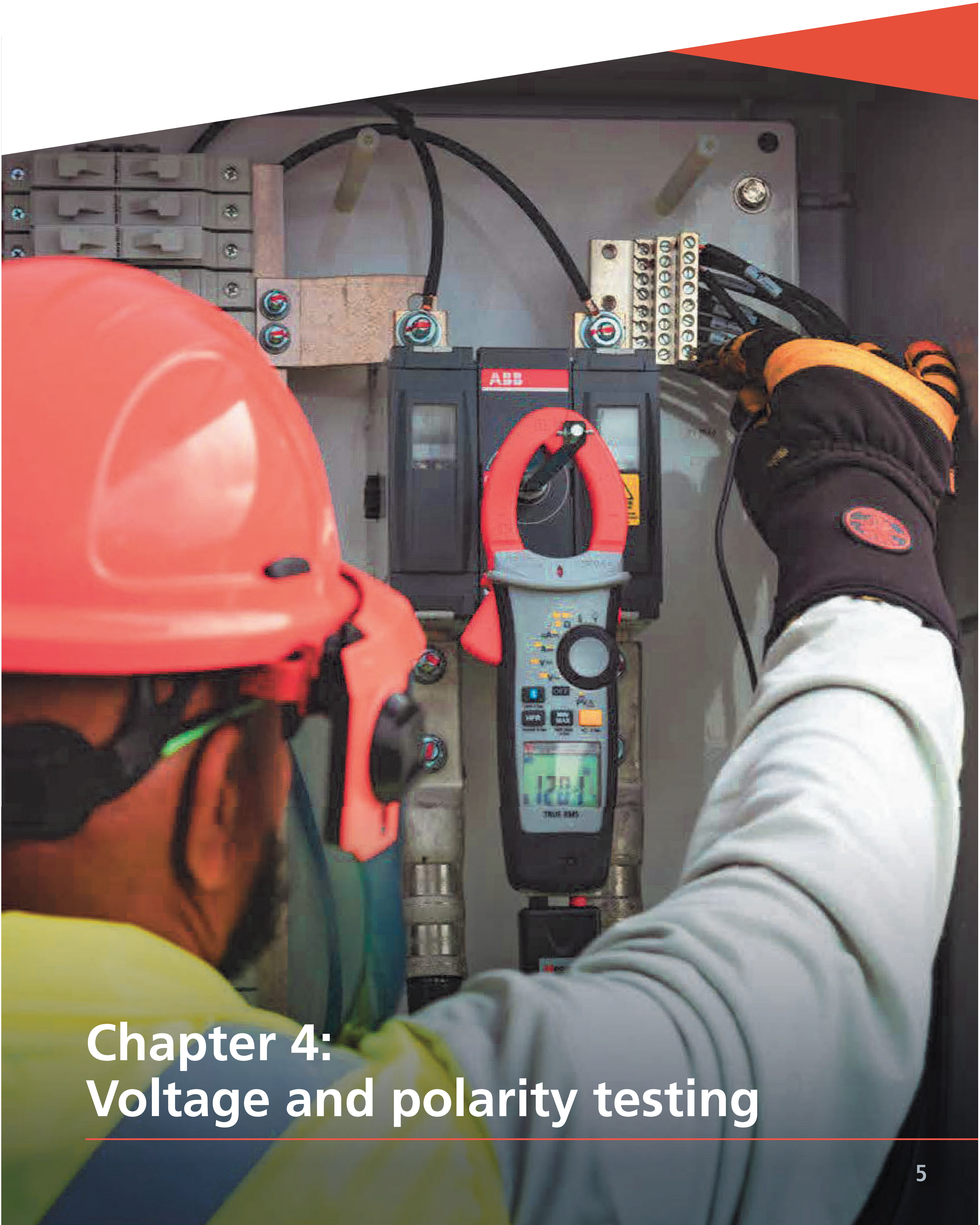
Electrical Testing
Standards Guide

Megger



Chapter 4:
Voltage and polarity testing

Introduction

Voltage and polarity overview

For technicians who are working on photovoltaic (PV) systems, it is critical to measure and document voltage and confirm polarity. These measurements enable technicians to assess the potential for current flow and identify potential shock hazards. PV systems are unique electrical installations because of the presence of both direct current (DC) and alternating current (AC) power sources. Therefore, technicians must understand how to properly use digital voltmeters or multimeters (DMMs) on both sides of the system.

