

Keysight Technologies

Testing Terrestrial Solar-Powered Inverters Using Solar Array Simulation Techniques

Application Note



Introduction

Overview

Terrestrial solar inverter designers and manufacturers must ensure their products are capable of extracting and delivering the maximum power that is available from the solar modules to which they are attached. Power available from a solar module is highly dependent on its illumination and temperature. The maximum available power is known as the maximum power point (MPP), and it changes with operating conditions. For inverter design, development and qualification, it is critical to test with an array of MPPs. To obtain a full range of MPPs and other operating points from a solar module with which to test your inverter, it must be exposed to a predictable, repeatable and broad range of illumination and temperature conditions for extended periods. That is impractical to do in a test environment with a solar module. The Keysight Technologies, Inc. E4360 solar array simulator will simulate controllable, consistent, stable, and wide-ranging solar module performance.

Problem

Controllable, consistent, stable, and wide-ranging solar module performance cannot be easily achieved, and in some cases is nearly impossible to obtain, with a solar module when you need to be able to:

- Develop and verify performance of inverter peak power tracking circuits and algorithms
- Measure and verify inverter efficiency
- Verify the ability of the inverter to produce power grid level output at high and low input voltage extremes.
- Perform qualification tests – confirm inverter performance during or after exposure to environmental conditions
- Perform accelerated lifecycle tests that introduce the effects of years of operation in just weeks
- Perform certification tests



Solution

With the Keysight E4360 modular solar array simulator you can controllably and consistently reproduce stable and wide-ranging I-V curves with which to test your inverter. With the E4360 you have the flexibility of choosing from three curve generation methods:

- SAS mode
- Table mode
- A built-in offset feature

All three methods are described in this Application Note. You can select from two levels of curve resolution and operation with a list feature that can reduce and even eliminate the need to program.



SAS mode

When you provide the E4360A with a module's open circuit voltage (V_{oc}), short circuit current (I_{sc}), and its voltage and current (V_{mp} , I_{mp}) at the maximum power point, the simulator's internal firmware algorithm uses the equations of an exponential solar cell model shown in Figure 1 to establish an I-V curve with either 4096 or 256 current and voltage data pairs.

Figure 1. Equations for the generation of I-V curves

The exponential model is described in the paper: Britton, Lunscher, and Tanju, "A 9-KW High-Performance Solar Array Simulator," Proceedings of the European Space Power Conference, August 1993 (ESA WPP-054, August 1993)

$$V = \frac{V_{oc} * \ln \left[2 - \left(\frac{I}{I_{sc}} \right)^N \right]}{\ln(2)} - R_s * (I - I_{sc})$$

$$1 + \frac{R_s * I_{sc}}{V_{oc}}$$

$$R_s = \frac{V_{oc} - V_{mp}}{I_{mp}} \quad N = \frac{\ln(2 - 2^a)}{\ln \left(\frac{I_{mp}}{I_{sc}} \right)}$$

$$a = \frac{V_{mp} * \left(1 + \frac{R_s * I_{sc}}{V_{oc}} \right) + R_s * (I_{mp} - I_{sc})}{V_{oc}}$$

Table mode

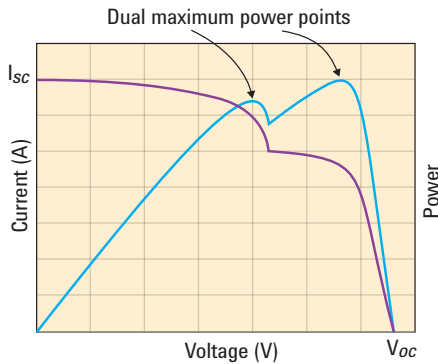


Figure 2. Complex I-V curves resulting from solar modules connected in parallel

You can provide the E4360 with up to 4000 current and voltage data pairs to precisely model the curve you want to simulate. This method is useful when the simulator's internal algorithm does not provide sufficient correlation with the module you must simulate or when the I-V curve is complex. Multiple solar modules connected in parallel, for example, may give rise to the possibility of curves with multiple maximum peak power points that cannot be reproduced with the internal algorithm.

The complex curves in Figure 2 represent an application-specific implementation representing modules in parallel, isolated by diodes, and with a part of one of the modules in shadow.

You can enter from 3 to 4000 current and voltage (I-V) pairs in table mode. Regardless of the number of data pairs you enter, the E4360 will generate either a 256 or 4096 pair table through linear interpolation, depending on which resolution you select. Every I-V pair must consist of a current and a voltage value. Refer to Table 1. The maximum analog current resolution is based on the full scale rating of the solar array simulator module model you choose. If you do not provide values for the open circuit voltage (V_{oc}) and the short circuit current (I_{sc}), the E4360 will interpolate with the given data to generate V_{oc} and I_{sc} .

