Solving the Challenges of Solar Array Simulation

Helping you select the optimal power solution for satellite ground testing

Application Note

Satellites are some of the world's most delicate and expensive electronic devices. Because most take a one-way trip into space, they are thoroughly tested on the ground before launch. Within the complement of electronic ground support equipment (EGSE), a typical test system contains two major elements: The instrumentation that tests the various electronic subsystems; and one or more power sources for the subsystems. The power sources must accurately simulate the behavior of solar arrays that face widely varied operating conditions in space.

During testing, it's seldom possible to use actual solar arrays to provide power. Two of the reasons for this are obvious: There is no direct sunlight in a test bay, and it isn't practical to test outside. Two additional reasons are crucial to accurate testing: repeatability and controllability. These attributes make it possible to simulate the effects of varying operating conditions—light intensity, temperature, shadow, eclipse—at multiple operating points and achieve consistent results.

The recommended solution is to simulate a solar array with electronic test equipment, but it isn't easy to accurately mimic the behavior of solar cells and solar arrays. Fortunately, purpose-built solar array simulator (SAS) instrumentation is commercially available. Compared to "homebrew" simulators, an SAS offers the advantages of standard, commercial off-the-shelf equipment:

- Predictable delivery vs. long (and unknown) development time
- Designed and tested for reliability
- Published, verifiable specifications
- Easier calibration, maintenance and repair

Module-based SAS solutions provide two additional advantages: greater scalability via configuration with one to many channels of power; and better system uptime with the ability to swap out individual power modules.

The goal of this note is to help you define the optimal power solution for satellite ground testing. We do this in four parts: a brief overview of solar cell behavior; a review of operational conditions in orbit; an outline of the need for a purpose-built SAS; and the key attributes of the optimal solution. For additional information, a list of related literature is included at the end of the note.

Modeling solar cell output

A typical satellite carries multiple solar panels or arrays, each of which contains multiple solar cells. The behavior of the individual cells affects the overall performance of each panel or array.

Three key factors affect solar array output. One is the operating scenario, which includes irradiation level, temperature, spin, eclipse and shadow; these are covered in the next section. Another factor is the loading conditions, which dictate the current and voltage point on the array's I-V curve.

The third factor spans the inherent characteristics of photovoltaic cells. When a cell is illuminated it behaves like a current source in terms of its I-V curve and equivalent circuit (Figure 1). When in shadow, its I-V curve and equivalent circuit are more like those of a diode (Figure 2). By observation, it is clear that the shunt resistance (R_{sh}) and series resistance (R_s) will have a significant effect on the maximum available output power.