Voltage is an invisible safety hazard that must be accurately measured when working on solar PV systems. Field technicians commonly measure various voltages at nearly every stage of PV installation. Measurements are required throughout the system, beginning at the PV module level and continuing to combiner boxes, inverters, and the AC electrical distribution equipment. Each location presents a different safety hazard that technicians need to be aware of.

This chapter focuses on voltage measurements of the PV system when the system is not in operation, also called an open-circuit condition. Functionally, the methods for measuring the voltage of an operating system are identical to measuring the voltage of a system in an open-circuit condition. However, the tools, methods, and impacts of environmental conditions can vary between the two. Throughout this chapter, the methods and examples focus on systems that are not in operation.

Figure 4-1: Digital multimeters are used throughout PV installation and maintenance activities.

Voltage concepts explained

Voltage is quantified as the difference in electrical potential between two points in volts (V) and is analogous to water pressure. A difference in water pressure at either end of a pipe forces water to flow from the side with higher pressure to the side with lower pressure. Similarly, measuring a nonzero voltage between two points in a circuit indicates that an electrical current can flow between the two points.

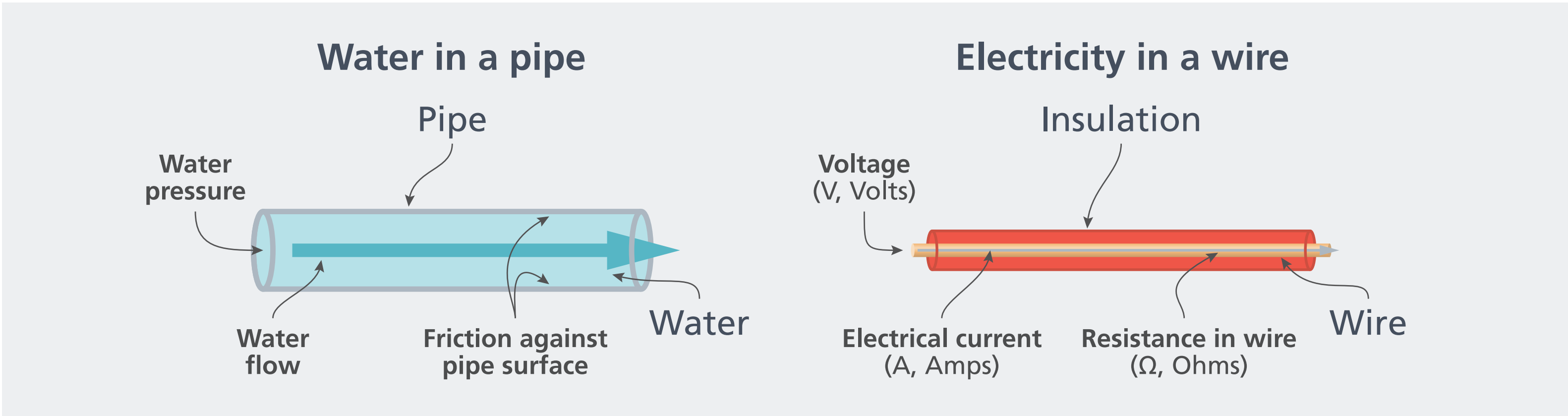


Figure 4-2: Comparison of water pressure with with electrical voltage.

Voltage is closely related to current and resistance by Ohm's Law, which states that voltage is the product of current and resistance. Returning to the water pipe analogy, voltage is equivalent to water pressure, current is the water flow rate, and resistance is friction working against water flow. Thus, an increase in voltage leads to an increase in current, assuming that the resistance of the conductor does not change.

