



# Photovoltaic System Commissioning and Testing

## A Guide for PV System Technicians and Engineers





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## 1 INTRODUCTION

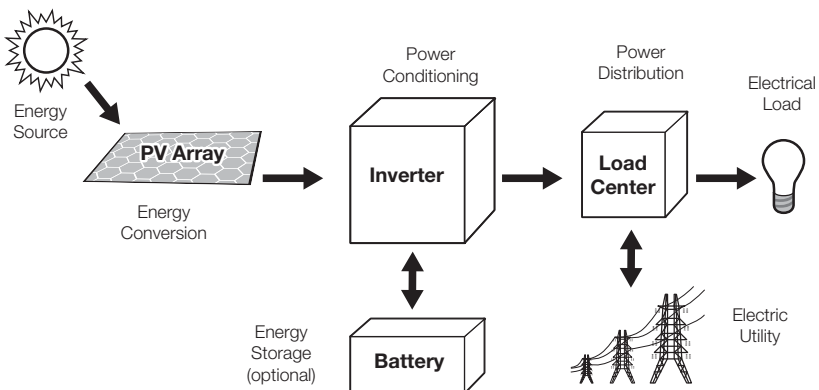
Solar photovoltaic (PV) systems are being installed in ever increasing numbers throughout the world, and are expected to safely and reliably produce electrical energy over several decades of operation. However, many systems are not satisfactorily evaluated prior to being placed into service, and many have had little, if any, scheduled maintenance or testing over their lifetime. Unfortunately, this often leads to unsafe and underperforming systems with reduced value to their owners.

Any electrical system can be tested to verify performance and to evaluate the condition of the wiring systems and equipment. This is particularly important for PV installations, which are subjected to extreme environmental conditions and deteriorating effects of the elements over many years. To help ensure the long-term safe

operation of these systems, quality PV installation and service contractors execute a thorough commissioning process followed by a regular periodic testing and maintenance program. These practices can help promote safety and optimize performance, and provide essential information required to effectively troubleshoot, diagnose and remedy problems with the system.

All PV systems require testing for performance and safety verifications. The level of testing required will depend on local regulators, the customer desires, and quality commitments of installation and maintenance contractors. This document provides an overview of the commissioning and testing process, and applies generally to interactive PV systems that are interconnected to the utility grid. It addresses the applicable codes and standards, in addition to testing equipment, procedures, and interpretation of the results. See Figure 1.

**Figure 1. PV system overview**



## 1.1 Codes and Standards

*The National Electrical Code® (NEC), NFPA 70* governs the requirements for most non-utility electrical installations in the U.S., including solar photovoltaic (PV) systems. When adopted into the building codes by states or local jurisdictions, the NEC becomes the basis for inspections and approvals of electrical installations.

Chapters 1–4 of the NEC generally apply to all electrical systems, covering installation requirements, wiring and protection, wiring methods and materials, and equipment for general use. Article 690 of the NEC covers special installation requirements for solar photovoltaic systems, however many other articles also apply. Additionally, Article 705 covers requirements for the interconnecting PV systems and other distributed generation equipment to other sources, such as the utility grid.

While the NEC does not specifically address PV system performance, it does establish requirements for the overall quality and safety of electrical installations. Many of these requirements can be verified through visual inspections and a review of the system design and installation documents. However, certain NEC requirements can only be validated by electrical tests and measurements. These

include verifying the continuity of grounding systems, verifying system voltages and currents, and measuring insulation resistance to determine wiring integrity.

Other standards also apply to the testing and commissioning of PV systems. Compliance with these additional codes or standards may be required by local authorities, or requested by buyers, lenders or underwriters to help ensure the highest levels of safety, quality and performance for PV installations.

The international standard *IEC 62446 Grid Connected PV Systems – Minimum Requirements for System Documentation, Commissioning Tests, and Inspection* defines minimum documentation, commissioning tests and inspection criteria for grid-connected PV systems. Information derived from this standard is intended to verify the safe and proper operation of PV systems, and to serve as a guide for designers, installers and service personnel. This IEC standard covers specific requirements for testing and commissioning PV systems not addressed by the NEC and other electrical installation codes, such as IEC 60364: Electrical Installations for Buildings. Section 712 of IEC 60364 addresses specific requirements for solar photovoltaic (PV) power supply systems.

Compliance with the IEC 62446 standard is required for many PV projects in Europe and similar requirements are being listed in procurement documents for new projects in the U.S. Many of the testing procedures outlined in this standard correlate directly with NEC requirements for the verification of safety for all electrical systems, which are addressed throughout this document.

**NFPA 70B Recommended Practice for Electrical Equipment Maintenance provides guidelines on test methods and the preventive maintenance of electrical systems. This standard can be used in part to help verify NEC requirements through electrical system measurements**

## 1.2 Safety

Conducting electrical testing on any PV system should be performed by qualified individuals having knowledge and experience with electrical systems measurements, the test equipment used, the equipment or systems being tested, and an awareness of the hazards involved. Working with PV systems involves exposure to energized circuits with high voltages and potentially lethal currents, presenting electrical shock hazards. Battery systems and higher voltage installations can also present electrical burn and arc flash hazards. When these electrical hazards are combined with other hazards such as working at heights and in difficult locations exposed to the elements, it is imperative for those installing and servicing PV systems to follow all applicable safety standards and guidelines.

### Qualified Person

The NEC defines a *qualified person* as “one who has skills and knowledge related to the construction and operation of the electrical equipment and installations and has received safety training to recognize and avoid the hazards involved”. However, the NEC is not very specific about the extent of safety training required relative to the level of hazards and types of work involved, presuming individuals may be qualified for certain tasks and not others. Generally, individuals installing or servicing PV installations should have appropriate experience in working with PV systems as well as electrical systems, and safety training consistent with the requirements outlined in NFPA 70E-2009, Standard for Electrical Safety in the Workplace.

The Occupational Safety and Health Administration (OSHA) issues and enforces standards in the U.S. for worker safety and health in the U.S. In particular, OSHA regulations covered in CFR 29 Part 1926 — Safety and Health Regulations for Construction address a broad scope of safety hazards likely to be encountered in constructing and maintaining PV installations. The standards can be freely downloaded from the OSHA website, see: [www.osha.gov](http://www.osha.gov)

OSHA regulations require that employers provide a safe and healthy workplace free of hazards, and follow the applicable OSHA standards. Employers must provide safety training to affected employees addressing all probable hazards on a construction site. Workers are responsible for following the employer's safety and health rules and wearing and maintaining safety gear as instructed. An OSHA 10-Hour Construction Industry Training program covers the requirements for avoiding and mitigating a number of jobsite safety hazards addressed in 29 CFR 1926, including electrical safety, personal protective equipment (PPE), fall protection systems, stairways and ladders, hand and power tools, cranes and lifts, excavations, scaffolding, and others.

Best practices for preventing electrical hazards and other common safety hazards associated with PV installations include the following:

- Carry out a risk assessment before conducting any work at the site.
- Working on electrical equipment and circuits in a de-energized state using documented lockout and tagout procedures.
- Wearing the appropriate PPE, including protective clothing, nonconductive Class E



hardhat, electrical hazard (EH) rated foot protection, and safety glasses at all times.

- Using electrically insulated hand tools and properly grounded or double-insulated power tools maintained in good condition.
- Avoiding contact with overhead power lines and buried electrical conductors.
- Using ladders with wooden or fiberglass rails when working on or near energized conductors.
- Mitigating fall hazards and using personal fall arrest systems (PFAS) whenever working at unprotected heights of 6 feet or more.
- Maintaining an orderly work site and cautious approach.

In some cases, working on energized equipment is unavoidable, for example when making measurements on PV arrays that are always energized when exposed to sunlight. Certain test equipment, such as megohmmeters and insulation testers also produce high test voltages, and appropriate safety precautions must be observed when using this equipment. Proper electrical insulating gloves and other applicable PPE should always be worn when working on or testing energized circuits. The level of PPE required depends on the voltage levels and fault currents for the circuits under test. Particular care should be exercised whenever touching a PV array or associated conductive surfaces to protect against electrical shock, especially when faults are suspected.

General safety recommendations for using electrical test equipment include:

- Follow manufacturer's instructions for the

safe operation of any test instruments.

- Only use test instruments for their intended purpose, within their established limits and ratings.
- Carefully inspect test equipment and leads prior to each use.
- Properly maintain test instruments and recommended calibrations.
- Plan and review all testing, safety and emergency procedures in advance.
- Use appropriate personal protective equipment, including electrical insulating gloves.
- Work with a partner.

## 2 PV SYSTEM FUNDAMENTALS

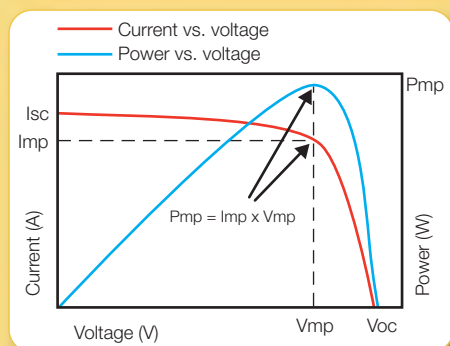
Photovoltaic systems convert solar radiation into electrical energy suitable for powering electrical loads or other utilization equipment. A fundamental understanding of PV device performance and system designs is essential for conducting meaningful tests and evaluations and interpreting the results.

### 2.1 PV Module Performance

Photovoltaic cells, modules and arrays produce dc power when exposed to sunlight. Their electrical performance is represented by their current-voltage (I-V) characteristic. An I-V curve represents an infinite number of current and voltage operating point pairs for a PV generating device, at a given solar irradiance and temperature operating condition. See Figure 2. PV modules produce voltage and current output that varies with solar irradiance and temperature. Key operating points along the I-V curve are

rated by the manufacturer at specified test conditions and affixed on product labels. These rated I-V parameters are the basis for sizing and designing the photovoltaic source and output circuits, and for comparing with field measurements on PV arrays.

**Figure 2. I-V curves represent the electrical performance for PV modules and arrays.**



■ **Open-circuit voltage ( $V_{oc}$ )** is the maximum dc voltage on a given I-V curve, and is the operating point for a PV device with no connected load.  $V_{oc}$  corresponds to an infinite resistance or open-circuit condition, and zero current and zero power output. Open-circuit voltage is independent of cell area and increases with decreasing cell temperature, and is used to determine maximum circuit voltages for PV modules and arrays. For crystalline silicon solar cells, the open-circuit voltage is typically on the order of 0.5 V to 0.6 V at 25°C. Typical PV modules have between 60 and 72 series-connected cells with  $V_{oc}$  ranging from about 34 V to 44 V.

■ **Short-circuit current ( $I_{sc}$ )** is the maximum current on an I-V curve.  $I_{sc}$  corresponds to a zero resistance and short-circuit condition, at zero voltage and zero power output. Short-circuit current is directly proportional to solar irradiance, and rated values are used to size PV circuit conductors and overcurrent devices. Because PV modules are inherently current-limited, PV modules can be short-circuited for testing using an appropriately rated shorting device. Individual solar cells may produce  $I_{sc}$  be up to and over in area, with  $I_{sc}$  ratings 8 A and higher.