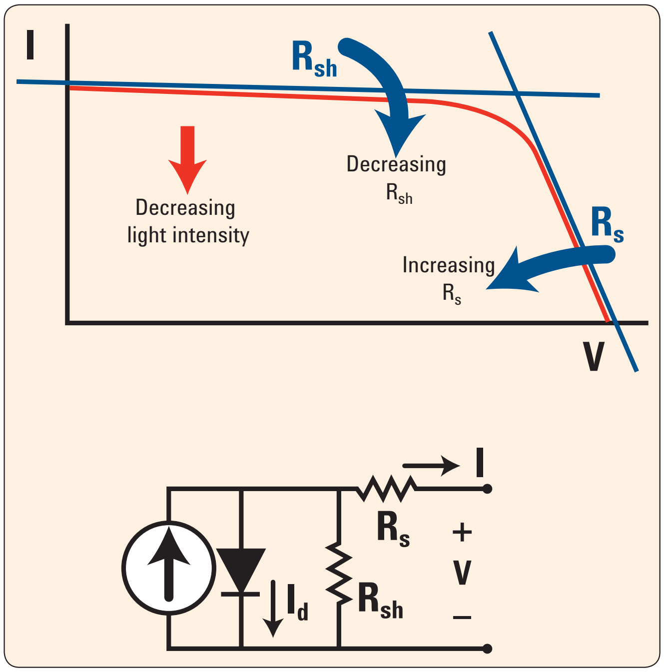

Figure 1. I-V curve and equivalent circuit for illuminated photovoltaic cell

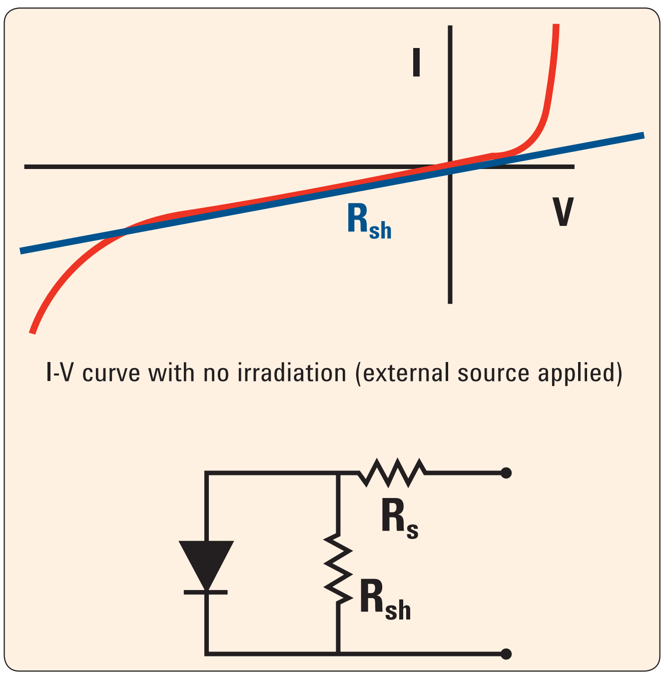

Figure 2. I-V curve and equivalent circuit for photovoltaic cell in shadow

These two distinct curves provide the variables needed to create an accurate simulation of solar cell output (Figure 3). A mathematical approximation of the curves includes four key parameters:

- V_{oc}: Open-circuit voltage (lower right)
- I_{sc}: Short-circuit current (upper left)
- V_{mp}: Voltage at the maximum-power point
- I_{mp}: Current at the maximum-power point

This isn't the only way to model cell output; however, it is the most widely accepted method in use today.

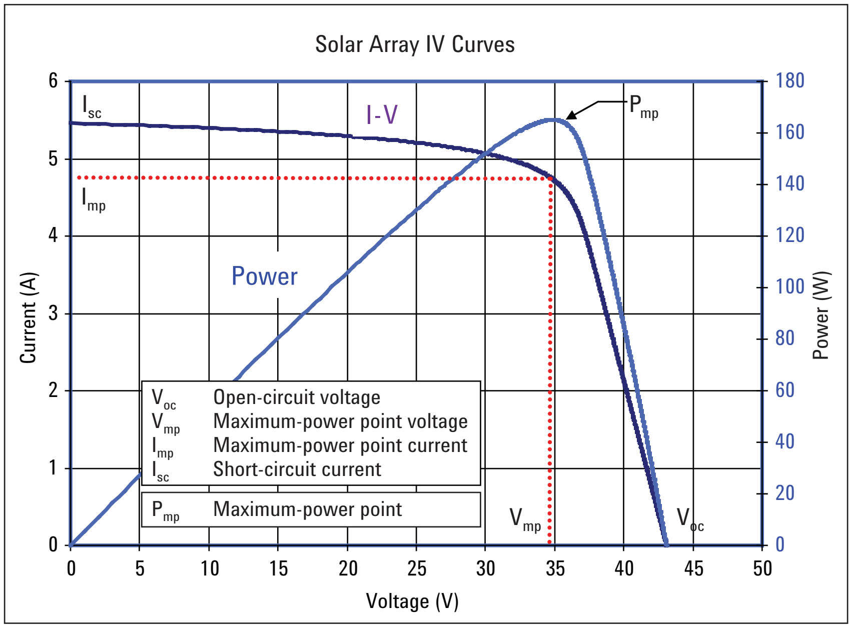

Figure 3. Four variables determine the I-V and power curves that can be used to approximate solar-cell output

