relationship is given by

$$\mathrm{var}(f(x, y, z, ...)) \approx \frac{\partial}{\partial x}^2 \sigma_x^2 + \frac{\partial}{\partial y}^2 \sigma_y^2 + \frac{\partial}{\partial z}^2 \sigma_z^2 + ... \; . \tag{1}$$

Evaluating each partial derivative in 1, we arrive at the expressions given in Figure 1. The following sections further explore the robustness of the algorithm.

$$\frac{\partial}{\partial T_c}\left(\frac{S}{S_{ref}}\right) = \frac{I_0\left[\exp\left[\frac{(V+IR_s)q}{N_s n_1 k_b T_c}\right]\left(\frac{3T_c^2}{T_{c,ref}^3} - \frac{(V+IR_s)q}{N_s n_1 k_b T_c^2} + \frac{E_g}{T_c^2}\frac{q}{k_b}\right) - \frac{E_g}{T_c^2}\frac{q}{k_b}\right]}{f_1(M)\left[\alpha_{I_{SC}}(T_c - T_{c,ref})\right] - \frac{V+IR_s}{R_{sh,ref}}} - \frac{\left[I + I_0(\exp\left[\frac{(V+IR_s)q}{N_s n_1 k_b T_c}\right] - 1)\right] f_1(M)\alpha_{I_{SC}}}{\left[f_1(M)\left[\alpha_{I_{SC}}(T_c - T_{c,ref})\right] - \frac{V+IR_s}{R_{sh,ref}}\right]^2} \tag{2}$$

$$\frac{\partial}{\partial I}\left(\frac{S}{S_{ref}}\right) = \frac{1 + I_0\frac{R_s}{a}\exp\left[\frac{(V+IR_s)}{a}\right]}{f_1(M)\left[\alpha_{I_{SC}}(T_C - T_{c,ref})\right] - \frac{V+IR_s}{R_{sh,ref}}} - \frac{R_s/R_{sh,ref}\left[I + I_0(\exp\left[\frac{(V+IR_s)}{a}\right] - 1)\right]}{\left[f_1(M)\left[\alpha_{I_{SC}}(T_C - T_{c,ref})\right] - \frac{V+IR_s}{R_{sh,ref}}\right]^2} \tag{3}$$

$$\frac{\partial}{\partial V}\left(\frac{S}{S_{ref}}\right) = \frac{I_0/a\exp\left[\frac{(V+IR_s)}{a}\right]}{f_1(M)\left[\alpha_{I_{SC}}(T_C - T_{c,ref})\right] - \frac{V+IR_s}{R_{sh,ref}}} - \frac{1/R_{sh,ref}\left[I + I_0(\exp\left[\frac{(V+IR_s)q}{N_s n_1 k_b T_c}\right] - 1)\right]}{\left[f_1(M)\left[\alpha_{I_{SC}}(T_C - T_{c,ref})\right] - \frac{V+IR_s}{R_{sh,ref}}\right]^2} \tag{4}$$

Figure 1: Propagation of error expressions.

2 Air Mass

Absorption and scattering of light by the atmosphere changes the spectrum of incoming radiation, which in turn affects the output power of a PV cell. The air mass environmental parameter is used to model this effect. Air mass M is a dimensionless quantity representing the number of atmospheres light must travel through in order to reach the module. Orbiting satellites receive radiation with $M = 0$, while a module at sea level with the sun directly overhead receives $M = 1$. Air mass 1.5 has been arbitrarily chosen as a typical value, balancing the low airmass of midday with the higher air mass experienced when the sun is at a lower angle. In the PV performance models considered here, the air mass modifier $f_1(M)$ summarizes the effect of changing air mass on power output. $f_1(M)$ is a fourth-degree polynomial with empirically determined coefficients:

$$f_1(M) = a_0 + a_1 M + a_2 M^2 + a_3 M^3 + a_4 M^4. \tag{5}$$

Figure 2 shows King et al.'s values for $f_1(M)$ for a typical crystalline silicon PV module, with airmass ranging from 1 to 35, corresponding to solar zenith angles of approximately 0 to 90 degrees.

The air mass modifier is potentially problematic for the irradiance estimation procedure presented here, since the effect of partial shading on the spectrum of incoming light is unknown. However, the air mass modifier $f_1(M)$ is very near 1 for air mass $1 < M < 4$. The vast majority of available solar energy arrives at a zenith angle of 75° or less, indicating that the effect of air mass can be neglected without destroying the fidelity of the estimation, at least as

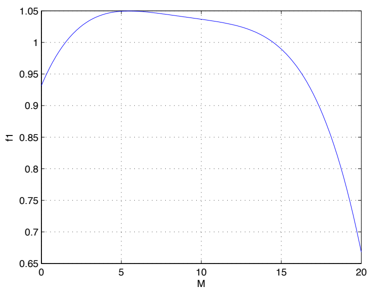

Figure 2: Airmass factor $f_1(m)$.

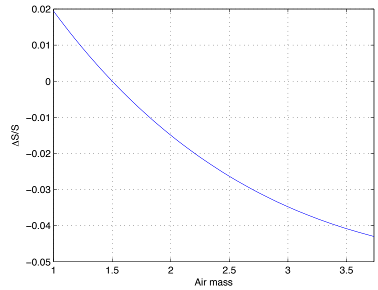

Figure 3: Normalized error in estimated irradiance for varying air mass for Sharp NT-175U1 module, other parameters held at STC.

far as modeling of partial shading is concerned. Figure 3 shows the effect of error in airmass on estimated irradiance at STC. Note that if an airmass of 1.5 is assumed by the algorithm, an irradiance error of only approximately 4% is observed, even if actual airmass is a relatively large value of 3.5.

3 Temperature Bias

Module back surface temperature measurements are easy to acquire, but do not accurately represent the cell temperature. A reasonably accurate method has been proposed to estimate cell temperature [3], but this remains a potential source of error for the irradiance estimation algorithm. persistent temperature errors of up to $4°C$ may occur.

A first-order description of the relationship between temperature bias and error has already been given in Section 1. Figure 4 extends this model by plotting the error in irradiance as a function of the error in temperature bias at STC (standard test conditions), as well as three other temperature and irradiance conditions. Temperature errors of $4°C$ or less produce at most a 0.2% error in estimated irradiance, corresponding to an error of only 2 W/m^2. In a mismatch mitigation application this is an acceptable level of error.

References

[1] D. King, J. Kratochvil, and W. Boyson, "Photovoltaic array performance model," Sandia National Laboratory, Tech. Rep., 2004.

[2] F. Kasten and A. T. Young, "Revised optical air mass tables and approximation formula," *Appl. Opt.*, vol. 28, no. 22, pp. 4735–4738, Nov 1989. [Online]. Available: http://ao.osa.org/abstract.cfm?URI=ao-28-22-4735

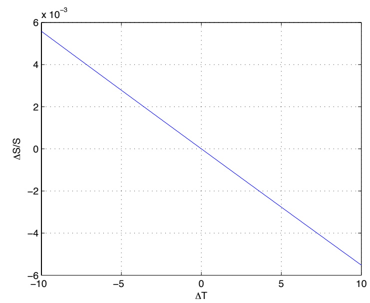

Figure 4: Normalized error in irradiance estimates as a functon of error in temperature. Sharp NT-175U module at standard reference conditions and maximum power point.

[3] D. King, “Photovoltaic module and array performance characterization methods for all system operating conditions,” in *AIP Conference Proceedings*. IOP Institute of Physics Publishing ltd., 1997, pp. 347–368.