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Improving Module Temperature Measurements using Averaging Resistive Temperature Devices

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***Abstract* — Determination of module temperature coefficients for voltage, current and power requires measuring the average of cell temperatures. Conventional practice is to place thermocouples or resistive temperature devices (RTDs) at a few locations on a module's back surface and to average the readings, which may not accurately represent the average temperature over all cells. We investigate the suitability of averaging RTDs, which measure average temperature along a 1m length, to accurately measure the average cell temperature when determining temperature coefficients outdoors.**

***Index Terms* — resistive temperature device, temperature coefficient, photovoltaic modules, testing.**

I. Introduction

Current IEC PV module test standards [1] prescribe measuring module temperature during outdoor testing by averaging temperatures obtained from 3 temperature sensors attached at specified locations on the module's back surface. Previous analysis found that using three or four thermocouples was not enough to provide a sufficiently accurate estimation of the module's average cell temperature in outdoor testing [2]. When average cell temperature is not determined accurately during thermal testing, the estimated temperature coefficients can vary substantially and cause significant differences in predictions of energy production.

Previous work [2] with a 72 Cell module attempted unsuccessfully to determine suitable locations for 3 or 4 thermocouples to improve the accuracy of average cell temperature (Table I). In practice, the number of sensors to be attached to a module should be minimized to reduce the work required to instrument the module and the demands on data acquisition systems. Here we describe an effort to efficiently and accurately measure average cell temperature on a 60 cell module by using at most 10 linear averaging RTDs.

TABLE I
TEMPERATURE COEFFICIENTS FOR 72 CELL MODULE

	αIsc (1/°C)	αImp (1/°C)	βVoc (V/°C)	βVmp (V/°C)
Indoor	3.36E-04	-2.49E-04	-0.1358	-0.1441
All TCs	3.56E-04	-1.87E-04	-0.1335	-0.1421
IEC 61853	3.77E-04	-1.97E-04	-0.1413	-0.1505
4 TCs	3.34E-04	-1.76E-04	-0.1253	-0.1335
3 TC Alt.	3.47E-04	-1.83E-04	-0.1302	-0.1386

II. Measurements

A. Thermal Testing

Thermal tests were conducted by instrumenting the module with both thermocouples and linear RTDs and placing the module on a two axis tracker at Sandia National Laboratories (Figure 1). The module was shaded and allowed to reach near ambient temperatures. Insulation was placed on the backside of the module in accordance with current practice to allow the module to rise to a higher maximum temperature when exposed to the sun and to reduce variability in the temperature measurements. The shade was then removed, the tracker was maintained normal to the sun, and IV curves were recorded as frequently as possible while the module heated to operating temperature.

Fig. 1. 60 cell module mounted on tracker with data loggers

B. Instrumentation

A total of 60 thermocouples and 10 linear platinum wirewound RTDs were attached to the back surface of a 60 cell module. The 60 thermocouples were placed on the back sheet of the module near the center of each cell and the RTDs placed as close to cell center as possible (Figure 2). The RTDs, manufactured by Translogic Inc, are 3 feet in length and measure the average temperature along the length of the sensor.

The RTD's wirewound platinum resistor runs the length of the sensor and is encased in a Kapton polyimide film. The RTDs were attached to the module using Kapton polyimide tape which allows the sensor to remain flexible and follow the uneven contours of the module. The sensors were monitored using two Campbell Scientific solid state multiplexers and three Campbell Scientific data loggers. The three time-synchronized data loggers recorded data samples every 3 seconds. Each thermocouple measurement channel was calibrated using an Omega CL24 high precision calibrator.

The linear RTDs were referenced to the manufacturer supplied resistance measurements at 0°C for each of the individual sensors. The RTDs were manufactured to a target 500 ohm resistance at 0°C and were found to vary by less than 3 ohms at the reference temperature. The variation in resistance was compensated for in the data logger. Before being installed on the module the RTDs calibration was verified against three calibrated thermocouple channels in a thermal test chamber at 50 °C.

