Temperature Coefficients for PV Modules and Arrays: Measurement Methods, Difficulties, and Results

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ABSTRACT

The term "temperature coefficient" has been applied to several different photovoltaic performance parameters, including voltage, current, and power. The procedures for measuring the coefficient(s) for modules and arrays are not yet standardized, and systematic influences are common in the test methods used to measure them. There are also misconceptions regarding their application. Yet, temperature coefficients, however obtained, play an important role in PV system design and sizing, where often the worst case operating condition dictates the array size. This paper describes effective methods for determining temperature coefficients for cells, modules, and arrays; identifies sources of systematic errors in measurements; gives typical measured values for modules; and provides guidance for their application in system engineering.

INTRODUCTION

Temperature coefficients provide the rate of change (derivative) with respect to temperature of different photovoltaic performance parameters. The derivatives can be determined for short-circuit current (I_{sc}), maximum-power current (I_{mp}), open-circuit voltage (V_{oc}), maximum-power voltage (V_{mp}), and maximum power (P_{mp}), as well as fill factor (FF) and efficiency (η). ASTM standard methods for performance testing of cells and modules address only two temperature coefficients, one for current and one for voltage [1, 2]. Outdoor characterization of module and array performance has indicated that four temperature coefficients for I_{sc}, I_{mp}, V_{oc}, and V_{mp}, are necessary and sufficient to accurately model electrical performance for a wide range of operating conditions [3]. ASTM also specifies that temperature coefficients are determined using a standard solar spectral distribution at 1000 W/m^2 irradiance, but from a practical standpoint they need to be applied at other irradiance levels as well. A variety of practical issues regarding the measurement and application of temperature coefficients still need to be addressed.

MEASUREMENT PROCEDURES

Temperature coefficients for cells are typically measured by placing the cell on a temperature controlled test fixture, illuminating the cell with a solar simulator, measuring the cell's current-voltage (I-V) curve over a range of cell temperatures, and then calculating the rate of change of the desired parameter with temperature.

Coefficients for modules can be measured either indoors with a solar simulator or outdoors under operational conditions. For indoor tests, the module is usually illuminated using a solar simulator and then heated from the rear surface in order to achieve a range of temperatures. For outdoor tests, the module can first be shaded to lower its temperature to near ambient temperature then unshaded with I-V curves measured as it heats up to operating temperature. In both cases, the average module temperature should be measured using multiple thermocouples attached to the rear surface. Additional issues associated with the measurement of temperature coefficients in the laboratory are documented elsewhere [4].

For arrays of modules, it is usually impractical to measure the coefficients directly, so the coefficients are typically calculated from previously measured module coefficients by accounting for the series/parallel configuration of modules in the array. Alternatively, temperature coefficients for arrays have also been estimated using regression analysis from performance data measured over a range of operating conditions [5].

SYSTEMATIC INFLUENCES

Fundamentally, the temperature coefficients for modules and large arrays should be directly related to the temperature coefficients for their individual cells. In principal, it should be possible to measure temperature coefficients for a large number of cells, average the values, and then calculate coefficients for modules and arrays using the average values. However, test results for modules and arrays often don't support this premise. Systematic influences that occur during testing or system operation often result in apparent temperature coefficients that differ from anticipated values. Typically the difference results from nonuniform temperature distributions and/or

measured temperatures that are not indicative of actual cell temperatures.

For individual cells, nonuniform temperature during measurements can result if the temperature-controlled test fixture has a nonuniform temperature distribution, or if it is of inadequate size for the cell. Fig. 1 illustrates the results for a case where the temperature-controlled test fixture covered only 75% of the surface of the cell being tested. As the cell was heated up, the outer 25% of the cell operated at a lower temperature than in the central region where the temperature was both controlled and measured. The net result was temperature coefficients for V_{oc} and V_{mp} that were about 20% smaller in magnitude than the "true" values with the entire cell at uniform temperature, also shown in Fig. 1.
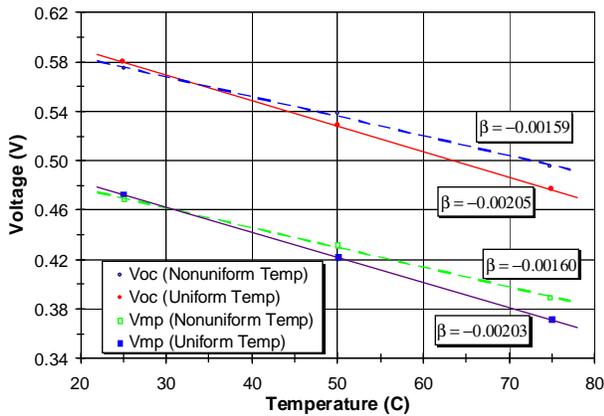

Fig. 1: Measured temperature coefficients for voltage for a Solarex 130-cm^2 mc-Si cell with uniform and nonuniform temperature during testing.

