NREL Advances in Technology at the National Renewable Energy Laboratory

Technology Brief

Simple Analytic Tool for Photovoltaic Module Diagnostics

Nondestructive Technique Measures Shunt Resistance of Individual Cells in PV Modules

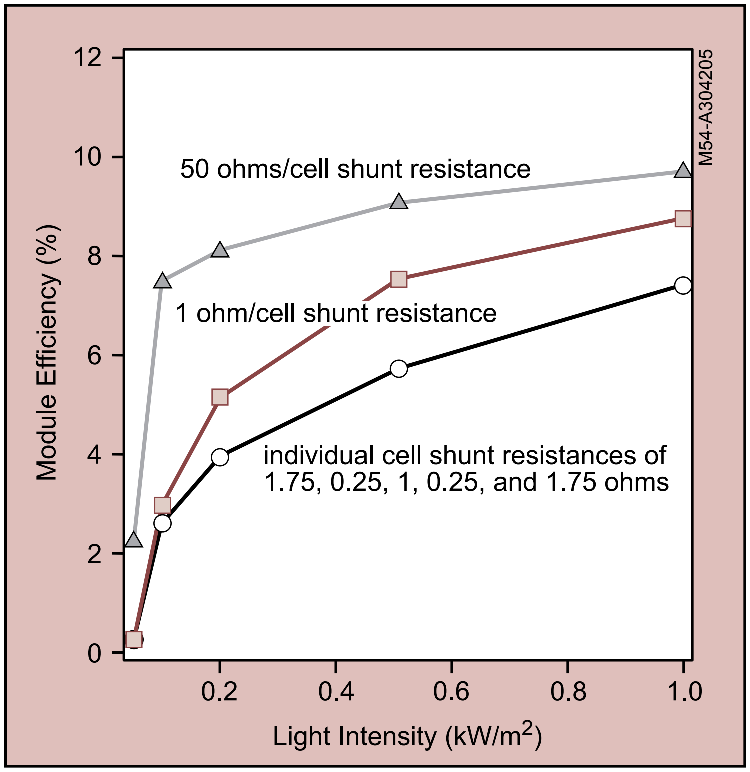
It's simple, it's free, and it quickly gives you accurate quantitative data for one of the more important characteristics of individual cells in a photovoltaic (PV) module. Too often overlooked, shunt resistance is one of the most basic and informative parameters of PV performance. Low shunt resistance of individual cells should be one of the first signs to look for in identifying electrical performance problems with PV modules. Until now, however, once a module was encapsulated, it was no longer practical to measure those resistances. Researchers at the National Renewable Energy Laboratory (NREL) recently developed a method that allows easy and accurate measurement of the shunt resistance, from fractions of an ohm to thousands of ohms, of each cell of a completed series-connected encapsulated module—without damaging the module. The technique is quick and simple, and it requires only standard, inexpensive electronic equipment.

Powerful Diagnostic

Electrical shunts are low-resistance leakage paths that divert current away from the intended power load in PV systems. For PV modules with otherwise effective materials and design, shunt losses are a primary symptom of problems that can cause cell failure or poor performance. Cells with very low shunt resistance are effectively dead. Cells with marginal shunt resistance may function adequately at high light levels, but not at low levels, when, under reduced light, a greater proportion of their output is lost, so that their efficiency decreases dramatically (see figure at top of next page). Also, cells with localized shunts—as possibly indicated by marginal shunt resistance—may be more likely to short out and fail when subjected to the stresses of environmental exposure and when connected together as a generating system as they are in commercial modules.

Tom McMahon, NREL

The NREL technique for individual cell shunt-resistance measurement of photovoltaic modules needs only inexpensive, readily available equipment.



This graph shows calculated maximum power conversion efficiencies for a "good" module (50 ohms/cell shunt resistance) and for "marginal" ones. Low shunt resistance substantially reduces performance, especially when the light intensity is less than a full sun (approximately 1 kW/m^2) and when shunt resistances vary from cell to cell.

Shunt resistance is a particularly powerful diagnostic parameter. It applies to any normal light condition, not just the one under which it was measured. Because shunt resistance is quantitative, you can set threshold values for quality control and compare values from different cells or modules. You can also check the values again after stress testing or regular use or if the module later fails. Shunt-resistance values can also be used in computer models to predict the performance of modules under the varying light intensities found at particular locations.

Shunt resistance measurement can detect problems with individual cells that are not readily detectable by traditional full-module current-voltage (I–V) tests. And the NREL technique is most accurate for the low shunt-resistance values that indicate problem cells. (The per-cell-average slope of a module's current-voltage curve at short-circuit current is a good indicator of the cell shunt resistance needed for effective performance. Resistance less than that slope indicates a serious shunt; less than several times that slope will be only marginal.)