Accounting for operational conditions

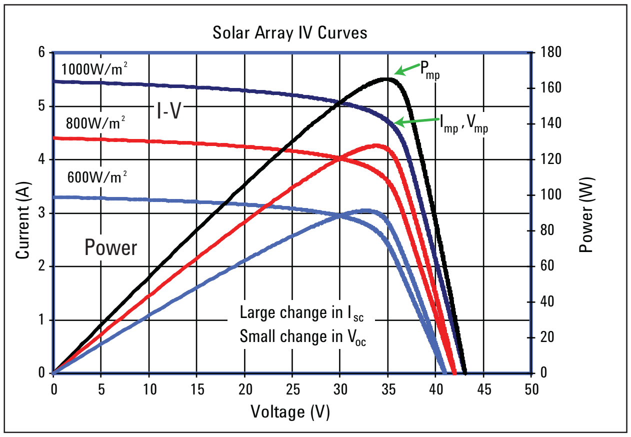

Figure 4. A solar array's I-V and power curves vary with irradiation level

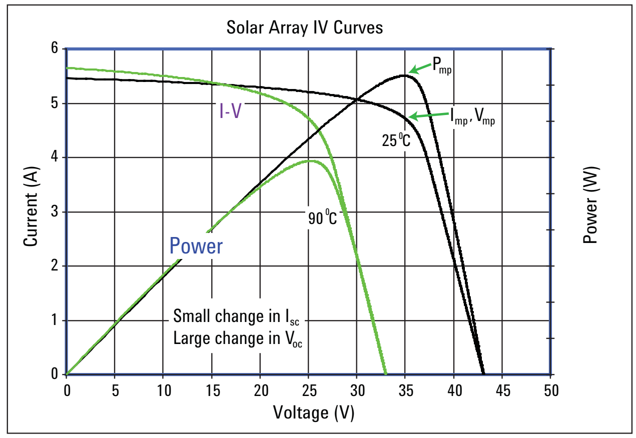

Figure 5. Temperature variation has a strong effect on output power

Achieving maximum output from a solar array can be complex given the range of effects that will diminish available power. These effects start with five factors that define the operational scenario for the solar panels on any satellite: irradiation level; temperature; and conditions in orbit, which include spin, eclipse and shadow. A closer look at each of these will help frame the rest of the discussion.

Irradiation level

Not surprisingly, the maximum power available from a solar cell or array varies with the irradiation level. As shown in Figure 4, output current varies dramatically with irradiation level. In contrast, the change in output voltage versus irradiation level is relatively small compared to the change in output current.

The family of power curves shows the decrease in available power at decreased irradiation (upper, middle and lower curves). Power diminishes to zero as either a short or open circuit is approached in the equivalent circuit model of the solar cell.

Temperature

In space, drastic temperature variations are the norm. As solar cells and arrays undergo temperature fluctuations, output power will vary significantly. Figure 5 assumes a constant irradiation level and shows the I-V and power curves at +25 °C and +90 °C as labeled on the respective traces.

Comparing Figures 4 and 5 provides an important contrast: voltage changes rapidly but current changes very little with temperature; current changes rapidly but voltage changes very little with irradiation level.

This has another important consequence: Power losses in cabling and wiring harnesses exhibit an $I^2 \times R$ relationship. As a result, changes in current caused by irradiation level may have a greater impact on overall power efficiency than will voltage variations caused by temperature changes.

Orbital conditions

Whether a satellite is orbiting a celestial body or traveling through space, the available power is affected by its spin rate as well as periods of eclipse or shadow. Each of these effects makes it more difficult to simulate the behavior of solar cells and arrays.

Spin

Figures 6 and 7 illustrate the mechanism and results of spin. In Figure 6, each rectangular panel on the surface of the satellite is a solar panel. As the satellite spins, each panel experiences changes in irradiation and temperature that depend on the rate of rotation.

Figure 7 plots the rising and falling cycles of output that occur as a set of four panels enters and exits a period of sunlight. The actual available power depends on four key factors: the number of panels and their size; the spin rate; the ongoing heating and cooling experienced by each panel; and the irradiation level, which depends on factors such as orbit plane (e.g., relative angle to the sun), distance from the sun and relative motion relative to the sun (i.e., approaching or receding).