Ohm's Law and Power Law

$E = I \times R$

E = Voltage in Volts

I = Current in Amperes

R = Resistance in Ohms

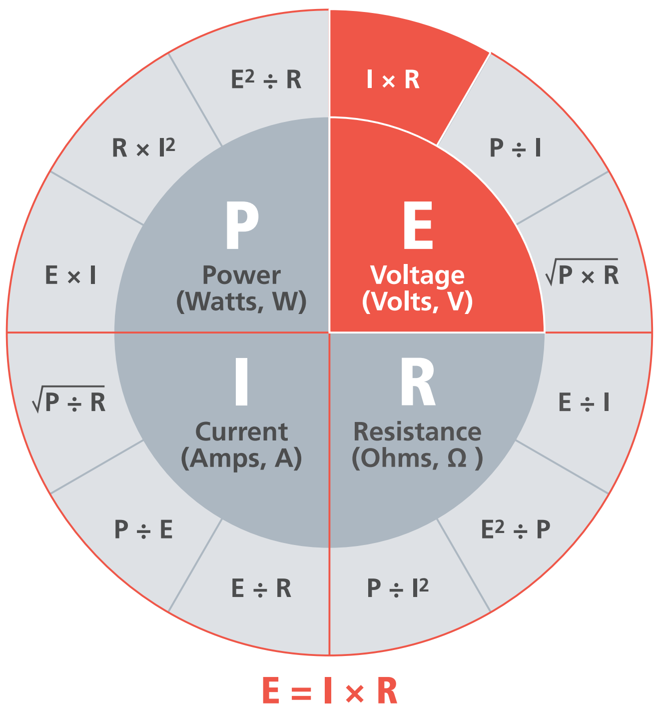


Figure 4-3: Although Ohm's Law is typically represented as E (volts) = I (amps) x R (ohms), we can rearrange the formula to solve for voltage using combinations of measured current, resistance, or power.

What is a voltmeter?

A voltmeter is used to measure the voltage across two points in a circuit. A digital multimeter (DMM) is a common tool that enables technicians to measure voltage in an electrical system. A DMM enables technicians to perform multiple tests with a single tool, such as current measurements, continuity verification, and capacitance testing.

For PV systems, any DMM that technicians use should, at a minimum, be capable of measuring AC and DC voltages and incorporate a clamp meter that can measure current in AC and DC. The ability to measure DC is the biggest differentiator between a DMM that is used in PV applications and one that is intended purely for AC installations. In addition, before a meter is purchased, its DC voltage limits should be verified. Large ground-mount PV arrays commonly have voltages greater than 1000 V DC. Therefore, any meter that technicians use must be capable of measuring these higher voltages, 1500 V DC minimum.