Simple and Nondestructive

Taking less than a minute per cell to measure, the NREL technique gives cell-by-cell shunt resistance for modules with any number of series-connected cells (nearly all PV modules currently produced). It does so without de-encapsulating (removing protective cover material to get at individual cells) or otherwise damaging the module. So far as we know, this is the only such nondestructive test for individual-cell shunt resistance. The technique requires an AC signal generator, a DC voltage supply, an operational amplifier, and a phase-sensitive amplifier—all common laboratory equipment. This remarkably simple technique is based on sequentially blocking the light to each cell in a module, measuring the open-circuit resistance, and subtracting the open-circuit resistance of the fully exposed module. If that difference is small, the cell has low shunt resistance that will significantly impair module performance.

Many Valuable Applications

Individual-cell shunt-resistance testing is valuable for all phases of the product life cycle of PV modules. Measuring shunt resistance can verify the adequacy and optimization of cell fabrication steps. It can be used for module performance characterization and qualification testing. During manufacture, it can be an excellent quality-control and quality-assurance tool. And it is very helpful for failure analysis.

Fabrication verification can be determined by shunt-resistance testing. Because measurements are quantitative and can be easily taken at any step in the production process, it is possible to pinpoint at which step problems are introduced. For example, visual defects do not necessarily cause performance problems. Shunt-resistance measurement would tell whether visual defects are of concern and would also identify problems that may have no visible manifestation.

Module performance testing assesses module output during exposure to see how performance will change with time and use. Shunt resistance of individual cells can be quickly measured at the beginning of the test period and again at desired intervals. It will often show problems that other module diagnostic tools do not. Modeling that includes shunt-resistance values can predict performance for the actual sunlight levels at a particular location.

Qualification testing screens modules for reliability and durability. Shunt-resistance testing can provide an electrical baseline, including immediate identification of problem cells, and can then be repeated at any stage of the full qualification test procedure.

Just Follow These Steps

To measure the shunt resistance of individual, series-connected cells in a photovoltaic module using the NREL method:

(1) Set up a circuit consisting of a low-frequency (2–10 Hz) AC voltage source (signal generator), a DC voltage source, and an operational amplifier connected to a phase-sensitive lock-in amplifier.

(2) Connect the circuit to a 1000-ohm resistor and set the AC voltage (which will be 2–5 millivolts) to get a reading of 1 millivolt on the lock-in amplifier.

(3) Replace the resistor with the module to be tested. Set the DC voltage source to match the open-circuit voltage of the module for the light conditions under which it will be tested (sunlight through a window—about 30 mW/cm^2—is fully adequate).

(4) With the module exposed to constant, uniform light, simultaneously apply both the DC and AC voltages to the terminals of the module and record the lock-in amplifier reading (this voltage reading is the inverse of the resistance; divide 1000 by this value to get the shunt resistance of the entire module—R_A in the equations at right).

(5) Sequentially darken each cell of the module by covering it with opaque tape or an appropriately shaped rubber mat and record the reading for each cell (R_B in the equations at right).

(6) The difference in resistance between the reading for each cell as it is covered and the reading with no cells covered is the shunt resistance for the covered cell (R_C in the equations at right).

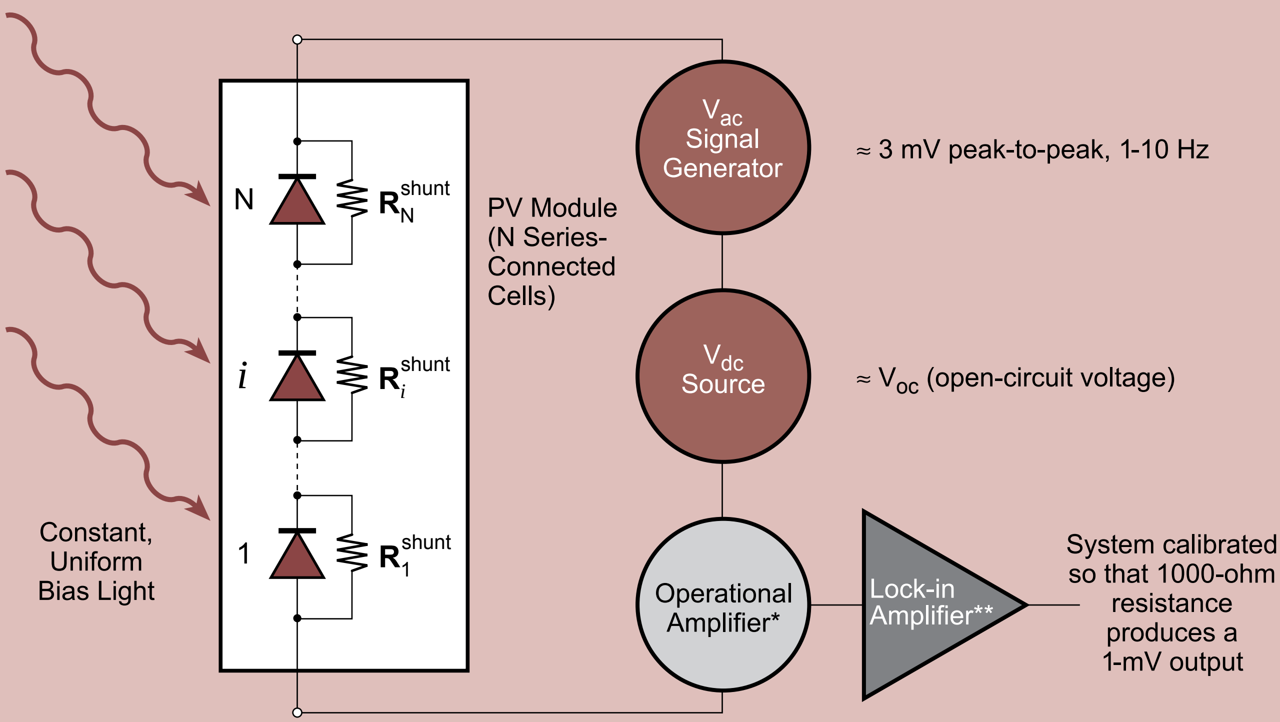
Step 4: $R_A = \sum_{1}^{n} R_i^{light}$