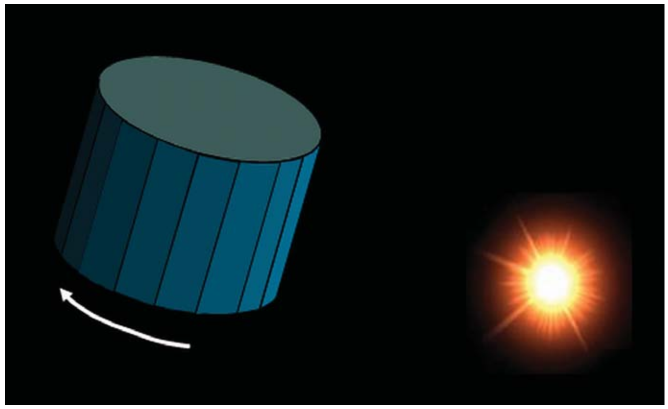

Figure 6. Changes in array segment irradiation depend on the rate of rotation

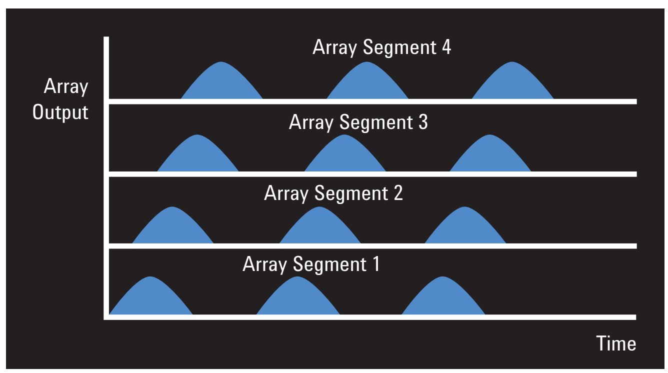

Figure 7. Available output power from each panel rises and falls as the satellite spins

Eclipse

A solar array is in eclipse whenever the Earth, Moon or other celestial body is between it and the Sun. The duration of the eclipse depends on the plane and radius of the satellite's orbit. The rate at which eclipse is entered and exited depends on the orbital velocity. Figure 8 shows the typical shape of an array's output during penumbra, umbra and full-sun conditions.

Dealing with eclipse conditions requires the use of solar arrays and batteries. The batteries provide power while the satellite is in eclipse and are recharged when the spacecraft is in sunlight. To ensure continuous power to on-board systems, the arrays, voltage regulators and charging circuits must work perfectly, and in perfect harmony.

Temperature also comes into play during eclipse. Cold arrays are more efficient than warm arrays. As a result, an array is at its maximum power-generation capacity as it emerges from full eclipse and re-enters full-sun conditions. Its efficiency declines over the course of its time in full sunlight.

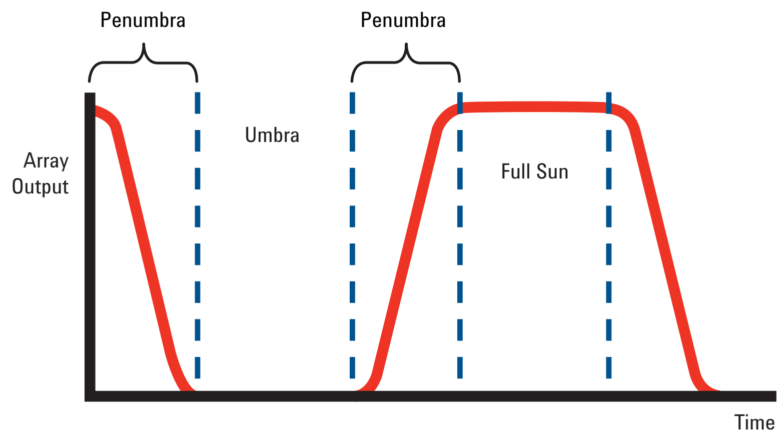

Figure 8. Available output power varies as the satellite enters, transits, and exits darkness and then re-enters full-sun condition

Shadow

A solar cell in shadow is partially obscured from sunlight, as shown in Figure 9, and any shadowed cells reduce the overall power available from an array. It is important to note that the extent of the reduction depends on the actual construction—serial or parallel connection—of the cells or segments in an array.