For modules measured indoors with a back surface heating blanket, multiple temperature sensors are usually used on the rear surface to obtain an average temperature. However, the heating apparatus and the rate of heating must be optimized to give spatially uniform module temperatures. Otherwise, physical irregularities such as junction boxes, module frames, or mounting brackets can introduce nonuniform temperature across the module (cells) during testing, which in turn results in measured temperature coefficients that are often smaller than the true values. Metal frames tend to keep the module edges cooler, and junction boxes tend to isolate the cells in front of them from the rear surface heater, both effects producing a situation analogous to the nonuniformly heated individual cell. The location of thermocouples relative to the heating elements in the heating blanket can also be problematic.

Outdoor measurements of temperature coefficients using the shading procedure provide additional information related to the thermal time constant of modules, but have additional test requirements to avoid systematic errors. During the transient outdoor test, nonuniform temperature

distributions can be introduced by wind, intermittent sunshine, module frames, junction boxes, mounting brackets, etc. In addition, measurements of the back surface temperature of the module during the transient test may not be indicative of actual cell temperature due to a temperature gradient through the back surface material and/or heat capacitance of the module. Testing procedures must be controlled in order to obtain repeatable results that are beneficial to photovoltaic system engineers.

If the "true" temperature coefficients are desired, i.e. those that agree with individual cell results, then the back surface and edges of the module can be thermally insulated and tests can be restricted to conditions with stable sunshine and calm winds (<2 m/s). Adding the thermal insulation influences the test in several ways; a larger range for module temperature is achieved, a more uniform cell temperature distribution results, there is less thermal influence by junction boxes, and back surface module temperatures are more equivalent to actual cell temperatures.

Fig. 2 illustrates the effect of thermally insulating the module's back surface on the measurement of temperature coefficients for V_{oc} and V_{mp}. The temperature coefficients determined without back surface insulation were approximately 10% larger than for the case with back surface thermal insulation. Again, the cause for this difference in measured coefficients was the nonuniform cell temperature distribution introduced by junction boxes. The cells in front of junction boxes were effectively insulated on the back surface, heated up more rapidly than other cells, operated at lower voltage, and consequently biased the temperature coefficient to a higher value. (Average module temperature was based on thermocouples located in areas not influenced by junction boxes.) Note that the maximum module temperature achieved with the back surface insulated was 15 to 20 °C hotter than when the back surface was exposed. For photovoltaic systems designed with minimal back surface cooling, for instance some roof integrated systems, higher operating temperatures should be anticipated and the "true" temperature coefficients are likely to be the most appropriate.
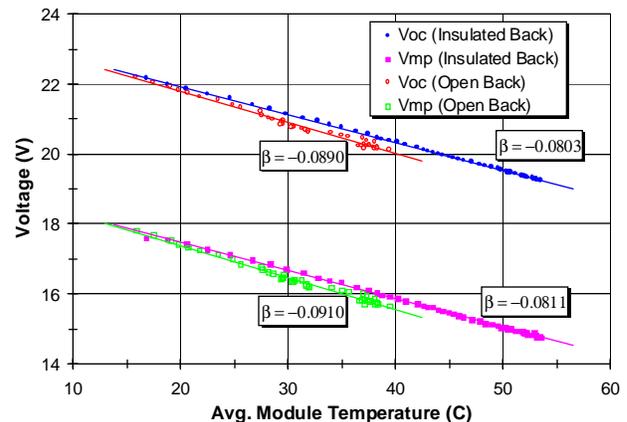

Fig. 2. Measured temperature coefficients for voltage for a 36-cell c-Si module measured outdoors, with and without back-surface thermal insulation.

For photovoltaic systems with modules mounted in open rack structures, there is also a valid rationale for using "effective" or "apparent" temperature coefficients measured with the module fully exposed to environmental conditions. Performance models used for designing and analyzing photovoltaic systems rarely consider the effects of a module's heat capacitance or nonuniform module temperature. Therefore, temperature coefficients measured with the module fully exposed to the environment might be considered to implicitly account for nonequilibrium thermal conditions. Particularly since the outdoor measurement procedure closely simulates a common condition relevant to energy production; namely, cloud cover with modules near ambient temperature followed by clear sky and full sunshine. The thermal transient in photovoltaic systems on clear days during morning start up is also an equivalent thermal condition. The difference between "true" and "effective" temperature coefficients also depends on the module design; the difference is typically smaller for more massive modules with glass front and rear surfaces than for more common modules with a glass front and polymer back surface.