Testing PV voltage with a digital multimeter

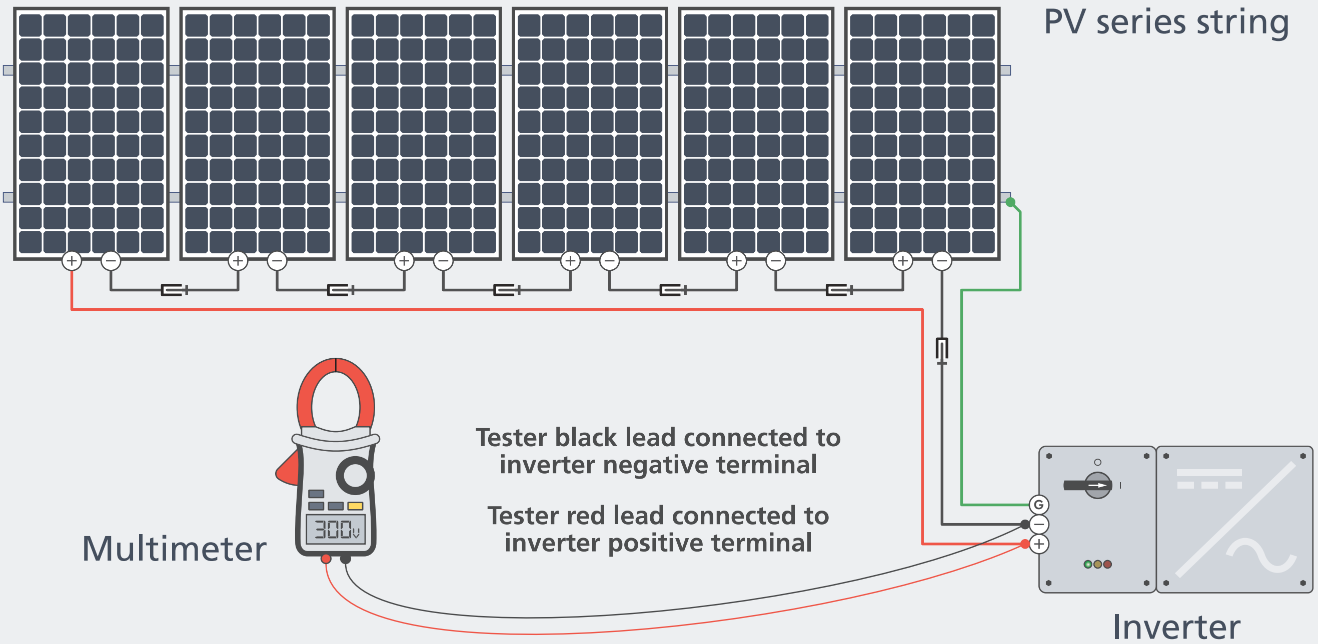


Figure 4-4: A DMM will measure voltage between the two points that the black and red leads are applied. DMMs are used throughout PV systems including to measure the PV array voltage at the inverter.

Basics of I-V curves

An I-V curve is a common graphical method to display the electrical output of PV modules, and it is provided with module product documentation. This curve shows the relationship between a module's current (I) and voltage (V). The following are the key points to consider:

Short-circuit current (Isc) is the point on the curve where the positive and negative leads from a module directly connect. The current is at its highest point, and the voltage is zero. No damage to the module will occur internally, because PV modules are current-limited. The safety risk is when the module leads are disconnected. See the Safety Considerations section of the Current chapter.

Open-circuit voltage (Voc) is when the module leads do not connect to anything, and the circuit is open. The module voltage is at its highest point, and the current is zero.

Maximum power current (Imp) and **maximum power voltage (Vmp)** are the points on the curve where the module produces the maximum power. These readings occur during operation.

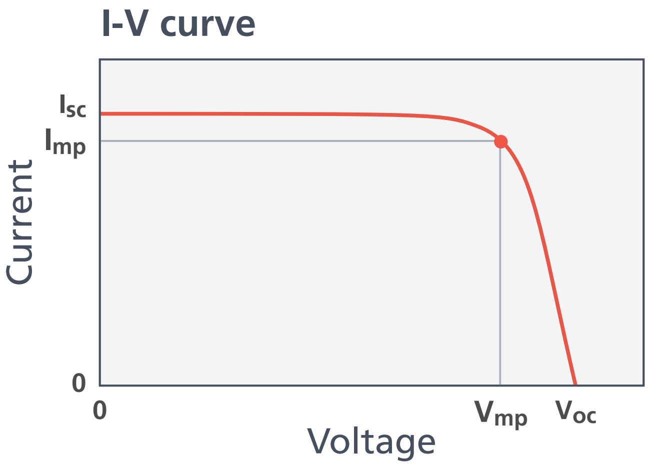


Figure 4-5: A typical PV module I-V curve. The open-circuit voltage (VOC) is the point on the curve with the maximum voltage value and zero current.

Polarity

PV modules produce DC voltage. Meaning, a polarity, or direction, is associated with the power flow. This directional nature of the power means that the positive pole of the modules must connect to the positive pole of the power electronics (DC-to-DC converters or inverters). Wiring the modules backward results in reverse polarity. This condition can cause catastrophic failure of the power electronics connected to the PV array.

Technicians should carefully read voltages at the various connection points within the PV system to detect any reverse-polarity conditions before they become an issue. DMMs display the same numerical value for voltage, regardless of polarity. The difference is that the meter displays a negative sign when reverse polarity is measured. This negative sign may not be obvious, and it can be easy to miss.

Technicians should take the voltage reading with the correct polarity, then switch the meter leads, and recheck the polarity. With this step, the technician is prompted to look for the negative sign on the meter and to verify the polarity. Details for this methodology are in the **Step-by-step voltage measurement instructions** later in this chapter.