Step 5: $R_B = \sum_{1}^{n - ith} R_i^{light} + R_i^{dark}$

Step 6: $R_C \equiv R_B - R_A = R_i^{dark} - R_i^{light}$

If $R_B \gg R_A$, then $R_C = R_i^{dark} - R_i^{light} \approx R_i^{shunt}$

If $R_B \sim R_A$, then cell *i* is shunted;
by experience, $R_C \approx R_i^{shunt}$



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* Converts current to voltage
** Measures voltage but can be read as resistance (1000/voltage)

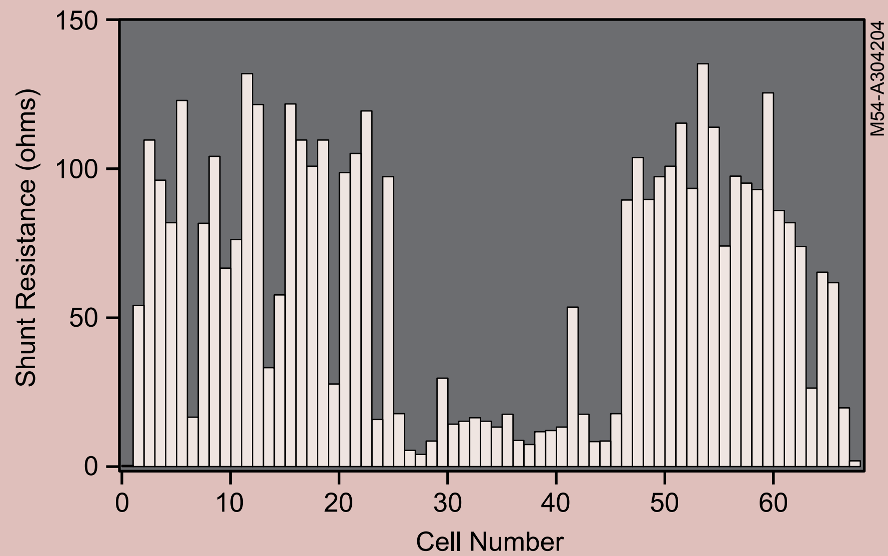
Quality assurance/quality control could benefit greatly from the NREL shunt-resistance measurement technique. The technique can be automated for a particular module design, providing rapid quantitative assessment at any desired step in the production process. Minimum acceptable shunt-resistance limits can be set, and patterns of low resistance can point out problems with the production process. For example, for thin-film modules, low-resistance cells occurring at the same spot in the module may indicate a scribing problem or a problem with the manufacturing system.

Failure analysis determines what went wrong with modules that have failed. Shunt resistance is an exact value that enables direct quantitative comparison of cells to other problem and nonproblem cells. Shunt-resistance testing identifies the individual cells that have electrical problems. Researchers can then examine those cells using microscopic or chemical analysis or other diagnostic tools to look for possible root causes.

Thus, in all phases of the PV-module product life cycle, the NREL shunt-resistance measurement technique quickly locates individual cells that are poor contributors to the electrical performance of the module, providing a focus for further investigation and corrective action.

Technique Yours to Use

Individual-cell shunt-resistance testing is a simple diagnostic tool, applicable to all phases of photovoltaic device design, development, and manufacture. It measures one of the more informative parameters of PV cell and module performance. The NREL shunt-resistance measurement technique allows quick and easy testing of series-connected cells for any size module without damaging the module. It is particularly valuable for assessing thin-film PV modules, many of which—even before encapsulation—do not allow access to individual cells without causing damage. Increased consideration of shunt resistance could greatly enhance analysis for many facets of the PV product life cycle. NREL is pleased to offer you this straightforward technique for shunt-resistance measurement. If you have any questions about the technique, please contact us.



The NREL technique provides quantitative individual-cell shunt-resistance data such as this histogram of a 68-cell PV module. The center cells of this module all had visual defects, but only cells 27 and 28 had marginal shunt-resistance that could reduce efficiency. Cells 1 and 68 have serious shunts that will hurt performance.

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