TABLE 1. I-V table with n current and voltage pairs

Current	0	I_2	I_3	I_4	I_5	I_6	I_7	.	.	.	I_{n-1}	I_{sc}
Voltage	V_{oc}	V_2	V_3	V_4	V_5	V_6	V_7	.	.	.	I_{n-1}	0

Continued

Table mode *continued*

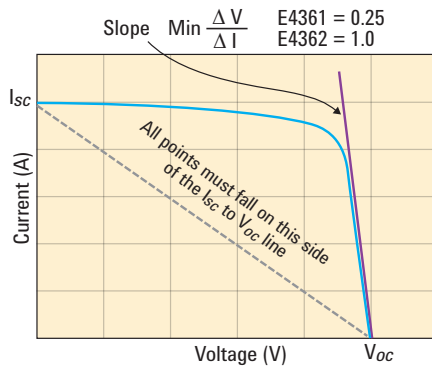


Figure 3. The graph identifies the boundary conditions that must be met when entering I-V data in table mode.

The E4360 will accept entries for maximum power point currents (I_{mp}) equal to the short circuit currents you provide. Entries for maximum power point voltages (V_{mp}) must be less than the open circuit voltages (V_{oc}) you enter. The data must be monotonic, must fall above a straight line drawn from I_{sc} to V_{oc} , and the slope (converted to and expressed as $\Delta V / \Delta I$) everywhere on the resulting curve must meet minimum requirements. See Figure 3. The E4360 checks for monotonicity along the entire curve and the slope of the curve as it terminates at V_{oc} .

Offset feature

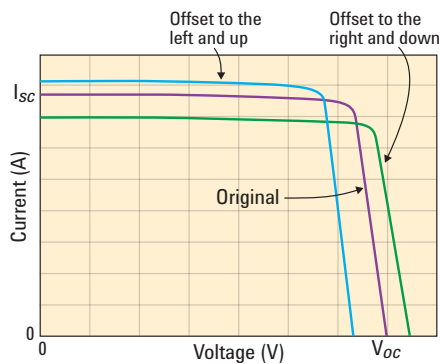


Figure 4. Illustration of shifting an original curve in horizontal and vertical directions simultaneously

An I-V curve that the E4360 generates with the entry of current and voltage pairs (Table mode) can be adjusted without modifying its basic shape. If the module you want to simulate will generate I-V curves that will retain a basic shape with changing conditions, that shape can be used as a template. Offset values are applied to each of the original I-V data pairs you entered prior to the generation of an internal table through interpolation. Programmatically adding or subtracting offsets in voltage and/or current can effectively simulate changing illumination and temperature levels without the need to enter additional curve data. Refer to Figure 4.

List feature

In addition to the three curve generation methods above, the E4360A list feature offers you the capability of queuing separate curves in each of up to 512 list steps. You can enter a separate dwell time for each step or execute a trigger to move from step to step. You can also trigger a list to begin and repeat from 1 to 256 times or run continuously.

Ensuring inverter performance

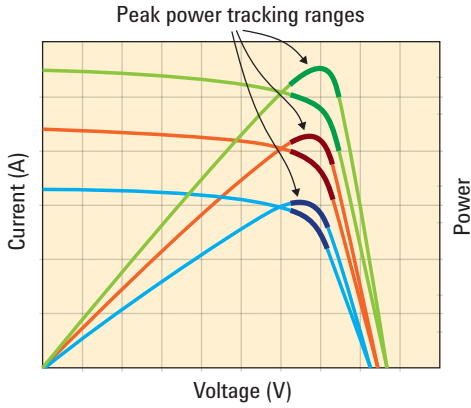


Figure 5. Peak power tracking with a range of illumination and power tracking range

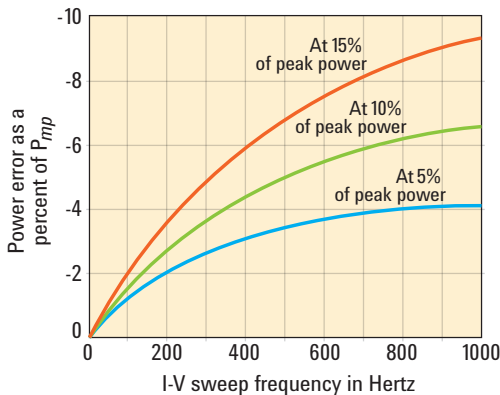


Figure 6. Percentage error as a function of the sweep frequency and the power tracking range

Using the capabilities of the E4360 outlined above, you can perform the tasks required to ensure inverter performance.

Developing and verifying performance of inverter peak power tracking circuits and algorithms

When your objective is to develop an inverter that will extract as much of the available solar module power under all environmental conditions as is possible, you will generally employ maximum peak power tracking techniques. In the design and development of your circuits you must consider the peak power tracking range, as depicted in Figure 5, and the tracking frequency. The peak power tracking range is the distance on the I-V curve on either side of the maximum peak power point that will be traversed by the action of the inverter's peak power tracking circuitry and algorithm, and the tracking frequency is the rate with which the tracking range is traversed. The tracking range must be broad enough and the tracking frequency high enough to ensure that the inverter is always capable of finding the maximum peak power point as the module I-V curve undergoes changes. To verify that your design is valid, the tests to confirm the performance of your inverter must be based on accurate, reproducible I-V curves.