The equivalent circuit of a photovoltaic cell provides insight into the electrical behavior of cells in shadow. For example, any current in a shadowed cell flows through its shunt resistance. Adding a bypass diode to each cell improves the performance of the overall array when it is in shadow.

This behavior has an important implication for simulation: Series and parallel combinations of multiple cells in shadow can create interesting I-V curves that are challenging to simulate (Figure 11).

Implications for simulation

As noted at the beginning of this section, all of the preceding factors play a role in limiting the maximum output power available from a solar array. This translates into the key challenge for simulation: realistically and reliably reproducing these effects and thereby ensuring meaningful test results.

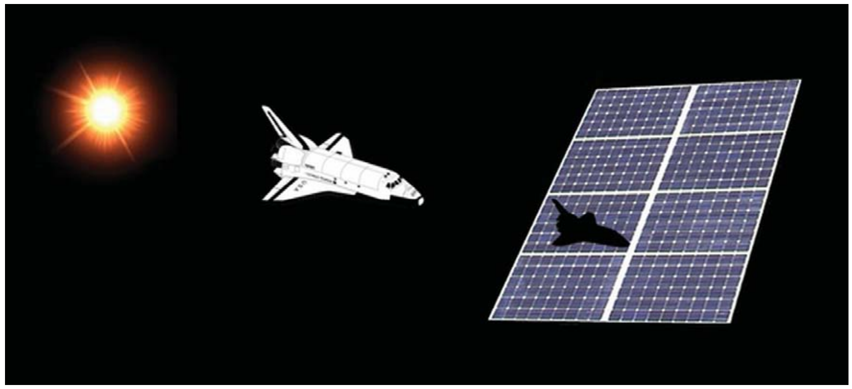

Figure 9. Cells in shadow produce no current, limiting total power available from an array

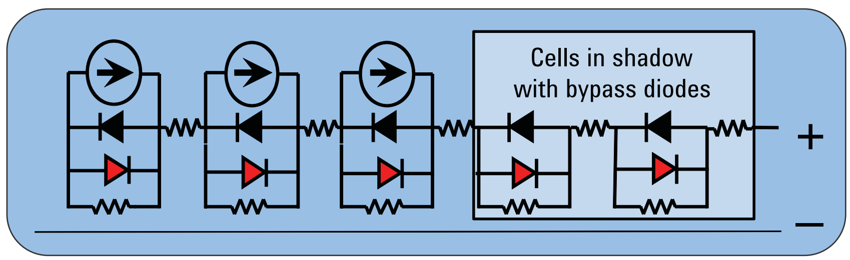

Figure 10. Adding bypass diodes to the cell design will improve performance when the array is in shadow

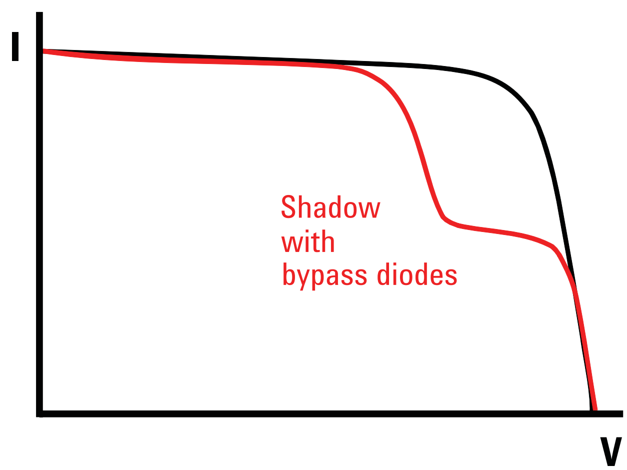

Figure 11. Some solar array simulators are capable of mimicking solar arrays in shadow

Reviewing bus regulation topologies

The range of solar array effects described above is central to the definition of an SAS system. It is also important to consider the type of bus regulation that is used within the satellite.

A typical satellite will use one of four bus-regulation topologies: direct connection, series switching, sequential shunt switching and maximum peak power tracking (MPPT). Today, sequential shunt switching and MPPT dominate.

Shunt switching

In sequential shunt switching the control process is relatively simple: It either directs current from each solar array segment to the load when needed or shorts the output of a segment when not needed.