Fig. 3 illustrates the effect of a module's heat capacitance during transient thermal conditions. For simultaneous testing with stable solar irradiance, three situations are shown in the figure. The module temperature shown is the average of three thermocouples on the back surface. Two of the modules used in the test were identical c-Si modules with glass front surface and Tedlar rear surface. One of the two c-Si modules had the back surface thermally insulated. The third module was a thin-film amorphous silicon module with glass front and glass back surfaces. These tests indicated that about 15 minutes were required for a typical glass/Tedlar module to reach a quasi-steady operating temperature starting from an ambient temperature condition. The more massive glass/glass module required about 25 minutes, as did glass/tedlar modules with the back surface insulated. Note that the module with insulated back surface reached an operating temperature about 15 °C higher than the modules with open back surfaces.

MEASURED RESULTS

Table 1 summarizes outdoor measurements of "effective" temperature coefficients for a variety of commercially available photovoltaic modules. In the table, the units for the temperature coefficients have been normalized to 1/°C by dividing the coefficient by the value for the parameter at ASTM Standard Reporting Conditions (1000 W/m^2, AM=1.5, 25 °C). The normalized coefficients are more easily applied to different photovoltaic array configurations with different series/parallel combinations of modules.
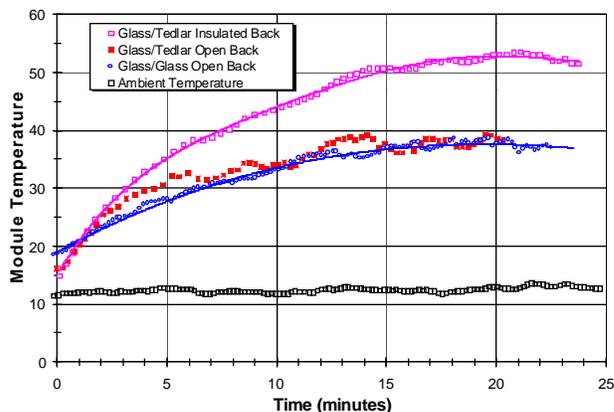

Fig. 3. Average module temperature versus time starting from shaded condition with rapid exposure to irradiance of 1100 W/m^2 with wind speed less than 3 m/s.

Several things are interesting to note about the results in Table 1. The normalized voltage coefficients were "nominally" the same for all the modules shown, of different technologies. The V_{mp} and V_{oc} coefficients for each module were approximately equal, with the V_{mp} coefficients being slightly larger in c-Si and mc-Si modules. The most obvious distinctions were in the I_{sc} and I_{mp} coefficients for each module with a significant difference in magnitude between the two and often a difference in sign. Results in the table suggest that a shortcoming in the ASTM method for translating I-V curves to different operating conditions [2] is the use of a single current and a single voltage coefficient.

Module	dI_{sc}/dT (1/°C)	dI_{mp}/dT (1/°C)	dV_{oc}/dT (1/°C)	dV_{mp}/dT (1/°C)
ASE300, mc-Si	.00091	.00037	-.0036	-.0047
AP8225, Si-Film	.00084	.00026	-.0046	-.0057
M55, c-Si	.00032	-.00031	-.0041	-.0053
SP75, c-Si	.00022	-.00057	-.0039	-.0049
MSX64, mc-Si	.00063	.00013	-.0042	-.0052
SQ-90, c-Si	.00016	-.00052	-.0038	-.0048
MST56, a-Si	.00099	.0023	-.0041	-.0039
UPM880, a-Si	.00082	.0018	-.0038	-.0037
US32, a-Si	.00076	.0010	-.0043	-.0040
SCI50, CdTe	.00019	-.0012	-.0037	-.0044
±U_{95} (%)	10	12	5	7

Table 1: Typical "effective" temperature coefficients for commercial modules at 1000 W/m^2 and AM_a=1.5 measured outdoors without back surface insulation.

APPLICATION OF COEFFICIENTS

Before providing the equations that are used to apply temperature coefficients, a couple of technical clarifications need to be made. First, the temperature

coefficients for V_{oc} and V_{mp} are usually assumed to be independent of the solar irradiance level. Although this assumption is not strictly correct, it is a reasonable simplification. For a typical flat-plate module with solar irradiance varying from perhaps 100 W/m^2 to 1000 W/m^2, there is typically less than a 5% change in the voltage coefficients. Second, the temperature coefficients for I_{sc} and I_{mp} must be scaled by the ratio of the actual irradiance level to the irradiance level (1000 W/m^2) used for determining the coefficients.