■ **The maximum power point ( $P_{mp}$ )** of a PV device is the operating point where the product of current and voltage is at its maximum. The maximum power point is located on the “knee” of the I-V curve, and represents the highest efficiency operating point for a PV device under the given conditions of solar irradiance and cell temperature. Typical PV modules have rated maximum power of 200 W to 300 W.

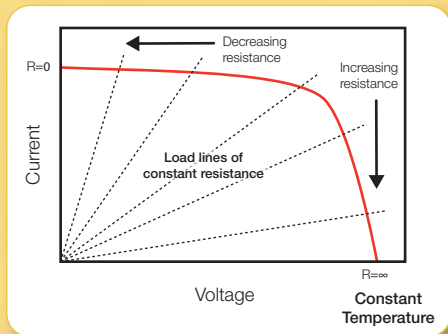
■ **The maximum power voltage ( $V_{mp}$ )** is the corresponding operating voltage at  $P_{mp}$ , and is typically about 70% to 80% of the open-circuit voltage.

■ **The maximum power current ( $I_{mp}$ )** is the operating current at  $P_{mp}$ , and typically about 90% of the short-circuit current.

The specific operating point on an I-V curve is determined by the electrical load according to Ohm’s Law. Consequently, the load resistance to operate a PV module or array at its maximum power point is equal to the maximum power voltage divided by the maximum power current ( $V_{mp}/I_{mp}$ ). For example, consider a PV module

with maximum power voltage ( $V_{mp}$ ) = 35.8 V, and maximum power current ( $I_{mp}$ ) = 4.89 A. The load resistance required to operate this module at maximum power is equal to  $V_{mp} \div I_{mp} = 35.8 \text{ V} \div 4.89 \text{ A} = 7.32 \, \Omega$ . The maximum rated dc power is simply the product of the maximum power current and voltage. See Figure 3.

**Figure 3. The operating point on an I-V curve is determined by the electrical load resistance according to Ohm's Law.**



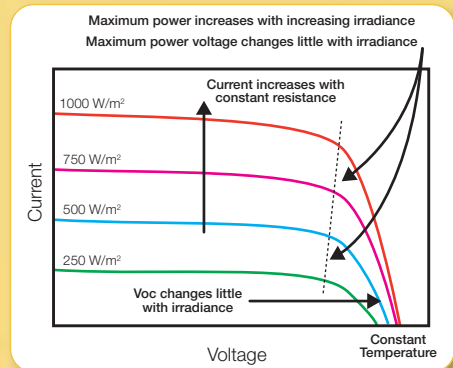
In application, the operating point on the I-V curve is determined by the specific equipment connected to the output of the PV array. If the load is a battery, the battery voltage sets the operating point on the I-V curve. If the PV array is connected to an interactive inverter, the inverter seeks to operate the PV at its maximum power point as long as the array voltage operates within the inverter limits. Maximum power point tracking (MPPT) refers to the process or electronic equipment used to operate PV modules or arrays at their maximum power point under varying I-V curve conditions. MPPT circuits are integral to interactive inverters, some charge controllers and also available as separate equipment or part of

PV array source circuit combiner boxes. Measurements of PV array operating points and maximum power point tracking can be verified during system testing.

### 2.1.1 Response to Irradiance

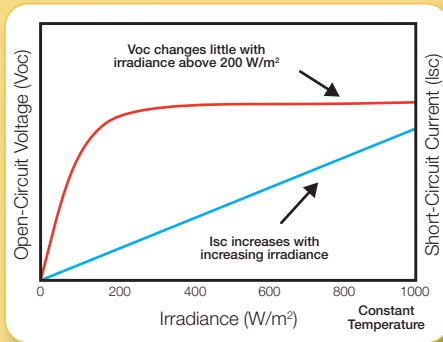
Changes in solar radiation have a linear and proportional effect on the current and maximum power output of a PV module or array. See Figure 4.

**Figure 4. Changes in solar radiation have a direct linear and proportional effect on the current and maximum power output of a PV module or array.**



Therefore, doubling the solar irradiance on the surface of the array doubles the current and maximum power output (assuming constant temperature). Changing irradiance has a smaller effect on voltage, mainly at lower irradiance levels. Because voltage varies little with changing irradiance levels over 200 W/m², PV devices are well-suited for battery charging applications. See Figure 5.

**Figure 5. PV module current and voltage are affected differently by solar irradiance.**



The short-circuit current (Isc), maximum power current (Imp), and maximum power (Pmp) at one condition of solar irradiance may be translated to estimate the value of these parameters at another irradiance level:

$$Isc2 = Isc1 \times (E2/E1)$$

$$Pmp2 = Pmp1 \times (E2/E1)$$

$$Imp2 = Imp1 \times (E2/E1)$$

where

Isc1 = rated short-circuit current at irradiance E1 (A)

Isc2 = short-circuit current at new irradiance E2 (A)

E1 = rated solar irradiance (W/m²)

E2 = new solar irradiance (W/m²).

Pmp1 = rated maximum power at irradiance E1 (W)

Pmp2 = new maximum power at new irradiance E2 (W).

Imp1 = original maximum power current at irradiance E1 (A)

Imp2 = new maximum power current at new irradiance E2 (A).

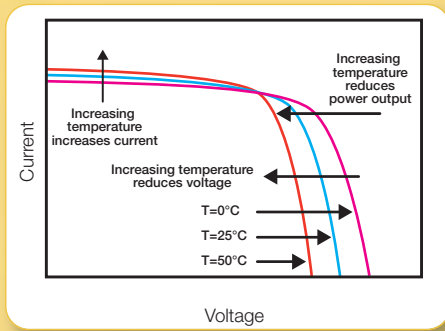
Installers and commissioning specialists verify the performance of PV systems in the field by measuring the solar irradiance incident on PV arrays, and correlating the measured power output with specifications. For example, if it has been established that the rated peak output of a PV array is 10 kW under incident radiation levels of 1000 W/m² at normal operating temperatures, then the output of the array should be expected to be around 7 kW if the solar irradiance is 700 W/m², assuming constant temperature.

### 2.1.2 Response to Temperature

The current and voltage output of a PV module are temperature dependent. For crystalline silicon PV devices, increasing cell temperature results in a measureable decrease in voltage and power, and a slight increase in current. Higher cell operating temperatures also reduce cell efficiency and lifetime. The temperature effects on PV module current are an order of magnitude less than on voltage and power, and neglected as far as any installation or safety issues are concerned.

Temperature coefficients relate the effects of changing PV cell temperature on its voltage, current and power output. For crystalline silicon PV devices, the temperature coefficient for voltage is approximately  $-0.4\%/^{\circ}\text{C}$ , the temperature coefficient for short-circuit current is approximately  $+0.04\%/^{\circ}\text{C}$ , and the temperature coefficient for maximum power is approximately  $-0.45\%/^{\circ}\text{C}$ . Note that the power and voltage temperature coefficients are negative, as these parameters decrease with increasing temperature. See Figure 6.

**Figure 6. For crystalline silicon PV devices, increasing cell temperature results in a decrease in voltage and power, and a small increase in current.**



Since PV modules produce their highest voltage at the lowest temperatures, this voltage determines the minimum voltage ratings required for the modules and associated dc circuit components [NEC 690.7]. For crystalline silicon PV modules, the maximum voltage for PV arrays

is determined by multiplying the module rated open-circuit voltage (Voc) by the number of modules in series, and by a voltage correction factor [NEC Table 690.7]. Where other than crystalline silicon (thin-film) PV modules are used, or if temperature coefficients are provided with listed installation instructions, temperature translations should follow manufacturer's instructions using provided coefficients.

### 2.1.3 Rating Conditions

*Standard Test Conditions (STC)* is a universal rating condition for PV modules and arrays, and specifies the electrical output at a solar irradiance level of 1000 W/m<sup>2</sup> at AM 1.5 spectral distribution, and 25°C cell temperature. The performance of PV modules and arrays is sometimes represented at other test conditions closer to actual field operations, such as PVUSA Test Conditions (PTC), which is based on 1000 W/m<sup>2</sup> solar irradiance, 45°C cell temperature, 1 m/s wind speed.

#### **Example: PV Module Voltage-Temperature Correction**

Consider a crystalline silicon PV module with a rated open-circuit voltage of 44.4 V at 25°C, and a voltage-temperature coefficient of  $-0.33\%/^{\circ}\text{C}$ . What would the open-circuit voltage be at a cell temperature of 60°C?

$$V_{trans} = V_{stc} + [V_{stc} \times C_v \times (T_{pv} - T_{stc})]$$

$$V_{trans} = 44.4\text{V} + [44.4\text{V} \times -\frac{0.0033}{^{\circ}\text{C}} \times (60 - 25)^{\circ}\text{C}] = 39.2\text{V}$$

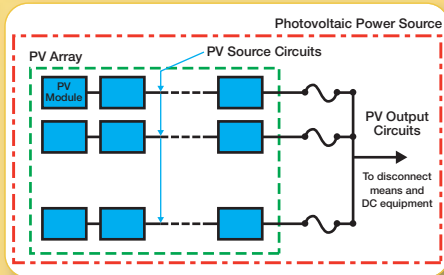
If the same PV module operates at  $-10^{\circ}\text{C}$  (35°C lower than the reference temperature), the translated voltage is:

$$V_{trans} = 44.4\text{V} + [44.4\text{V} \times -\frac{0.0033}{^{\circ}\text{C}} \times (-10 - 25)^{\circ}\text{C}] = 49.6\text{V}$$

### 2.1.4 PV Arrays

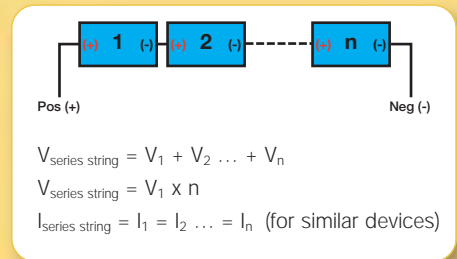
Photovoltaic power sources are constructed from the series and parallel connections of individual PV modules to achieve an intended dc current and voltage output. Photovoltaic source circuits typically consist of individual modules wired in series to achieve a desired output voltage intended for the connected dc utilization equipment. PV source circuits are then connected in parallel at combiner boxes located within the array or at inverters to build current and power output to the desired levels. See Figure 7.

**Figure 7. Photovoltaic power sources consist of parallel-connected source circuits of series-connected PV modules.**

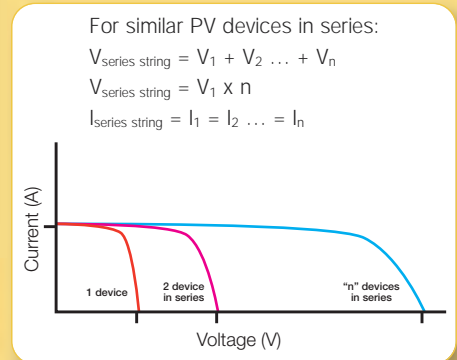


A string is a series connection of PV devices. PV cells or modules are configured electrically in series by connecting the negative terminal of one device to the positive terminal of the next device, and so on. For the series connection of similar PV modules, the voltages add and the resulting string voltage is the sum of the individual module voltages. The resulting string current output remains the same as the current output of an individual module. See Figure 8 & Figure 9.