Fig. 2. Module backside with instrumentation

III. ANALYSIS

We compared each RTD with the six thermocouples at the corresponding cells. Figure 3 shows the measured temperatures for a single RTD and the six corresponding thermocouples in column 6.

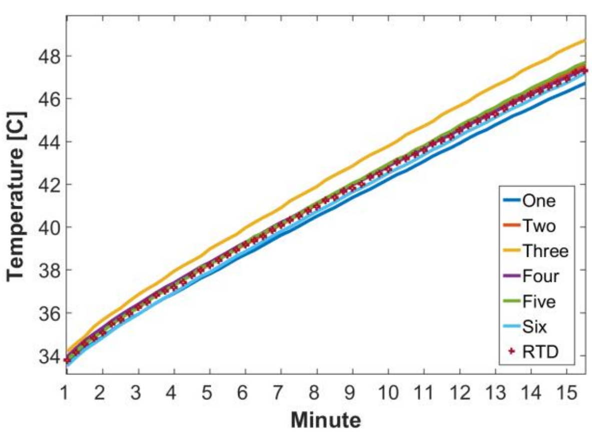

Fig. 3. Single RTD and six corresponding thermocouple temperatures

The RTD consistently records the average of the six thermocouples during a 15-minute period when the relative temperatures of the individual thermocouples may vary substantially (Figure 4).

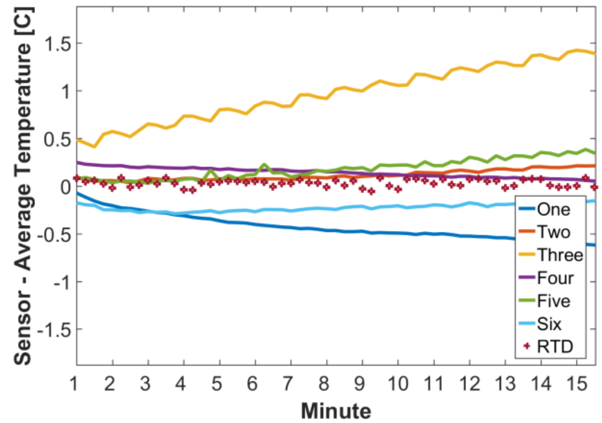

Fig. 4. Difference in sensor measurement and the average column temperature for column 6

We next compared the average temperatures determined from thermocouples at the IEC 61853 locations [1], locations typically used by Sandia National Laboratories (SNL), all 60 thermocouples and the RTDs (Figure 5). In comparison to the average over all 60 thermocouples, we found that the IEC 61853 configuration consistently underestimated the average cell temperature and the SNL configuration overestimated the average temperature. This under or overestimation alters the slope of the line used to fit the voltage vs. temperature data and thus results in biased temperature coefficients.

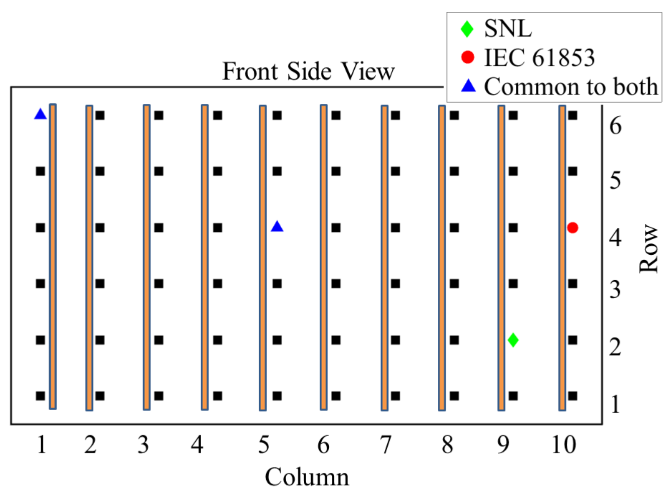

Fig. 5. Thermocouple and RTD locations for IEC 61853 and SNL testing procedures

Thermal gradient maps were created from the 60 thermocouple data to view the temperature distribution across the module at each minute of the test. The temperature maps showed an uneven distribution of temperatures over the first 15 minutes of the test (Figure 6). To distinguish the variation in cell temperatures, the plot's temperature color bar begins at the minimum temperature of the time sample and increases ten degrees. This variation in cell temperatures illustrates the difficulty in selecting a few locations where measurements will reliably yield the average cell temperature.