Figure 4-6: When meter leads are reversed, a negative sign of the same voltage value verifies proper polarity in each circuit. If a negative voltage value is measured with the leads in the correct position, this indicates that the PV string was connected incorrectly during installation.

Environmental impacts on voltage testing

A DMM enables technicians to measure voltage between any two points in an electrical system. However, environmental conditions affect DC voltage readings for PV systems. Understanding the fundamental voltage characteristics can help technicians evaluate voltage readings in the field.

The technician who runs the tests must record the environmental conditions, including ambient temperature and irradiance, during testing. Comparison of the recorded environmental conditions with future datasets helps with proper analysis. And, in the moment, these conditions are used as a basic check on the measurement. (This check requires some simple math, which is discussed in the next subsection). If the environmental conditions are significantly different from one reading to the next, technicians may draw inaccurate conclusions from the results.

Effect of temperature on PV module voltage

It may seem counterintuitive, but PV module voltage decreases as temperature increases. PV module specification sheets list this relationship as the temperature coefficient, which quantifies the reduction in output voltage for each degree of module temperature increase above the standard test condition (STC) of 25 °C.

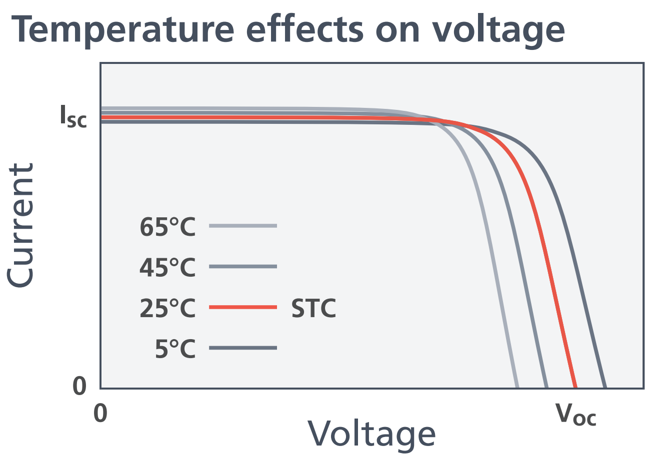


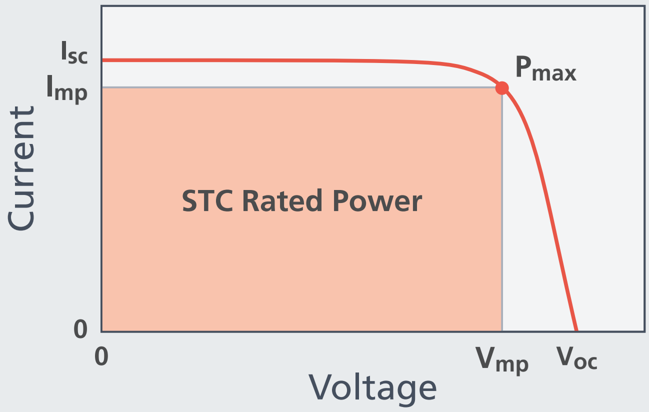
Figure 4-7: Current versus voltage for a typical PV module. Note that the module voltage decreases as temperature increases.

Figure 4-8: A technician measures the module temperature with a temperature sensor integrated into a DMM.

What is STC?

PV modules are lab-tested under fixed standard test conditions (STC) to establish consistent output characteristics. STC specifies a module cell temperature of 25 °C, irradiance of 1000 watts per square meter (W/m²), and an air mass of 1.5. Technicians can measure variances from these values in the field and apply correction factors to verify the proper electrical output.