**Figure 8. PV cells or modules are configured electrically in series by connecting the negative terminal of one device to the positive terminal of the next device, and so on.**



**Figure 9. Connecting similar PV devices in series increases voltage while current stays the same.**

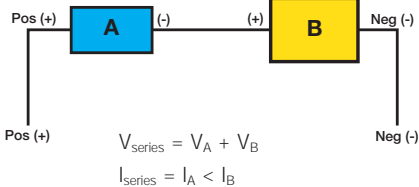


Connecting PV modules in series with dissimilar current ratings results in loss of power, similar in effect to partially shading an array, or having parts of a series source circuit located on surfaces facing different directions and receiving different levels of solar irradiance. The resultant

current output for a string of dissimilar current output devices is ultimately limited to the lowest current output device in the entire string, and should be avoided. However, it is acceptable to connect PV modules with different voltage output in series, as long as each module has the same rated current output. See Figure 10.

**Figure 10. Avoid connecting dissimilar PV devices in series.**

- When dissimilar PV devices are connected in series, the voltages still add, but the current is limited by the lowest current output device in series.
- Not acceptable.

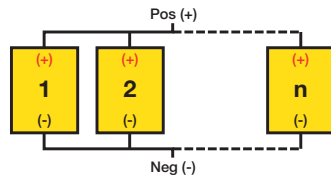


Series strings of PV modules are configured electrically in parallel by connecting the negative terminals of each string together and the positive strings together. Usually, an overcurrent device is required in each string [NEC 690.9]. For the parallel connection of strings, the string currents add and the resulting string voltage is the average of the individual string voltages. Parallel connections of strings with different current output, or from strings in different planes are acceptable, but may require different circuit sizing as required. See Figs 11 & 12.

### Module-Level Inverters

PV arrays designed using ac modules and micro-inverters are becoming increasingly popular for smaller installations having non-homogeneous arrays. Module-level inverters can optimize the output for arrays located in different planes receiving different amounts of solar radiation, or using different types of modules, or for arrays with partial shading. These designs have no field-installed PV dc source or output circuits, but rather combine the ac output of multiple inverters in parallel at dedicated overcurrent device. These designs are essentially feeder circuits consisting of ac sources, as opposed to branch circuits supplying electrical loads.

**Figure 11. PV cells or modules are connected in parallel by connecting the negative terminals together and the positive terminals together at a common point.**



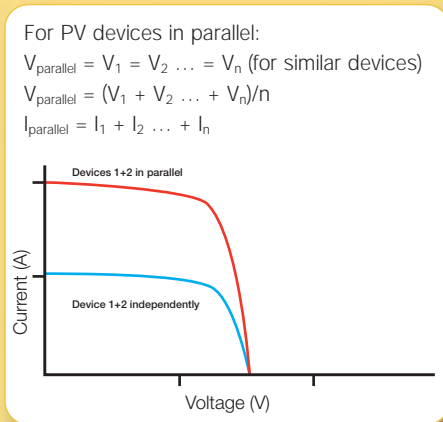
For PV devices in parallel:

$$V_{\text{parallel}} = V_1 = V_2 \dots = V_n \text{ (for similar devices)}$$

$$V_{\text{parallel}} = (V_1 + V_2 \dots + V_n)/n$$

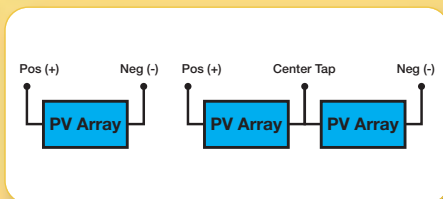
$$I_{\text{parallel}} = I_1 + I_2 \dots + I_n$$

**Figure 12. Connecting similar PV devices in parallel increases current while voltage stays the same.**



Monopole PV arrays consist of two output circuit conductors, a positive and negative. Bipolar PV arrays combine two monopole arrays with a grounded center tap. Consequently, bipolar arrays have a positive and negative voltage referenced to ground. Certain inverters are specifically designed and listed for use with bipolar arrays. See Figure 13.

**Figure 13. Monopole PV arrays consist of two output circuit conductors; while bipolar PV arrays combine two monopole arrays with a center tap.**



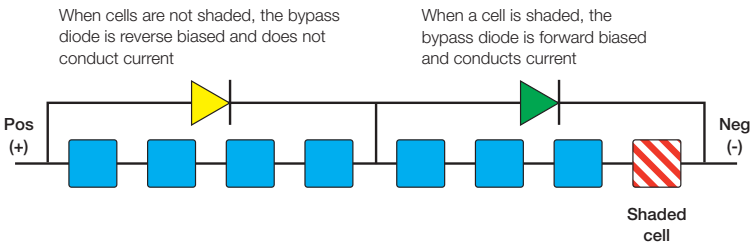
Bypass diodes are connected in parallel with series strings of cells to prevent cell overheating when cells or parts of an array are shaded. See Figure 14. Bypass diodes are essentially electrical check valves that permit the flow of current in only one direction. When modules in series strings are partially shaded, it may cause reverse voltage across the shaded cells or modules. The bypass diode shunts current around the shaded area and prevents cells overheating. Most listed PV modules are equipped with factory installed bypass diodes. Bypass diodes may or may not be serviceable via module junction boxes in the field.

## 2.2 Types of PV Systems

Types of PV systems are classified based on the loads they are designed to operate, and their connections with other electrical systems and sources. The specific components needed depend on the type of system, and its functional and operational requirements.

*Stand-alone PV systems* operate independently of other electrical systems, and are commonly used for remote power or backup applications, including lighting, water pumping, transportation safety devices, communications, off-grid homes and many others. Stand-alone systems may be designed to power dc and/or ac electrical loads, and with a few exceptions, use batteries for energy storage. A stand-alone system may use a PV array as the only power source, or may additionally use wind turbines, an engine-generator, or another auxiliary source in hybrid applications. Stand-alone PV systems are not intended to produce ac output that operates in parallel with the electric utility system or other sources. See Figure 15.

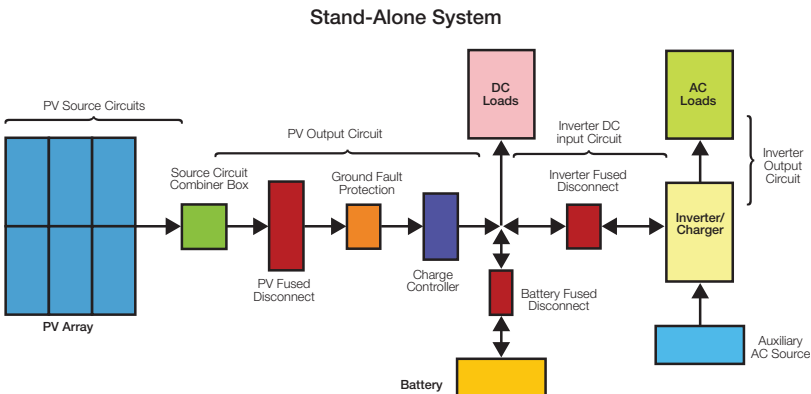
**Figure 14.** Bypass diodes are connected in parallel with series strings of cells to prevent cell overheating when cells or parts of an array are shaded.



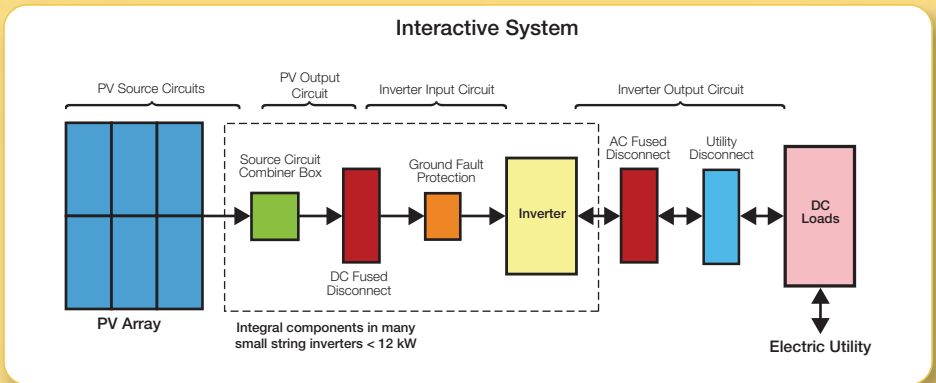
Interactive PV systems operate in parallel and are interconnected to and synchronized with the electric utility grid. When connected to local distribution systems, interactive PV systems supplement utility-supplied energy to a building or facility. The ac power produced by interactive systems either supplies on-site electrical loads or is back-fed to the grid when the PV system

output is greater than the site load demand. At night, during cloudy weather or any other periods when the electrical loads are greater than the PV system output, the balance of power required is received from the electric utility. Interactive PV systems are required to disconnect from the grid during utility outages or disturbances for safety reasons. Only special battery-based interactive

**Figure 15.** Stand-alone PV systems operate autonomously and are designed to meet specific electrical loads.



**Figure 16. Utility-interactive PV systems operate in parallel with the electric utility grid and supplement site electrical loads.**



inverters can provide stand-alone power for critical loads independent from the grid during outages. See Figure 16.

### 3 SYSTEM DOCUMENTATION

All PV installations should have adequate documentation providing details of the system design and all components and materials used in its construction. The documentation should also include safety information, and procedures for operating and maintaining the system. Proper system documentation helps ensure safe and reliable system operations, and is generally required for the following purposes:

- Plan review and permitting process with local building officials
- Interconnection approval from the local utility
- Installation and maintenance contractors
- Owners and caretakers
- Informing emergency services
- The system DC and AC power ratings; the manufacturer, model and quantity of PV modules, inverters, batteries, controllers and all other major components, as applicable. The dates of the system installation, commissioning and inspection should also be noted.
- The names, postal addresses, phone numbers and email addresses for the customer/owner, system designer, installation contractor and any other responsible parties or subcontractors.
- A site layout identifying equipment locations

on buildings or relative to property lines or easements. In some cases, a shading analysis and performance estimates may be provided with project proposals, and should also be including with the final system documents.

- A single line diagram depicting the overall system design, including the types of modules, total number of modules, modules per string and total number of strings; the types and number of inverters; and any other major components. For larger projects, complete as-built electrical and mechanical drawings are usually required at project close out.
- The types, sizes and ratings for all balance-of-system components annotated on the single line diagram, or noted and provided in a separate table, including specifications for all conductors, raceways, junction boxes, source circuit combiner boxes, disconnects, overcurrent protection devices, and grounding equipment, as applicable.
- Data sheets and specifications for PV modules, inverters and other major components, including module mounting systems. For most inverters, installation and user/operator manuals are available and provide important information regarding the safe operation and maintenance of the equipment.
- Operation and maintenance information including procedures for verifying proper system operation and performance, and how to determine if there is a problem and what to do. Procedures for isolating/disconnecting equipment and emergency shutdown procedures should also be provided. A maintenance plan and intervals should be provided for all routine (scheduled) system maintenance, such as array cleaning as required. Operating and maintenance guidelines should differentiate what tasks can be performed by the owner or caretakers, from those that require professional service due to the complexity of the tasks, special equipment needs, or safety concerns. Maintenance agreements, plans and recordkeeping forms or sheets should also be provided to document maintenance activities over time.
- Warranty details on major components indicating the terms and conditions, and how the warranty process is handled and by whom. System warranties should also be addressed, including quality of workmanship, roof weathersealing or performance warranties as applicable.
- Copies of all commissioning test reports and verification data.
- Contracting and financial details are also an important part of system documentation, and may be included with the technical items discussed above or under a separate file. These documents would include construction contracts, invoices and payments for materials and labor, building permits, inspection certificates, interconnection agreements, and applications and approvals from incentive programs, such as rebates and tax forms.
- A variety of aids are available for installers, including software products such as the SolarCert from Seaward Solar and testing and commissioning report.