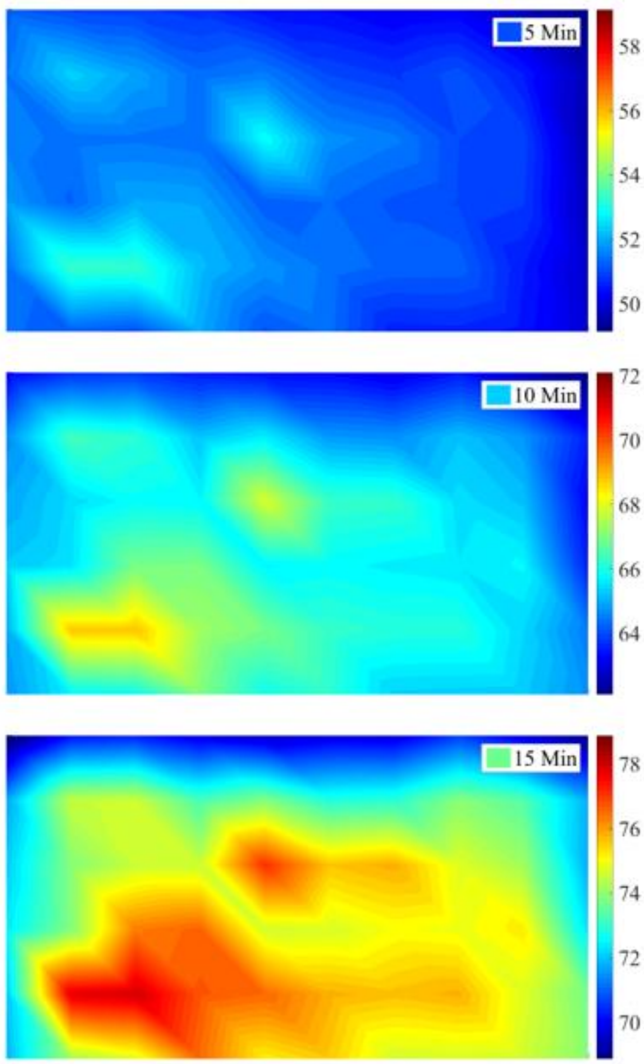

Fig. 6. Thermal maps over 15-minute period

B. Comparison of Temperature Coefficients

We calculated module temperature coefficients using each of the four estimates of average cell temperatures. The bias observed in the average temperatures determined from the IEC 61853 locations and the modified IEC 61853 locations used by Sandia can also be seen in the temperature coefficients for βVoc and βVmp. The temperature coefficients resulting from using the 10 RTDs and the 60 thermocouples are nearly identical.

TABLE II
TEMPERATURE COEFFICIENTS FOR 60 CELL MODULE

	αIsc (A/°C)	αImp (A/°C)	βVoc (V/°C)	βVmp (V/°C)
All TCs	.0037	-.0025	-0.1178	-0.1253
All RTDs	.0037	-.0025	-0.1177	-0.1252
IEC 61853	.0038	-.0025	-0.1184	-0.1260
SNL Testing Procedure	.0037	-.0025	-0.1164	-0.1238

IV. CONCLUSION

Although the temperature coefficients determined for this 60-cell module were not greatly different, previous testing has shown that a significant bias may occur when using only a few thermocouples to measure the average module temperature [2]. The linear averaging RTDs provide accurate results when compared to the 60 thermocouples and require using only 10 sensors. The accuracy and linearity of the RTDs for measuring temperatures, combined with their ease of installation and reusability, make the linear RTDs a good alternative to the traditional thermocouples used for measuring module temperatures. It is possible that accurate temperature coefficients could be determined using a smaller number of linear RTDs.

ACKNOWLEDGEMENT

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