The set of formulas given in Eqn. 1 can be used to calculate module or array performance parameters at a desired or reference temperature, T_r, given performance values measurements at an arbitrary temperature, T. The temperature coefficients used (α_{Isc}, α_{Imp}, β_{Voc}, β_{Vmp}) have "normalized" units as previously given by the derivatives in Table 1. This formulation simplifies calculations for arrays of modules. The current coefficients are automatically scaled for irradiance level independent of the number of modules connected in parallel. The two voltage values (V_{oc}^{STC} and V_{mp}^{STC}) required in the equations are the values expected at ASTM standard reporting conditions (1000 W/m^2, AM=1.5, 25 °C). These voltages can be readily determined by obtaining module values from manufacturers' specification sheets, and then multiplying by the number of modules connected in series in the array. The correct method for translating P_{mp} from one temperature to another is given by Eqn. 2.

$$I_{sc}(T_r) = I_{sc}(T) \cdot \left[1 - \alpha_{Isc} \cdot (T - T_r)\right]$$
$$I_{mp}(T_r) = I_{mp}(T) \cdot \left[1 - \alpha_{Imp} \cdot (T - T_r)\right]$$
$$V_{oc}(T_r) = V_{oc}(T) - \beta_{Voc} \cdot V_{oc}^{STC} \cdot (T - T_r)$$
$$V_{mp}(T_r) = V_{mp}(T) - \beta_{Vmp} \cdot V_{mp}^{STC} \cdot (T - T_r)$$

(1)

$$P_{mp}(T_r) = I_{mp}(T) \cdot \left[1 - \alpha_{Imp} \cdot (T - T_r)\right]$$
$$\cdot \left[V_{mp}(T) - \beta_{Imp} \cdot V_{mp}^{STC} \cdot (T - T_r)\right]$$

(2)

Maximum Power Versus Temperature

Contrary to common practice, the derivative of maximum power temperature with respect to temperature should not be considered a constant for a given irradiance level. The maximum power, P_{mp}, is the product of two factors, I_{mp} and V_{mp}, both of which vary with temperature and irradiance. Therefore, the derivative, or temperature "coefficient," should be calculated as in Eqn. 3. After doing so, Figs. 4 and 5 illustrates the temperature "coefficient" of maximum power at different irradiance and temperature conditions for a crystalline silicon and an amorphous silicon module, respectively. The maximum power temperature coefficient for crystalline silicon is always negative in sign with largest magnitude at high temperature and low irradiance. For amorphous silicon, the temperature coefficient is small but negative in sign at high temperature and irradiance, changing to a positive coefficient at low temperature and irradiance.

$$\frac{dP_{mp}}{dT} = V_{mp} \cdot \frac{dI_{mp}}{dT} + I_{mp} \cdot \frac{dV_{mp}}{dT}$$

(3)

CONCLUSIONS

Information has been provided that should help improve the design and evaluation of photovoltaic systems through improved understanding of measurement methods and procedures for application of temperature coefficients for photovoltaic performance parameters.
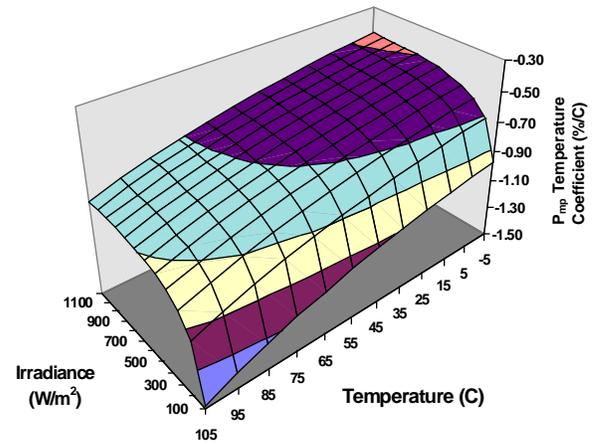

Fig. 4. Maximum-power temperature "coefficient" for a Siemens SP-75 crystalline silicon module as a function of irradiance and temperature.
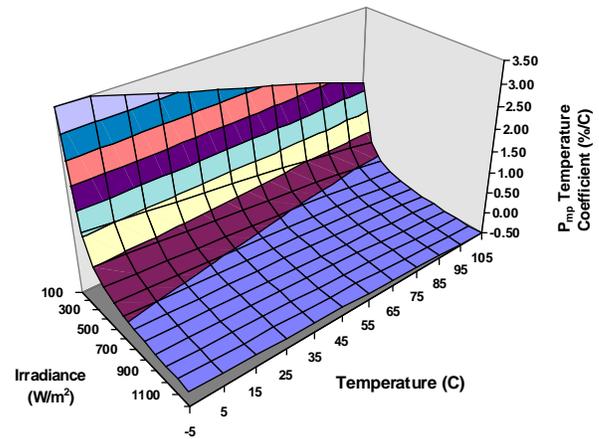

Fig. 5. Maximum-power temperature "coefficient" for a Solarex MST-56 tandem amorphous silicon module as a function of irradiance and temperature.

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