## 4 COMMISSIONING PV SYSTEMS

Commissioning of PV systems involves visual observations as well as tests and measurements to verify the safe and proper operation of the system. Commissioning is performed immediately after PV installations are completed, prior to being operated and put into service for the first time. A thorough commissioning process helps improve safety and quality control, provides verification the installation matches the plans and code requirements, and is performing as expected. Some of the tests conducted during commissioning may be repeated during periodic routine maintenance to help ensure that the system remains in a satisfactory operating condition over its lifetime.

Key steps of a PV system commissioning procedure typically include:

- Completing final installation details.
- Completing visual inspections.
- Verifying compliance with NEC requirements.
- Conducting electrical verification tests.
- Vo/c, Is/c, insulation resistance, polarity.
- Verifying system functionality including start-up, operations, shut-down and emergency procedures.
- Verifying system power output and energy production meet performance expectations.
- Completing system documentation, including changes for as-built drawings.
- Conducting user orientation and training on system operations and safety.

### 4.1 Final Installation Checkout

A final checkout confirms that the installation is

complete before conducting any testing and beginning operations. Typically, the installation contractor will perform the final checkout, prior to formal inspections by building officials. With the exception of the PV array, all circuits should be de-energized wherever possible in preparation for system testing. A punch list can be used to help check off items as they are completed, and typically includes the following items:

- Verifying that all structural and electrical components are properly installed and secured.
- Verifying that all components are installed in a neat and workmanlike manner, including wire management practices.
- Verifying proper connections and terminations, including terminal torque specifications.
- Verifying that all required system and equipment labels, marking and placards are correct and in the proper locations.
- Verify that any calibrations or adjustments for inverters, charge controllers or other equipment are properly set or programmed.
- Verifying that all disconnects are open, fuses are removed and lockout/tagout procedures are in place.
- Identifying and completing any unresolved items.
- Completing site clean-up and restoring site to original conditions.

### 4.2 Visual Inspection

Visual inspections of PV systems should be performed as part of commissioning and routinely over the system lifetime to verify and

ensure that the system remains in a safe and properly functioning condition. There are many areas to evaluate with visual inspections, with the frequency and level of detail depending on the type and size of the system involved. Visual inspections are supplemented with other observations, test measurements and performance data to fully evaluate the safety and condition of PV systems.

Initial inspections are primarily used to identify unfinished installation details and verify compliance with the applicable code requirements. Visual inspections conducted after installation during periodic routine maintenance tend to look for physical damage or degradation of equipment from temperature extremes, moisture or other environmental conditions.

Prior to initial operation, all PV systems should be inspected for full compliance with the many NEC requirements. Checklists are often used to review and verify these requirements at the time of inspection, for examination and approval by local authorities. Among the key NEC requirements covered in Article 110 Requirements for Electrical Installations include:

- All equipment shall be properly listed, identified and labeled, suitable for the conditions of use, and be installed according to the listed product instructions [110.3].
- All equipment shall be installed in a neat and workmanlike manner, consistent with quality craftsmanship standards in the electrical construction industry [110.12].
- All equipment shall be mechanically secured and provided with adequate ventilation or cooling as required [110.13].

- All electrical terminations and connections shall be made using approved products and installation methods [110.14]. This includes consideration of conductor and terminal materials, temperature ratings, and use of specially approved terminals for use with fine stranded conductors or more than a single conductor. Pressure connectors using a set screw have required tightening torques, and these values should be recorded and verified at commissioning.
- All electrical equipment shall be marked with the manufacturer's identification and applicable specifications and ratings [110.21].
- Sufficient working spaces shall be provided about any electrical equipment that is likely to be serviced or maintained while energized [110.26]. Clear spaces and dedicated spaces are also required about certain electrical equipment, such as panelboards or switchgear.

NEC requirements covered in Article 690 Solar Photovoltaic Systems should also be evaluated and verified during visual inspections. These requirements address the following areas:

- Calculating circuit voltages and currents
- Determining conductor and over current device sizes and ratings
- Locating disconnecting means
- Wiring methods and connectors
- Equipment and system grounding
- Markings and labels
- Connecting to other sources (also Art. 705)
- Installing batteries and charge controllers



Some sources for PV system inspection checklists and guidelines include:

- <http://www.nmsu.edu/~tdi/Photovoltaics/Codes-Stds/Codes-Stds.html>
- <http://irecusa.org/wp-content/uploads/2010/07/PV-Field-Inspection-Guide-June-2010-F-1.pdf>
- <http://www.jimdunlopsolar.com/vendorimages/jdsolar/PVInspectionChecklist.pdf>

Many articles in the first four chapters of the NEC also apply to most PV installations, including but not limited to:

- Article 110 Requirements for Electrical Installations
- Article 230 Services
- Article 240 Overcurrent Protection
- Article 250 Grounding and Bonding
- Article 300 Wiring Methods
- Article 310 Conductors for General Wiring
- Article 314 Outlet, Device, Pull, and Junction Boxes
- Article 338 Service-Entrance Cable: Types SE and USE
- Article 344 Rigid Metal Conduit: Type RMC
- Article 356 Liquidtight Flexible Nonmetallic Conduit: Type LFNC
- Article 358 Electrical Metallic Tubing: Type EMT
- Article 400 Flexible Cords and Cables
- Article 408 Switchboards and Panelboards
- Article 445 Generators
- Article 450 Transformers

■ Article 480 Storage Batteries

■ Article 705 Interconnected Electric Power Production Sources

#### 4.2.1 Labels and Markings

Numerous markings, labels and signs are required to identify PV systems and their components, and to warn operators, service personnel or emergency responders of hazardous conditions. Manufacturer markings and labels identify the size, type, specifications and ratings for PV modules, inverters, controllers, combiner boxes, conductors, raceways, overcurrent devices, switchgear and all other electrical components. These markings are placed on the product at the time of manufacture, and include listing marks from the approval agency. Building officials may verify these markings during inspections, and rely on them for their approvals [110.2, 110.3, 100.21].

Additional markings and labels are required for the overall system and certain components in PV systems, and are to be provided and placed by the installer. These include additional labels on dc conductors and raceways [690.4, 690.31], connectors [690.33], disconnecting means [690.14, 690.17], and at the point of utility connection [690.54, 705.10, 705.12]. Labels and markings are also required on PV modules [690.51], alternating-current modules [690.52], the PV power source [690.53], ground fault protection equipment [690.5] and battery storage systems [690.55]. Special labeling is also required for bipolar arrays [690.7], ungrounded PV arrays [690.35], facility with either stand-alone systems or multiple power sources [690.56] and stand-alone inverters providing a single 120-volt supply [690.10].

## 5 SYSTEM TESTING AND MEASUREMENTS

PV systems should be thoroughly tested at the time of commissioning and periodically over their lifetime to ensure proper performance and safe operation. Baseline measurements at the time of system commissioning are compared to the system ratings and expectations for acceptance, and serve as a baseline for comparison with future measurements. Changes in test results over time are used to track system degradation, and identify problems that require attention or service for safety or performance reasons. Circuits or components that are modified or replaced should be retested accordingly.

There are several types of electrical tests conducted on PV systems that are used to verify NEC requirements and system performance. Many of these tests can be conducted with common electrical test equipment, while some measurements require special meters and instruments. In many cases, system performance information is measured, recorded and displayed by PV system inverters or charge controllers, and can be used to verify system functions and proper operation.

The following summarizes common types of testing conducted on PV systems what information it provides:

- **Continuity and resistance testing** verifies the integrity of grounding and bonding systems, conductors, connections and other terminations.
- **Polarity testing** verifies the correct polarity for PV dc circuits, and proper terminations for dc utilization equipment.

- **Voltage and current testing** verifies that PV array and system operating parameters are within specifications.
- **Insulation resistance testing** verifies the integrity of wiring and equipment, and used to detect degradation and faults to wiring insulation.
- **Performance testing** verifies the system power and energy output are consistent with expectations. These tests also require measurements of array temperature and solar irradiance.

For stand-alone or hybrid PV systems incorporating energy storage and additional energy sources, the following additional tests may be conducted:

- Measurements of battery voltage, capacity and specific gravity.
- Verification of charge controller set points and temperature compensation.
- Verification of charging current and load control functions.
- Verification of performance and wiring integrity for other sources, such as generators.

Multi-function PV system testers are now available, such as the Seaward PV150, that conduct many of the recommended tests, including continuity and resistance, polarity, voltage and current tests, and insulation resistance tests. By combining these test functions into single instruments, testing personnel avoid having to purchase, carry and maintain multiple meters. Multi-functional PV system testers simplify and speed up testing. These instruments can also store data for later

retrieval and processing into commissioning test reports that become part of the system documentation record. See Figure 17.

**Figure 17. The Seaward PV150 handheld meter provides multiple PV array testing functions.**



A variety of instruments are available for the PV installer, but it is important to make sure the correct instrument is selected and avoid products which only provide one or two tests, reducing the number of instruments needed as well as calibration requirements. The Seaward Solar PV150 is a hand held meter that performs a variety of tests in a safe and simple fashion.

## 5.1 Continuity Testing

Continuity testing is commonly used to verify grounding and bonding connections in electrical systems. These tests also verify the proper operation of disconnecting means and the function of overcurrent protection devices like fuses and circuit breakers. Measurements of resistance can also be used for estimating voltage drop in conductors, terminations and other connections and for evaluating windings in motors and transformers.

Proper grounding of PV systems reduces the risk of electrical shock to personnel and the effects of lightning and surges on equipment. The grounding requirements for PV systems can be quite complex to understand and installation practices and hardware are continually evolving and improving. There are two basic types of grounding. System grounding connects a current-carrying conductor in an electrical system to ground, or earth potential. Equipment grounding connects non-current carrying metal parts to ground, such as PV module frames, racks, enclosures, junction boxes, conduit and other metallic components. All PV systems require equipment grounding, and most also require system grounding. Specific grounding requirements for PV systems are addressed in NEC Article 690, Part V and general grounding and bonding requirements are covered in NEC Article 250. See Figure 18.

Most PV arrays in the U.S. today are installed with a grounded dc circuit conductor, either the positive or negative conductor, or the center tap of bipolar arrays [690.41]. This connection must be made at a single point on the photovoltaic output circuit [690.42]. For interactive inverters

with ground-fault protection [690.5], this connection is usually made internal to the inverter at dedicated terminals according to manufacturer's instructions.