It is important to understand and take into consideration the boundaries of solar array simulator performance. The ability of a solar array simulator to reproduce the programmed I-V curve as the inverter maximum peak power tracking circuitry and algorithm change the operating point is partially a function of the power tracking range and the tracking frequency. Broader power tracking ranges and higher tracking frequencies will introduce greater simulation error than narrower ranges and lower frequencies. To ensure that measurements are valid, you can establish a baseline using an electronic load such as the Keysight N3300 to find the maximum power point of the programmed I-V curve to which you can compare the power extracted by the inverter. The power error as a percent of the power at the maximum power point (P_{mp}) with tracking frequency and power tracking range is depicted in Figure 6. The power tracking range indicated on the figure is expressed as a percent of peak power and traverses both sides of P_{mp} . In this example the load on the simulator is sinusoidally swept from -5%, -10%, or -15% on one side of P_{mp} to -5%, -10%, -15% on the other side of P_{mp} .

Measure and verify inverter efficiency

In addition to extracting as much of the available module power as possible, the inverter must efficiently convert the incoming DC power to AC power. Applying a range of fixed DC voltages to the input of an inverter may provide some meaningful results, but it does not fully exercise the maximum peak power tracking (MPPT) circuitry and its interaction with the DC-to-AC conversion function. Conversion efficiency can depend on the interaction of the MPPT and DC-to-AC conversion circuitry, and it can depend on the DC operating voltage levels in the power path. The greater the frequency and range of the maximum peak power tracking function, the more likely that the application of a range of I-V curves, rather than a range of fixed DC operating points, will yield precise inverter efficiency data.

Verify the ability of the inverter to produce power grid level output at high and low input voltage extremes

If your inverter must produce power grid level output with low and high voltage and power input extremes to take advantage of available solar module power at dawn and noon, for example, you will want to ensure that the inverter will function correctly with the I-V curves produced by a module under those conditions. Using a solar array simulator allows you to change curves gradually or rapidly from one extreme to another and will help you to determine if rates of change and extreme curves have a significant influence on the operation of your inverter. Consequently, if operation with such curves or the rate of change of curves has an undesirable outcome, the simulator can aid in isolating performance issues, or conversely, operation per expectations can be verified. With the E4360 you can change curves as quickly as 30 milliseconds. Much of the time is spent in preparation for the change. The actual transition from one curve to another occurs in less than 15 microseconds.

Perform qualification tests — confirm inverter performance during or after exposure to environmental conditions

The qualification process typically involves verifying performance to specifications under an array of environmental conditions. An inverter may be exposed to shock, vibration, transportation, temperature, humidity, altitude, etc., and to an array of electrical tests. Some of the tests will be performed in an environmental chamber, and for some of the tests, the inverter will be in operation. To ensure that an inverter is fully capable of performing to specifications over the entire range of input and environmental conditions, you will typically test with a full range of I-V curves. Where necessary, you can synchronize the changing of I-V curves with the test being performed. With the E4360A solar array simulator you can tailor the I-V curves to meet the requirements of your test, and with its built in simultaneous voltage and current measurement capability and data logger, you can capture voltage and current readings throughout your test procedure. In many cases, the accuracy of watts calculable from voltage and current readings is sufficient. An electronic load such as the Keysight N3300, a power grid simulator on which the voltage and frequency can be adjusted, and the Keysight E4360 solar array simulator form the perfect addition to your environmental test equipment for inverter qualification. When you need to measure current, voltage and power with greater precision, add a Keysight DMM and a precision wattmeter.

Perform accelerated lifecycle tests that introduce the effects of years of operation in just weeks

The E4360A facilitates the performance of accelerated life testing. As you test your inverter with chamber-based environmental conditions meant to simulate 24 hours per day, 365 days per year real-world exposure, you will want to simulate changes in solar module output with changes in temperature and incoming solar radiation. You may also need to simulate many other conditions that change module output, such as partial shadow, age, accumulation of dust and dirt, wind velocity, etc. To accelerate lifecycle tests the rate of change of environmental conditions and module output must be increased dramatically to achieve results in just weeks rather than years. With the E4360 you can generate and synchronize I-V curves that correspond to changing environmental conditions to which you expose your inverter. You can trigger I-V curve changes by external events via the digital I/O ports or programmatically.

Ensuring inverter performance *continued*

Perform certification tests

Certification tests may be required to participate in various renewable energy programs sponsored by governments and private entities. For example, the California Energy Commission (CEC) maintains a list of inverters and other types of equipment that are eligible for participation in state-sponsored programs. To qualify for inclusion on the eligibility list, inverters must conform to specific requirements and pass a series of tests. Inverter requirements and test procedures as well as the basic requirements of a solar array simulator are available on the CEC Web site. The E4362 solar array simulator provides the range of output, analog performance, stability, and accuracy to ensure valid, repeatable test results.

Summary

The flexibility and range of I-V curve generation and features offered by the Keysight E4360 will help you to develop and verify the performance of your inverter design and to perform qualification, lifecycle, and certification tests. The E4360 is a stimulus and measurement instrument that will increase your productivity.

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