The number of active shunt switches can vary from none to all—and this can have a significant effect on cooling in the SAS. The output stage of an SAS instrument uses a linear regulator to achieve the required performance. When a shunt switch is on, all of the power that would have been delivered to the bus is dissipated in the simulator. Thus, effective cooling is essential whenever all of the shunt switches are simultaneously shorted.

Shunt switching presents another challenge when creating a realistic simulation. Unlike voltage pulse width modulation (PWM), which regulates by averaging the modulation pulse with an LC filter, shunt switching modulates current to achieve regulation. Consequently, the SAS must be able to handle rapid current transients.

MPPT

As the name suggests, the MPPT technique continuously and dynamically seeks an array's maximum power point. This is a complex technique that uses two control loops to regulate power: a slow MPPT loop and a fast voltage loop within one or more DC-to-DC converters. It also increases overall efficiency by reducing the amount of power lost through heat dissipation (an effect commonly seen in sequential shunt switching).

In an MPPT system, a key parameter is the ability of the SAS to maintain operation along the programmed I-V curve while the tracking circuitry searches for the maximum power point. The SAS must also enable verification of power efficiency and MPPT accuracy.

Asking a logical question

On the surface it seems logical to ask, "Why can't I use a programmable power supply as an SAS?" There are at least three key reasons: output capacitance, solar output flexibility and protection for the device under test (DUT).

Output capacitance

General-purpose power supplies are voltage sources designed to deliver a stable voltage level under varying load conditions. This is fine for a variety of general applications but is less than ideal for solar array simulation. That's because solar panels are current sources, and that's why the best solar array simulators are designed to operate like a current source.

In most cases, a current source has relatively high output impedance and relatively low output capacitance. This has two benefits: faster switching speed for better simulations and shorter test times; and better DUT protection. Low output capacitance enhances DUT protection by reducing the stored power in the circuit. The lower the stored power, the lower the transient short-circuit current spikes that will be dissipated through the DUT (see below for more about DUT protection).

Solar output flexibility

Conventional power supplies adjust voltage and current along a rectangular-shaped "curve." In contrast, solar array panels have exponential-shaped I-V curves. As a result, solar array simulators must be capable of producing similarly shaped I-V curves. An SAS must also be capable of making rapid curve changes to create realistic simulations of changing irradiation levels and temperatures or the effects of spin, eclipse and shadow.

DUT protection

Because satellites are delicate devices, the power supplies used in ground testing must provide a greater level of protection than is typically available in conventional supplies. For example, over-voltage protection (OVP) and over-current protection (OCP) are built into a conventional power supply. These basic capabilities are certainly useful in satellite testing but they are not sufficient to limit transient current spikes or protect internal components against power dissipation.

Returning to the question

Summing up, a typical power supply can't match the capabilities of a purpose-built SAS, which provides lower output capacitance, greater solar output flexibility and better protection for the DUT. These capabilities translate into better simulations, shorter testing times, and greater peace of mind about the survival of the satellite during testing.

Defining the optimal solution

Agilent is the leading manufacturer of solar array simulators and our SAS solutions are in their fourth generation. The first generation was created by adding simple software to a standard DC supply. Applying the lessons learned from that experience, the succeeding generations were the purpose-built E4350A family, the E4350B family and today's E4360A family.

Along the way, we have incorporated five key ideas that address important considerations in the definition and selection of an SAS: output ratings and performance specifications; protection features; physical size and power density; uptime; and system-level considerations.

Output ratings and performance specifications

This is all about current, voltage, power and shunt-switching speed. The wider the variety of choices, the easier it is to select the best combination of power levels, shunt speeds and so on to meet the needs of a specific satellite design.

Protection features

As noted earlier, an SAS should include more than the OVP and OCP capabilities built into conventional power supplies. For example, Agilent's SAS solutions provide the following layers of extra protection:

- Programmable soft limits for OVP and OCP. This helps protect against operator error when typing in values.
- Gross current limiting to cut transient current spikes.
- Over-switching protection, which protects internal components against power dissipation if the switching frequency threshold is crossed.
- A programmable remote-inhibit function that validates user-defined shutdown procedures.