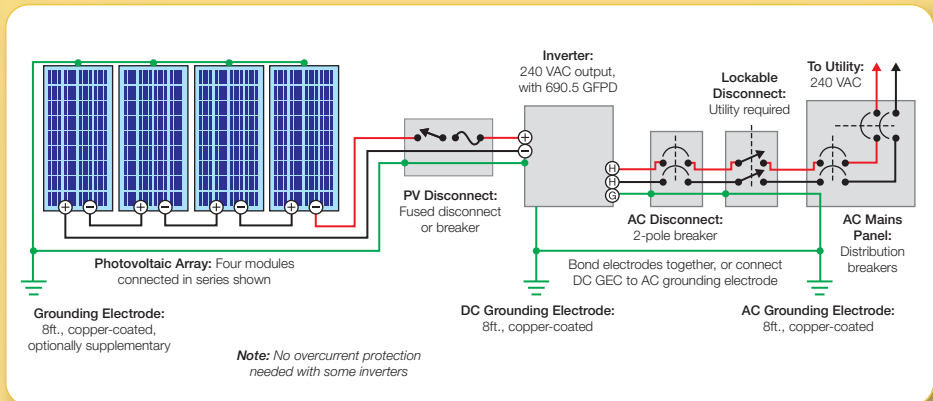
The connection between the grounded conductor and grounding electrode system is made through the ground-fault protection device. When a ground-fault condition is detected by current flow in this conductor, the circuit is opened and the inverter displays a ground-fault indication. Special labels are required to warn that normally grounded conductors may be ungrounded and energized. Appropriate safety precautions should be exercised around any PV arrays when ground-faults are suspected.

Ungrounded PV arrays are permitted by the NEC, but require specially listed inverters designed for use with ungrounded arrays, special cabling or protection for wiring, and require disconnecting means, overcurrent protection

and ground-fault protection in both ungrounded array dc conductors [690.35]. Ungrounded PV arrays are common in Europe, and expect to see more of these designs installed in the U.S. in coming years, due to lower inverter costs and capability for better array fault detection.

Equipment grounding for PV systems is particularly challenging, due the large numbers of individual PV modules in arrays, and their multiple connections to metallic support structures. PV module manufacturers are required to provide details of acceptable equipment grounding methods and components in their listed installation instructions, according to the UL 1741 standard for module safety. However, different mounting structures supplied by different manufacturers often require specialized grounding practices and hardware. Be sure to follow module and mounting system manufacturer's instructions for proper equipment grounding practices.

**Figure 18. All PV systems require equipment grounding, and most also require system grounding.**



Electrical resistance and continuity testing can be used to confirm the following NEC requirements:

- Verify the finish or anodizing on aluminum or other metallic components has been satisfactorily removed or penetrated for equipment bonding connections [250.12, 250.96].
- Verify that all available grounding electrodes in a building are bonded together and form a single grounding electrode system [250.50]. This includes underground metallic water pipes; building structural steel; concrete-encased electrodes; ground rings; and rod, pipe and plate electrodes, as available.
- Verify the grounding electrode conductor is continuous and the viability of any irreversible splices, welds or other connections are made using approved means where permitted [250.64]. Also verify the connection of the grounding electrode conductor to the grounding electrode.
- Verify that metal raceways, enclosures, frames, fittings, and other components serving as equipment grounding conductors are properly bonded together [250.86, 250.96]. Circuits operating over 250 volts to ground require special bonding methods to ensure electrical continuity of metallic raceways, such as the use of listed bonding lock nuts and bushing [250.97].
- Verify the continuity of the equipment grounding conductor is first-make last-break for any plug and receptacle equipment, and is not opened by any disconnect device [250.124].
- Verify that metallic raceways and enclosures are joined into a continuous electrical conductor [300.10]. Loss of mechanical continuity, due to improper installation or inadequate support can also lead to loss of electrical continuity [300.11, 310.12].
- Verify that metal parts of all PV module frames, support structures and other equipment are bonded to the equipment grounding system [690.43]. Special equipment bonding devices, listed and identified for bonding grounding module frames to support structures are allowed where approved for specific types of modules and mounting structures. Refer to PV module and mounting system manufacturer's instructions for additional information.
- Verify the continuity of equipment grounding connections and bonding jumpers when PV modules or inverters are removed from a circuit for service [690.48]. Similar requirements also apply to maintaining the continuity of equipment grounding conductors to metallic boxes containing receptacles, luminaires and other devices that may be removed for service [250.148].
- Verify that continuity between the grounded PV array source circuit and output circuit conductors remain bonded to the grounding electrode conductor whenever an inverter or other equipment is removed for service [690.49].

Continuity tests can be conducted using a conventional ohmmeter capable of measuring low resistances. Most digital multimeters also include continuity test features that produce and indication of pass or fail, such as an audible

alarm when continuity is verified. Oftentimes, extra-long test leads may be required to verify the continuity of grounding connections in PV systems due to the long separation distances between components. For accurate readings, the resistance of the test leads is accounted for or nulled by zeroing the ohmmeter prior to any resistance measurements. A clean surface and reliable test lead connection to the circuit under test is also crucial. Continuity and resistance testing should only be performed on de-energized circuits and conductors.

**An instrument such as the Seaward Solar PV150 is especially designed to provide continuity and resistance testing on PV installations.**

## **5.2 Polarity Testing**

As for any dc circuits, the polarity of array wiring and dc equipment is a critical concern for PV installations. The polarity of every source circuit and the entire PV power source must be verified prior to connecting to any dc utilization equipment, such as batteries, charge controllers, inverters or electrical loads. Without required PV array source and output circuit overcurrent protection [690.9, 240], reversing the polarity of an array connection to a battery can lead to disastrous results and damage PV modules or source circuit wiring. A reversed polarity array can also act as a load, and discharge current from a battery without some form of reverse current protection like a blocking diode. Some inverters have rectifiers on their dc input to protect them from reverse polarity connections, but many do not and can be damaged by inadvertently reversing the connections.

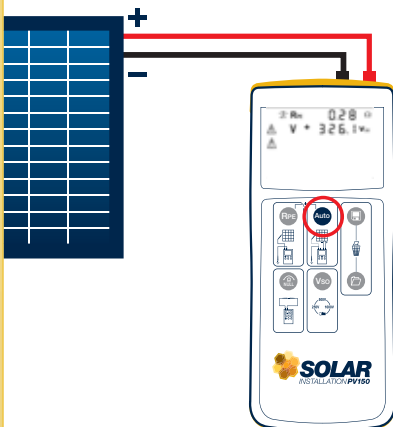
Reversing the polarity of a PV module within a given series source circuit can occur for hard-wired connections, although this problem has been largely eliminated by factory-installed PV module connectors and the requirement for them to be polarized, marked and non-interchangeable [690.33]. For PV modules using bypass diodes, reversing module polarity within a series source circuit will force that module to operate at reverse voltage limited by the voltage drop across the blocking diodes, usually around 0.7 V for each diode. The result is the current from other modules in the series string will “bypass” the reversed module, and the net voltage output for the entire string will be reduced by the voltage of the reversed module plus the voltage drop across the bypass diodes. Bypass diodes prevent PV modules from operating at large reverse voltages that can result in high power dissipation and damage to the module.

Reversing the polarity of an individual PV source circuit within a combiner box will simply cancel the current output from other parallel-connected strings wired with proper polarity. For larger PV installations with dozens of source circuits terminating at several combiner boxes throughout the PV array, keeping track of each source circuit and its polarity can be a challenge. To help reduce confusion and promote better wire management practices, the 2011 NEC requires all PV circuit conductors to be clearly identified by labeling, grouping, or color coding at all terminations, connections or splices [690.4]. All source circuit fuses and module bypass diodes should be checked if modules or strings are ever connected in reverse polarity.

Polarity is verified by measuring the voltage on energized circuits, prior to closing disconnects and operating the system for the first time. Most digital multimeters can be used for this purpose, as well as specialized PV array testing equipment capable of measuring dc voltage over the appropriate range. Electronic meters typically indicate the polarity of dc voltage measurements with a plus (+) or minus (-) symbol on the display, according to the connections of the positive and negative test leads. Analog voltmeters are not used for polarity testing, as the meter movements on these instruments can be damaged by connecting them in reverse polarity.

**Figure 19. PV String open circuit voltage**

Measured to ensure correct installation and operation of each PV string. Measured values should be compared with expected values. For systems with multiple identical strings, values should be within 5% of other PV strings in array.



Polarity should be verified on the following dc components and circuits PV system:

- Photovoltaic modules
- Photovoltaic source circuits
- Photovoltaic output circuits
- Disconnecting means
- Battery and charge controller circuits
- Inverter input terminations
- Electrical loads

### 5.3 Voltage and Current Testing

Basic voltage and current tests are conducted on both dc and ac circuits in PV systems to verify these parameters are within acceptable limits prior to closing disconnects and beginning system operations. Detailed voltage and current tests may be conducted on PV source circuits and arrays for performance verification purposes. Testing for performance verification requires additional measurements of solar irradiance and array temperatures, and translation of test results to a reference test condition.

Prior to operations, voltage should be verified for the following circuits and sources in PV systems:

- Verify ac voltage and correct phasing at utility supply, inverter ac terminals and disconnects, and electrical generators as applicable.
- Verify dc voltage and correct polarity for PV array source and output circuits and at dc disconnects.
- Verify dc voltage and correct polarity for battery, charger and charge controller subsystems.



Many PV inverters have integral data monitoring that measures many system parameters on the dc and ac sides of the inverter, including dc voltage, current and power. Usually, source circuit measurements need to be made at combiner boxes located throughout the array field in larger systems, where the source circuits can be isolated and identified for testing.

### 5.3.1 Open-Circuit Voltage Testing

Prior to closing the PV array dc disconnects, the open-circuit voltage (Voc) for each PV array source circuit should be tested and compared with expectations. This test can also be used to verify proper polarity. These tests simply verify correct installation, and are not intended to verify performance. Open-circuit voltage tests require a suitable voltmeter capable of reading AC and DC voltages of 600 V to 1000 V.

Most PV systems have identical strings consisting of the same number of series connected modules. In these cases, similar open-circuit voltage readings should be expected under the same testing conditions, typically within 5% of each other. Lower than expected voltage can be due to improper array wiring, failed modules or shorted bypass diodes. The string open-circuit voltage measurements should also be verified to operate within the dc voltage limits for inverters, charge controllers or any other dc utilization equipment.

If average cell temperatures are also measured, the open-circuit voltage measurements can be easily translated to a reference temperature condition for comparison with system specifications. Based on a standard  $-0.4\%/^{\circ}\text{C}$  voltage-temperature coefficient for crystalline

silicon PV modules, the corresponding voltage change should be 2.5% for every  $10^{\circ}\text{C}$  change in module temperature.

### 5.3.2 Short-Circuit Current Testing

Short-circuit current tests are conducted on PV string source circuits to verify proper readings and that the circuits are clear from major faults. Similar to the open-circuit voltage tests, these tests are only intended to verify proper system operation, not performance. Suitable test equipment, capable of safely short-circuiting high-voltage dc circuits is required. Most digital multi-meters can measure dc current up to 10 A, but require a suitable shorting device to safely measure the current. Clamp-on ammeters are also available for dc current measurements, and require an external shorting device as well. Some circuit breakers and disconnect switches may have appropriate DC current and voltage load-break ratings for shorting array source circuits. The ideal solution is a tester such as the Seaward PV150.

Short-circuit current is directly proportional to the solar irradiance incident on the array. Consequently, these tests must be done quickly, under steady clear sky conditions at as close to the same irradiance level as possible. Make sure the array is not shaded or particularly soiled prior to testing. Short-circuit current readings taken under steady conditions should typically be within 5% or one another for acceptance. If irradiance measurements are also made simultaneously with short-circuit current measurements, the results can easily be translated to a reference irradiance condition, for example  $1000\text{ W/m}^2$ , to compare with specifications.

The Seaward Solar PV150 performs a short circuit test at the touch of a button and avoids situations where installers are exposed to the possibility of arcing or exposure to high voltages in the measurement process.

#### 5.4 Insulation Resistance Testing

Insulation resistance tests are used to verify and demonstrate the integrity of electrical wiring systems and equipment, as required by the NEC [110.7]. These tests can be used to assess degradation or damage to wiring insulation and to locate faults within PV arrays and other system circuits. Insulation tests are an important element of commissioning, acceptance testing and preventative maintenance for PV systems.

Electrical conductors are usually insulated with an outer covering to protect them from coming into contact with personnel, equipment or other conductors. Where conductors are exposed at termination points or on busbars, the terminal spacing and air gaps provide insulating properties. Compared to conductors that have very low resistance on the order of a few ohms or less, insulators have very high resistance measured in megohms (M $\Omega$ ).

The quality of conductor insulation can be determined by measuring its resistance. Insulation resistance is determined by applying a constant test voltage to a conductor and measuring the current flow between the conductor and ground, or between other de-energized system conductors. This is analogous to pressure testing a plumbing system for water leaks. As wiring insulation degrades, its resistance decreases and the small current flow

through the insulation increases. The higher its resistance value, the better the conductor insulating quality. Excessive leakage current can present an electrical shock hazard, damage equipment and degrade system performance.

Damage to wiring insulation can result from improper installation, or any number of environmental factors, including from impacts or vibration, from animals or insects, or deterioration from temperature or sunlight, or other adverse conditions. Due to the degradation of PV modules and wiring systems over many years of direct exposure to the elements, older PV arrays will naturally have lower insulation resistance than when they were new. Insulation resistance tests are recommended on a 3-year maintenance interval, or more frequently as circumstances dictate.

Insulation resistance is measured between the conductors under test and ground, or between other conductors. Insulation resistance and leakage current testing are used to verify the integrity of the following PV system circuits and components:

- Verifying integrity of PV modules and array source and output circuit conductors.
- Measuring the leakage current through overcurrent and disconnect devices, including fuses, switches and circuit breakers.
- Measuring the insulation resistance for any equipment with windings, such as motors, generators, transformers and inductors.
- Testing the grounding electrode resistance.

To maintain safety and avoid damaging components during testing, the following guidelines and precautions apply to insulation testing of PV system circuits and associated equipment:

- Always use insulated rubber gloves with leather protectors when conducting insulation tests. Make sure test area and equipment are protected from access by unauthorized persons.
- Isolate circuits for testing by opening disconnects, and verify that circuits are de-energized using LOTO procedures prior to connecting insulation tester. The exception is for PV dc source circuits which are always energized when exposed to light.
- Grounded test lead should always be the first to make, and last to break any circuit measurement. Never use insulation testers in an explosive environment or around combustible materials.
- Never use insulation testers on circuits with any electronic equipment, including inverters, charge controllers, or instrumentation, or surge suppression equipment, as the application of high test voltages can damage this equipment.
- Never conduct insulation tests on batteries or other energy storage systems.
- Always ensure that circuits are properly discharged before and after insulation tests, either through the test equipment or externally with a load resistor. This is particularly important for PV modules, motor windings and parallel wiring methods with capacitive characteristics.

## Test Equipment

Insulation resistance testing is commonly measured with a megohmmeter. A megohmmeter is a special type of ohmmeter that measures very high values of resistance by applying high test voltages between conductors and measuring the leakage current. Megohmmeters may be powered by an external source, internal batteries or by a hand crank. Test voltages range from 50 Vdc to 5000 Vdc depending on the instrument and its purpose.

Handheld insulation multimeters often combine insulation test functions with voltage, resistance and continuity measurements. This test equipment is lightweight and easy to use, and can accommodate a variety of electrical system testing requirements. Specialized multi-function insulation multimeters are available that are purposely designed for testing PV arrays. See Figure 20.

**Figure 20. The Seaward PV150 Photovoltaic Tester measures and stores data for verifying PV electrical system integrity and performance.**



## Testing Considerations

Insulation resistance varies with the type of insulation and is inversely proportional to the volume of insulation tested. For example, an insulated conductor 500 feet long would typically have one one-fifth the insulation resistance as the same insulated conductor of only 100 feet in length. Insulation resistance also decreases with age as the insulation degrades, and is also affected by temperature and moisture. Insulation resistance is inversely proportional to temperature; as temperature decreases by 10°C, insulation resistance effectively doubles. For example, a conductor having an insulation resistance of 4 M $\Omega$  at 20°C would have a resistance of 1 M $\Omega$  at 40°C. Consequently, it is important to measure and evaluate insulation resistance readings at constant temperatures and record this information with test results. To avoid condensation and moisture effects, dry insulation resistance tests should only be conducted when the conductor temperature is above the dew point.

## Test Procedures

Insulation resistance testing is conducted by applying high voltages to conductors and equipment, and determining the resistance by measuring the leakage current. All circuits must be isolated from others for testing and discharged before and after testing. Grounding or bonding connections are left connected. Any surge suppression equipment must be removed from the circuits. The test leads must make a reliable connection with the circuit under test, and may require filing or grinding some coated metal components.

The test voltage depends on the circuits or equipment tested. It is usually higher than the operating voltages for the circuits or equipment under test, but not higher than the voltage ratings of the equipment or conductor. Higher test voltages may be used for proof testing of equipment by manufacturers than for field tests. Note that the maximum system voltage rating for most PV modules in the U.S market is 600 V. The IEC 62446 standard recommends a test voltage of 250 V for PV arrays with maximum voltage less than 120 V, a test voltage of 500V for PV arrays 120 V to 500 V, and a test voltage of 1000 V for arrays greater than 500 V (ensure that modules are rated for 1000 V for this test).

Insulation resistance and other electrical tests on PV arrays are generally measured at source circuit combiner boxes, where the individual array circuits can be accessed. The tests can be conducted dry, or a wetting agent can be sprayed on portions of an array to better pinpoint fault locations. Insulation tests may be performed using either of the following two methods:

1. Between the positive dc conductor and ground, and between the negative dc conductor and ground.
2. Between the shorted positive and negative dc conductors and ground. Requires an appropriate shorting device rated for circuit current and voltage.

The grounding connection is made to metallic module frames or support structures, the building grounding electrode systems, or directly to earth. Some modules and supports structure may not have a metallic support structure or frames.

For systems not bonded to ground, the tests should be carried out between array cables and ground, and also between array cables and frame.

The IEC 62446 standard recommends  $0.5\text{ M}\Omega$  as an acceptable minimum insulation resistance value for PV arrays operating at less than 120 V. For system voltages higher than 120 V,  $1\text{ M}\Omega$  or higher is considered acceptable. Tests conducted during system commissioning may be used as a baseline for which later measurements can be compared to evaluate wiring condition and degradation.

*ASTM E2047, Standard Test Method for Wet Insulation Integrity Testing of Photovoltaic Arrays* provides guidelines on test procedures and interpretation of results for wet insulation resistance testing of PV arrays. This standard can be used in conjunction with the IEC 62446 standard for conducting insulation resistance testing on PV arrays.

### 5.5 System Functional Testing

System functional testing verifies proper system operation, including start-up, shut-down and nominal operating conditions. These tests confirm that system operating parameters are within expected and nominal limits, but are not intended to verify system ratings in accordance with specifications or warranty provisions. Additional detailed testing, using additional measurements and normalizing data are required to verify performance with system ratings.

Knowledge of the specific equipment used and the product installation and operation instructions are crucial to verifying their safe and

proper operation during functional tests. Most inverters and charge controllers provide some indication of performance and operating status, such as power output or energy production, as well as fault or error indications such as out of limit parameters or array ground faults. This information is extremely helpful in verifying proper system operation, and may reduce the need to make hand measurements on energized circuits.

System functional tests ensure that the system starts and operates properly, and can be safely disconnected. Among the types of functional tests conducted on PV systems include:

- Verifying the proper operation of disconnecting means and component connection and disconnection sequences.
- Verify that interactive inverters and ac modules de-energize their output to utility grid upon loss of grid voltage [690.61]. This is a safety requirement to prevent interactive inverters from operating as an islanded electrical system without voltage or frequency control, and preventing them back feeding de-energized electrical systems. These functions are performed internally by all utility-interactive inverters listed according to the IEEE 1547 and UL1741 standards.
- Verify that interactive inverters automatically reconnect to their output to the grid once the voltage has been restored for at least 5 minutes [690.61].
- Verify that battery-based interactive inverters disconnect ac loads from the utility source when operating in stand-alone mode [690.61].

- Verify the proper grid voltage and frequency to operate inverters, including evaluating voltage drop between the inverter ac output and point of connection to the grid.

### 5.5.1 Test Reports

Measurements and test results for PV systems should be clearly summarized in a test report that includes the following information:

- System information.
- Visual inspection record and observations.
- Identification of circuits tested, tests performed, and record of measurements.
- Interpretation and summary of results, identifying special maintenance needs or corrective actions.
- Signatures of responsible person(s) and date(s) of tests.

An example test report format is presented in the annex of the IEC 62446 standard.

Seaward Solar provides a wide range of reports which are especially designed to meet the requirements of IEC 62446, simplifying the record keeping process. SolarCert Elements is an inexpensive software product, especially designed to produce test reports of PV systems and can be used in conjunction with the PV150 Solarlink™ Test Kit.

## 6 SYSTEM PERFORMANCE TESTING

PV systems are designed to produce a specified electrical output under certain operating conditions. Performance testing verifies the system power output and energy production are

as expected, based on component and system ratings and the given operating conditions. Performance data can also help identify problems that require service or maintenance, and may also be used for determining system financial revenues and warranty provisions.

### 6.1 Verifying Power and Energy Production

Power and energy production are the fundamental metrics for PV system performance. The methods and procedures to verify PV system performance are based on the principles of PV device operation, and accounting for the effects of temperature and solar radiation. Many parameters may be monitored automatically and displayed by meters, inverters, controllers or other power processing equipment in the system.

For interactive PV systems, the key indicators for system performance are ac power output (kW) and energy production (kWh). Measurement and verification of ac power output can be done at any time when the system is operating under steady sunlight conditions near peak output levels. Energy production is measured over longer periods of months and years to compare with expectations and the available solar resource.

Performance verification for stand-alone PV systems is inherently more complex, involving more measurements and multiple interactions between energy storage, charge control and system loads that affect PV system production. Battery health is the key to stand-alone PV system performance, and battery failure is often the indicator of many other system problems. Usually stand-alone PV systems are designed to produce a specified amount of energy on an average daily basis to meet system loads. Measurements of



daily energy consumption can be used by the system owner/operators to control their loads and manage the available energy. Measurements of daily minimum daily battery voltage and the net amp-hours delivered to and withdrawn from a battery can also be used to assess whether the battery is receiving enough charge. Deficit charging will usually be indicated by declining minimum battery voltages. The performance of electrical loads can be verified by measuring their current or power consumption, and if they function as intended.

### 6.1.1 Verifying AC Power Output

The ac power output for interactive systems is related to the rated maximum dc power output of the array adjusted by a number of derating factors. The factors include several types of ac and dc system losses and the inverter power conversion efficiency, which in combination result in ac power output normally 70 to 85 percent of the PV array dc rating at Standard Test Conditions (STC). The actual ac output of an interactive PV system at any moment can be compared with expectations, using the basic translation formulas for solar radiation and temperature.