Agilent's fourth-generation SAS

The Agilent E4360A modular solar array simulators accurately simulate the I-V curves of different arrays under various operational conditions. The product family includes a 2U, two-slot mainframe and six DC modules. Each mainframe can provide one or two outputs of up to 600 W.

Additional attributes include an independent controller within each mainframe, open connectivity (LAN, USB and GPIB) and hardware triggering between mainframes. One key capability is "list mode," which enables creation of user-generated curves and allows rapid transitions from curve to curve to simulate, for example, the stages of an eclipse.

E4360A-based solutions are available as individual instruments or custom turnkey systems. Whichever approach you prefer, an Agilent SAS offers advantages in five areas:

- Power density
- Flexibility
- Reliability
- Repeatability
- Off-the-shelf availability

For more information, please visit **www.agilent.com/find/E4360**.

Size and power density

In many cases, it is important to minimize the physical footprint of the test system while maximizing the per-instrument power density. An SAS with a compact form factor and a modular architecture makes it possible to fit more power—and more simulation channels—into less space. This is especially important when space is at a premium within a system rack and inside a high bay facility (Figure 12).

Uptime

Statistical quantities such as mean time between failures (MTBF) are a baseline for reliability. Attributes such as modularity and scalability do more than enhance flexibility and reusability: they also improve system uptime. As an example, modularity makes it possible to swap out a single power module when maintenance, calibration or repair is necessary. Scalability makes it easy to expand, reconfigure or repurpose a system or console when needed.

Figure 12. The rack on the left uses 12 Agilent E4360A SAS units to deliver 24 channels of simulation

System-level considerations

An SAS is typically part of a larger rack-based system. In that context, factors such as configurability and serviceability become important considerations.

A good starting point is ease of configuration for initial use. In a single-purpose system, modularity enables future reuse in new systems. For multi-purpose systems, dynamic reconfiguration helps ensure faster changeover. In either case, reconfiguration is simplified by interconnect features such as barrier-block termination coupled with relays.

To minimize downtime, instrument or system service should require minutes rather than hours or days. A modular SAS should make it easy to remove and replace individual power modules. The barrier-block/relay interconnect scheme mentioned above simplifies self-test procedures by supporting rapid disconnection and reconnection.

Summary and Conclusion

The inherent challenges of accurately simulating the effects of operational conditions—irradiation level, temperature, spin, eclipse and shadow—preclude the use of conventional power supplies. Related factors include output capacitance, output flexibility and DUT protection. The latter point is especially important in satellite testing. A dedicated SAS goes beyond OVP and OCP to provide additional layers of protection such as programmable soft limits (for OVP and OCP), gross current limiting, over-switching protection and programmable remote-inhibit functionality.

A modular, scalable and purpose-built SAS such as the Agilent E4360A family makes it possible to accurately—and efficiently—simulate the complex behavior of one or more photovoltaic cells and solar arrays. The E4360A interface is based on four parameters that enable efficient generation of the required I-V curve: open-circuit voltage, short-circuit current, voltage at the maximum power point and current at the maximum power point (V_{oc}, I_{sc}, V_{mp}, and I_{mp} respectively). The instrument's "list mode" enables creation of user-generated curves and allows rapid transitions from curve to curve to simulate, for example, the stages of eclipse.

Related literature

- *Sequential Shunt Regulation*, Application Note, Literature Number 5989-9791EN
- *Generating I-V Curves with the Agilent E4360A Solar Array Simulator Using the Parameters V_{oc}, I_{sc}, N and R_s*, Application Note, Literature Number 5990-3665EN
- *Conversion from R_s and N to V_{mp} and I_{mp}*, Spread Sheet, available from **www.agilent.com/find/E4360conversion**
- *Side-by-Side Comparison of Agilent E435xB and E436xA Solar Array Simulators*, Application Note, Literature Number 5989-9884EN
- *Agilent E4360 Modular Solar Array Simulators*, Data Sheet, Literature Number 5989-8485EN
- *SAS system capability overview*: **www.home.agilent.com/upload/cmc_upload/All/SASSystemCapabilities.pdf**

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