Accurate simultaneous measurements of module temperature and inplane solar radiation are required if power measurements are to be compared with reference data at STC. This can be achieved using an instrument such as the Solar Survey 100 and 200R.

The typical procedure for verifying the expected ac power output for interactive PV systems begins with the nameplate dc ratings for the PV array and applying applicable derating factors. The array dc rating is usually taken as the sum of all individual

module nameplate maximum power ratings (Pmp) at STC. The product of the derating factors and dc rating give the estimated system ac power output. Translations for temperature and solar radiation provide an estimate for actual operating conditions.

Following are the primary derating factors used to estimate the ac power output of PV systems under given operating conditions.

- **Nameplate Ratings:** This derating factor accounts for the accuracy of the manufacturer's power rating and guaranteed performance. Manufacturing tolerances result in most PV modules producing less than their rated power at STC, and the UL 1703 module listing standard only requires module power to be within  $\pm 10\%$  of the module rating. Additional design qualification tests covered in IEC 61215 may establish power tolerance within 3 percent of nameplate ratings. A derate factor of 0.95 represents that the array power output at STC is 5% less than the manufacturer's nameplate rating.
- **Inverter and Transformer:** The derating factor for the inverter and transformer is their combined efficiency in converting dc power to ac power. Modern interactive inverters have weighted efficiencies on the order of 95%. The efficiencies of transformers separate from inverters need to be considered additionally. This factor should also include the array maximum power point tracking efficiency for the inverter, which is generally around 98% to 100%.

- **Module Mismatch:** The derating factor for PV module mismatch accounts for manufacturing tolerances that yield PV modules with slightly different current-voltage characteristics. Consequently, when connected together electrically, usually in series, the modules do not operate at their respective peak efficiencies. A derating factor of 0.98 represents a loss of 2% due to mismatch, and is a reasonable assumption. PV systems using ac modules or micro-inverters would not have any module mismatch, because PV modules are individually connected to maximum power point tracking inverters.
- **DC Wiring:** This derating factor accounts for losses in the dc circuits from the PV array to the inverter. It includes voltage drops in wiring, connections, fuses, diodes, switches or any other components, as applicable. These losses can be determined in the field, by measurements of the current and voltage drops through the entire dc circuit. Losses in dc circuit conductors can be easily calculated from Chapter 9 Table 8 in the NEC. Total DC wiring and connection losses will usually be on the order of 2% for most PV systems, resulting in a derating factor of 0.98. Systems using ac modules or micro-inverters have insignificant DC wiring and connection losses, and ac modules are rated for ac, not dc specifications.
- **AC Wiring:** This derating factor accounts for losses in the ac circuits from the inverter to the point of utility interconnection, or where the system output is measured. It includes voltage drops in wiring, fuses and disconnects, and is usually on the order of 1% or less for most PV systems, resulting in a derating factor of 0.99.
- **Soiling:** This factor accounts for the accumulation of dirt, snow and other foreign matter on the surfaces of PV modules that reduces the amount of solar radiation received. PV arrays located in arid, dusty areas with infrequent rain can experience soiling losses 20% a year or higher.
- Routine maintenance and array cleaning as required can largely eliminate soiling losses, and a default derating factor of 1.0 may be used for clean arrays.
- **Age:** The derate factor for age accounts for losses in performance over time due primarily to degradation of the PV modules. The loss in performance is typically 0.5% to 1% per year for most crystalline silicon PV arrays.



### Example: Verifying AC Output for Interactive PV Systems

The following worksheet can be used to estimate the expected ac power output for interactive PV systems without energy storage. This procedure is only valid for interactive systems using flat-plate crystalline silicon PV arrays (no special bifacial modules or concentrating modules). The entire PV array must be oriented in the same

direction and unshaded. The inverter must be operating the array at its maximum power point, and not exceeding inverter ratings within prescribed voltage limits. Measurements of solar radiation, temperature and power output must be done simultaneously. For best results, measurements should be within  $\pm 2$  hours of solar noon with incident solar radiation levels  $800 \text{ W/m}^2$  or higher and under clear sky conditions.

### Example

## INTERACTIVE PV SYSTEM PERFORMANCE WORKSHEET

### Estimating and Verifying System AC Power Output

PV Array DC Power Rating at STC - $1000 \text{ W/m}^2$ , $25^\circ\text{C}$ (kW)	10
<b>Derating Factors</b>	
Nameplate Ratings	0.95
Inverter and Transformer	0.95
Module Mismatch	0.98
DC Wiring	0.98
AC Wiring	0.99
Soiling	1.00
Age	1.00
<i>Combined Derating Factors</i>	0.86
Estimated System AC Power Output at STC - $1000 \text{ W/m}^2$ , $25^\circ\text{C}$ (kW)	8.6
<b>Temperature Adjustments</b>	
Array Power-Temperature Coefficient ( $\%/^\circ\text{C}$ )	-0.5
Measured Array Operating Temperature ( $^\circ\text{C}$ )	60
Estimated System AC Power Output at $1000 \text{ W/m}^2$ and Operating Temperature (kW)	7.1
<b>Solar Radiation Adjustments</b>	
Measured Solar Irradiance in Plane of Array ( $\text{W/m}^2$ )	850
Estimated System AC Power Output at Operating Temperature and Solar Irradiance (kW)	6.0



### 6.1.2 Verifying AC Energy Production

A key metric for PV system performance is the ac energy (kWh) it produces over time. Energy production for interactive PV systems depends on many factors, including the size of the array, the local solar energy resource, and the array operating temperatures. It also depends on inverter efficiencies in converting dc to ac power, its effectiveness in tracking array maximum power, and other losses in the system, including voltage drop, shading and soiling of the array. Energy production is measured over periods of months and years to compare with sizing and long-term performance expectations.

Watt-hour meters measure electrical energy, and are commonly used by utility companies for revenue purposes. They are also used to record energy produced by PV systems, and integral to most interactive inverters. Traditional electro-mechanical types are being replaced by electronic types with capability for many additional power system measurements, including multi-directional and time of use power flows, and other electrical properties such as reactive power, power factor and peak power demand.

Watt-hour meters can also be used to measure average power over brief intervals. The watt-hour constant (Kh) indicates the watt-hours accumulated per revolution of the meter disk. Electronic meters use progressing LCD hash marks to simulate disk revolutions and the rate of energy flow. Most residential meters have  $K_h = 7.2$ . The smaller the constant, the faster the meter spins for a given amount of power passing through it. Larger and higher voltage meters have larger  $K_h$ , and use current and voltage

transformers to measure these parameters separate from the meter.

Multiply  $K_h$  by the disk revolution rate to calculate average power through the meter. The disk has markings on the top and sides with a scale of 0 to 100. For example, the average power through a meter with  $K_h=14.4$  that makes 20 complete revolutions in one minute is calculated by:  $P_{avg} = 14.4 \text{ Wh/rev} \times 20 \text{ rev/60 sec} \times 3600 \text{ sec/hr} = 6480 \text{ W}$ .

#### Example: Estimating and Verifying ac Energy Production

The following spreadsheet presents a simplified method for estimating the ac energy production for interactive PV systems without energy storage. This procedure requires data for the total solar energy received on the array surface, as well as for the average array operating temperatures. Solar radiation and temperature data can be obtained from historical databases, or better yet, from actual site measurements in the plane of the array.

Average array operating temperatures are difficult to quantify without measurements, but can be estimated by the site average daytime ambient temperature and array temperature rise. As with power or any other estimates, these results provide a general approximation, and the validity of the results depend on how accurate the user assumptions are. Generally, results using this procedure are acceptable if they are within 10% of expectations. Of course, whenever the parameters can be measured rather than estimated will yield more accurate results.



## Example

### INTERACTIVE PV SYSTEM PERFORMANCE WORKSHEET Verifying System AC Energy Production

PV Array DC Power Rating at STC - 1000 W/m <sup>2</sup> , 25°C (kW)	10
<b>Derating Factors</b>	
Nameplate Ratings	0.95
Inverter and Transformer	0.95
Module Mismatch	0.98
DC Wiring	0.98
AC Wiring	0.99
Soiling	1.00
Shading	0.85
Sun Tracking	1.00
Age	1.00
<i>Combined Product Derating Factors</i>	<i>0.73</i>
Estimated System AC Power Output at STC - 1000 W/m <sup>2</sup> , 25°C (kW)	7.3
<b>Temperature Adjustments</b>	
Array Power-Temperature Coefficient (%/°C)	-0.5
Average Array Operating Temperature (°C)	45
Estimated System AC Power Output at 1000 W/m <sup>2</sup> and Average Operating Temperature (kW)	6.6
<b>Solar Radiation Received</b>	
Solar Irradiation in Plane of Array (kWh/m <sup>2</sup> /day) [Peak Sun Hours per Day]	5
<b>Estimated System AC Energy Output at Average Operating Temperature (kWh/day)</b>	<b>29.5</b>

## 6.2 Array I-V Measurements

To evaluate the performance of PV modules and arrays for rating purposes, their I-V curves can be measured. This requires specialized test equipment that can load the module or array over the full range of the I-V curve, from short-circuit (zero resistance load) to open circuit condition (infinite resistance load). The array can be loaded with any device that is rated for the voltage and power of the PV device under, and can vary the

load. The load can be a variable resistor, or a variable dc power supply that can sink current from the PV device. Some, array I-V testers use a capacitive load that quickly charges from zero voltage up to the array open-circuit voltage while the current and voltage point are recorded with a high speed data acquisition system. Concurrent with the I-V measurements, the cell temperature for the PV device under test and the incident solar irradiance are also recorded. I-V data points

are then processed and normalized to a reference rating condition for comparison with module or array ratings.

In addition to obtaining all the current and voltage data discussed previously, detailed I-V curves can help evaluate the following for PV modules and arrays:

- Determine the true array maximum power point in relation to the operating voltage for inverters, battery systems and other dc utilization equipment.
- Determine voltage and power degradation rates from baseline measurements and subsequent measurements over time.
- Determine changes in array series and shunt resistance over time.
- Identify array wiring problems or module failures.
- Analyze the effects of shading on electrical output.
- Evaluate losses due to module mismatch and array wiring methods.
- Establish module or array ratings for performance guarantees or warranty purposes.
- Locate open bypass diodes; requires I-V curve test or dc power supply that reverse biases (applies negative voltage) to the module under test.

I-V testers are rated for maximum current and voltage inputs from PV arrays, and measure and record the I-V data points for each curve. I-V data or the I-V curve may be displayed on the tester, and the data can usually be downloaded to personal computers for translation to reference rating conditions. Most I-V testers use a 4-wire test lead measurements, one set of leads simply measures voltage while the other set measures the current, which eliminates measurement

errors due to voltage drop in the test leads. Additional resistance in the test circuit from conductors and connections will ultimately affect the I-V curves for arrays. Caution should be taken to never coil the test leads, as the inductance may clamp the voltage during the high speed I-V measurement.

The solar irradiance in the plane of the array and array temperature are measured concurrent with the I-V measurements and used to translate the actual output of PV arrays and systems to a reference condition to verify performance. Some I-V testers can make these measurements from external sensors attached to the I-V tester and include these parameters with the recorded I-V data, or may be measured by separate instruments and the data entered separately.

There are different types of solar irradiance instruments, some much more expensive and more accurate than others for scientific measurements. A pyranometer measures full spectral irradiance, whereas PV modules only respond to a section of it. This makes pyranometers unsuitable for accurately calculating array output. Since PV device short-circuit current is directly proportional to solar irradiance, a small PV reference cell can also be used to measure solar radiation levels. Small inexpensive meters using calibrated PV cells as sensors are available.

**Figure 21. Handheld solar meters use a small PV cell to measure solar irradiance.**



**The Seaward Solar Survey 200R features a digital compass and thermometer as well as USB download of results and wireless Solarlink™ connectivity with the PV150 tester.**

#### Test Procedures

Accurate I-V measurements in the field require ideal test conditions and an organized testing approach. For best results and to minimize errors in data translations, measurements should be made at solar irradiance levels on the array over 800 W/m<sup>2</sup> under steady, clear sky conditions near solar noon, with minimal wind speed.

*ASTM E1036 Standard Methods for Testing Electrical Performance of Nonconcentrator Terrestrial PV Modules and Arrays Using Reference Cells* provides guidelines for making I-V measurements on PV module and arrays in the field, and specifically, for normalizing the results

to Standard Test Conditions. This standard only addresses performance, and not safety. The translation methods prescribed are quite complex, and typically used in spreadsheets or computer programs to produce the results.

### 6.3 Other Tests

Special testing may also be conducted on PV systems, for preventative maintenance or to troubleshoot specific problems. These tests require the use of specialized equipment.

#### 6.3.1 Power Quality Analysis

Power analyzers are multi-function test instruments used to diagnose a number of issues with electrical systems. In addition to a basic digital multimeter, power quality analyzers have data acquisition capabilities and oscilloscope functions to evaluate waveforms. They can be used to monitor grid conditions, such as voltage sags and surges, power factor and phase angles, harmonics and other conditions over time. They can also be used to measure ac ripple currents on dc circuits that may need to be considered for conductor sizing and selection of overcurrent protective devices.

**The Seaward Solar Power Clamp is a multi-functional clamp meter which provides a wide range of measurements of AC and DC power systems and is supplied with the necessary connectors for solar PV systems.**

#### 6.3.2 Thermal Imaging

IR thermography is becoming a very popular tool for the evaluation of electrical systems and particularly PV arrays. Thermal imaging can identify hot spots or overheating equipment, thermal gradients within PV arrays, and can help

locate developing problems internal to individual PV modules before failure. Common problems that can be identified with thermal imaging including bad module connectors, shorted or failing bypass diodes, or module busbar failures. Thermal imaging can also identify bad or loose circuit breakers, fuses, or switchgear, or connections to and from or terminal to batteries or other equipment.

### 6.3.3 Inverter Efficiency Tests

Inverter efficiency is the ratio of the ac power output to the dc power input. Inverter efficiency varies with power level and input voltage, and also affected by inverter temperature. Most commercial utility-interactive inverters have weighted power conversion efficiencies of 95% and higher over most of their operating range. Sample efficiency measurement can be made in the field by simultaneously measuring the dc power input and ac power output at the inverter terminals. Many inverters measure and display this data, or it can be measured with separate equipment. The dc input voltage and current can also be measured to determine inverter input power, and for inverters with unity power factors the ac power can be determined by measuring the inverter ac voltage and current output as well. True watt-hour meters or power analyzers are needed to determine power for reactive circuits and components.

### 6.3.4 Maximum Power Point Tracking Tests

The effectiveness of maximum power point tracking (MPPT) circuits can be evaluated as part

of I-V testing. This measurement requires operating the PV system under steady conditions, and recording the operating voltage and power output for the array, then immediately disconnecting the array and measuring its I-V curve to determine the true maximum power. The ratio of the operating power to the true maximum power defines the MPPT efficiency.

### 6.3.5 Shading Analysis

A shading analysis evaluates and quantifies the impacts of shading on PV arrays. Shading may be caused by any obstructions in the vicinity of PV arrays that interfere with the solar window.

Ideally, there should be no shading on arrays between the hours of 9 a.m. and 3 p.m. solar time over the year, since the majority of solar radiation and peak system output occur during this period. Even a small amount of shading on PV arrays during peak generation times can dramatically reduce the output of the system.

Sun path charts are the basis for conducting shading evaluations. By measuring the worst-case altitude and azimuth angles of a shading object from an array location, a scale image of the obstruction can be plotted on a sun position chart for the given latitude. This shows the portion of the solar window that is obstructed by shading. Knowing the amount of receivable solar energy during different periods of a day, the shading analysis can be used to estimate the reduction in solar radiation received during the shaded times of the day and year, and ultimately estimate the reduced energy production for a PV system.

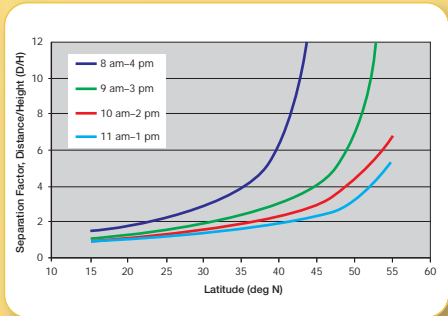
Several devices and software tools have been commercially developed to simplify shading evaluations. These devices project or record obstructions on sun path diagrams, and estimate the net solar energy received after shading. PV installers should be familiar with these tools, their principles of operation and how to obtain accurate results. Most system design and performance estimating tools also incorporate shading factors to derate the system output accordingly.

For larger PV systems with multiple parallel rows one in front of another in the array, one row of modules can shade the one in back during winter months if the rows are too closely spaced.

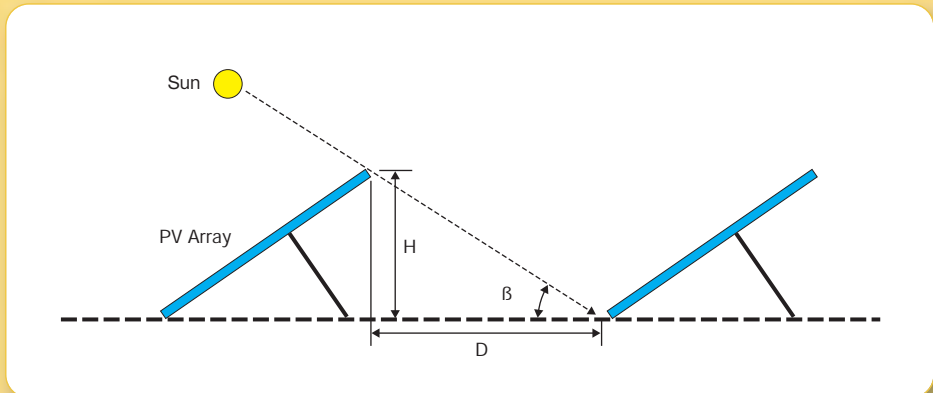
Multiple rows of PV arrays can be more closely spaced at lower latitudes and using lower tilt angles. The minimum required separation distances between PV array rows and other obstructions depends on latitude, the height of the obstruction, and the time of day and year that

shading is desired to be avoided. To avoid shading at the winter solstice between 9 a.m. and 3 p.m. solar time, the separation distance between PV arrays and obstructions should be at least 2 times the height of the obstruction at latitudes around 30°, 2½ times the height at latitudes around 35°, 3 times the height at 40° latitude and 4 times the height at 45° latitude. See Figure 23.

**Figure 23. Separation factor vs latitude for south-facing array rows.**



**Figure 22. Multiple rows of rack mounted PV arrays must be separated to prevent shading.**



## 7 SYSTEM MAINTENANCE

PV systems require periodic maintenance to ensure safe and reliable operations over the long-term, and to maximize performance. A maintenance plan ensures that essential service and testing is performed on a regular schedule. Maintenance helps identify and avoid potential problems that affect system functions, performance, or safety. When discrepancies are identified through system testing or performance measurements, a systematic troubleshooting process is used to diagnose and identify the problems, and take corrective actions.

The level and frequency of maintenance often depends on the size and type of system, and the consequences of system failure or under performance. A maintenance plan covers the types and schedule for all required system maintenance and service, including:

- Inspecting system components and wiring methods.
- Evaluating of structural attachments and weathersealing.
- Cleaning and removing debris around arrays.
- Performing maintenance on batteries or other equipment.
- Conducting electrical tests and verifying system performance.
- Replacing or repairing damaged or failed system components.

Visual inspections of the complete system should be performed with regular maintenance, similar to the inspections during commissioning. The main difference is that during maintenance

inspections, the code compliance aspects of the system do not necessarily need to be evaluated, as the equipment would not normally have been changed. However, the integrity of the electrical installation must be carefully evaluated for deteriorating effects over time, due to the site conditions, or due to poor quality components or from physical damage.

Visual inspections and regular maintenance for PV modules and arrays should include the following:

- Inspect for any physical damage to PV modules or arrays, including bent frames or broken glass. Modules with fractured or damaged laminates will eventually admit moisture and develop faults and high leakage current, and should be removed from the array and replaced.
- Inspect for any delamination, moisture or corrosion within modules, particularly near cell busbar connections and edges of laminates. Discolorations inside module laminates may be an indicator of hot spots and degrading internal cell connections that can result in module failure, reduced system performance and a fire hazard.
- Remove any leaves, trash or other debris that collects around PV arrays during regular maintenance. These materials can also present a fire hazard, as well as a problem for proper drainage and can lead to mildew and insect problems, or the degradation of wiring systems.
- Evaluate any conditions that contribute to increased shading of PV arrays, including growing vegetation and other obstructions.

Where visual observations cannot determine the extent of shading problems, a solar shading evaluation should be conducted.

- Clean PV array surfaces as required to minimize soiling from bird droppings, emissions, dust or dirt that settles and accumulates on the array surface. Extensive soiling can reduce array output by 10 to 20% or more in arid dusty regions with infrequent rainfall.
- Inspect the quality of all attachment points and building penetrations for signs of degradation or water leakage, including weathersealing and structural security, and make repairs as required.

Visual inspections and observations are supplemented with electrical tests and measurements to fully verify system integrity and performance. Many of the electrical tests conducted during commissioning are also conducted during maintenance testing. In particular, tests that help assess problems or degrading effects over time, like insulation resistance testing, grounding system continuity testing and performance verification are key indicators of system safety and health. Other specific tests may be repeated as necessary, depending on the project requirements.

### 7.1 Testing

Testing during maintenance activities should include many of the tests conducted during system commissioning, including voltage and current testing, insulation resistance testing, continuity testing and performance verification. Polarity testing is generally not required, unless problems are suspected. The frequency of

maintenance testing depends on the installation requirements.

Maintenance testing is primarily intended to evaluate trends in certain measurements, and to assess degradation over time. For example, the power and voltage output of most PV arrays is expected to degrade by between 0.5% and 1% per year, consistent with manufacturer performance warranties. Soiling or shading on PV arrays will also decrease expected current and power output accordingly.

### 7.2 Troubleshooting

Troubleshooting problems with PV system requires skilled individuals having a detailed understanding of system designs and fundamentals of component and system operations. Most PV system power processing components, including charge controllers and inverters generally include integral data monitoring and display functions, and this data can often be used to identify system problems. PV installation contractors often use these monitoring systems to track the performance of their installed systems, and review the data to verify performance and initiate service and maintenance activities as required. Experienced PV installers will be able to recognize certain trends and data to indicate specific problems with the systems, and dispatch an effective and quick solution to the problem.