I-V curve at STC Figure 4-9

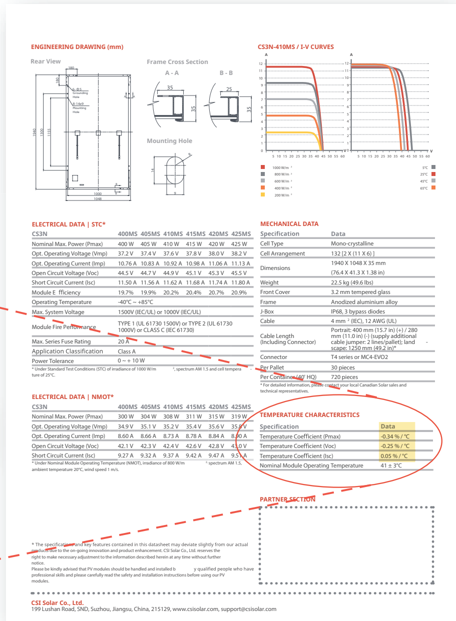


For example, let's look at a 400 W module with a temperature coefficient of –0.25 % / °C. This coefficient tells us that the module voltage output will decrease by 0.25% for each degree above 25 °C. Accordingly, module output would increase by 0.25% for each degree below 25 °C. So, calculating as follows, a module temperature of 50 °C would result in a 6.25% reduction in voltage output from the PV array:

50 °C – 25 °C = 25 °C

25 °C x –0.25 % / °C = –6.25%
(a reduction of 6.25%)

PV module spec sheet Figure 4-10



TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.34 % / °C
Temperature Coefficient (Voc)	**-0.25 % / °C**
Temperature Coefficient (Isc)	0.05 % / °C
Nominal Module Operating Temperature	41 ± 3°C

Effect of irradiance on PV module voltage

Solar irradiance refers to the power per unit area (W/m²) of electromagnetic radiation from the sun. A minimal amount of irradiance is required to generate nearly full output voltage from a PV module. For field measurements, technicians should consider any ambient light sufficient to bring the modules to the full open-circuit voltage.

Types of voltage tests

DC versus AC voltage

The distinction between DC and AC is essential for technicians to know, because both voltage forms are in PV systems. Under DC conditions, voltage is constant, and electrical current flows in a single direction. In contrast, under AC conditions, the voltage oscillates periodically between positive and negative values, and the current flows bidirectionally.

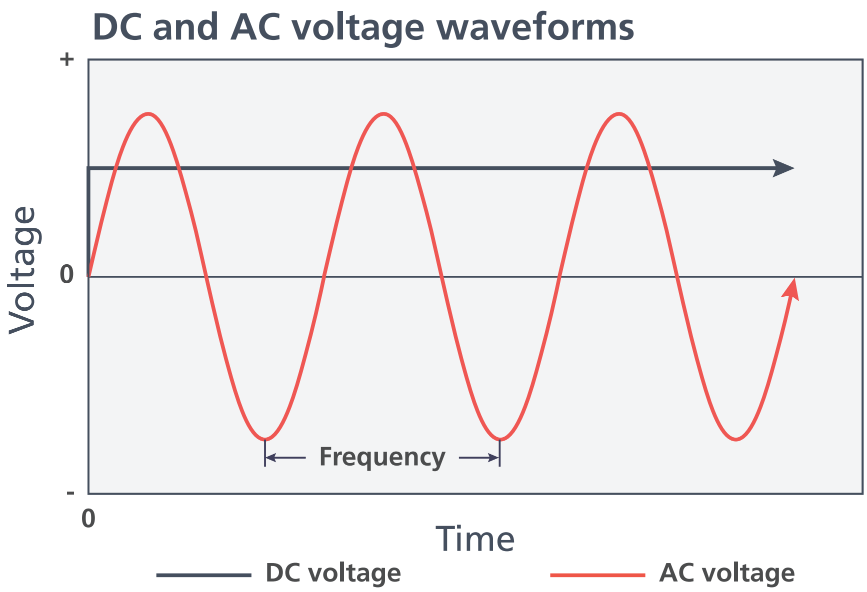


Figure 4-11: DC voltages are constant with respect to time while AC voltages are time-dependent waveforms with a frequency component. The frequency describes the number of complete cycles per second.

Where to take voltage measurements

PV modules produce DC power, but the electric grid and most residential and commercial loads require AC power. The inverter in a PV system acts as the bridge between the AC and DC sides of the system, converting DC power on its input side to AC power on its output side. Thus, DC voltage is most commonly measured on the circuit components that are upstream of the inverter.

Voltage measurements can be taken in multiple locations throughout the PV array. Recording the voltages that are in the inverter or combiner box(es) at the string level is a common starting point. If more granular readings are required, the technician can work toward the array and take readings at the module level.

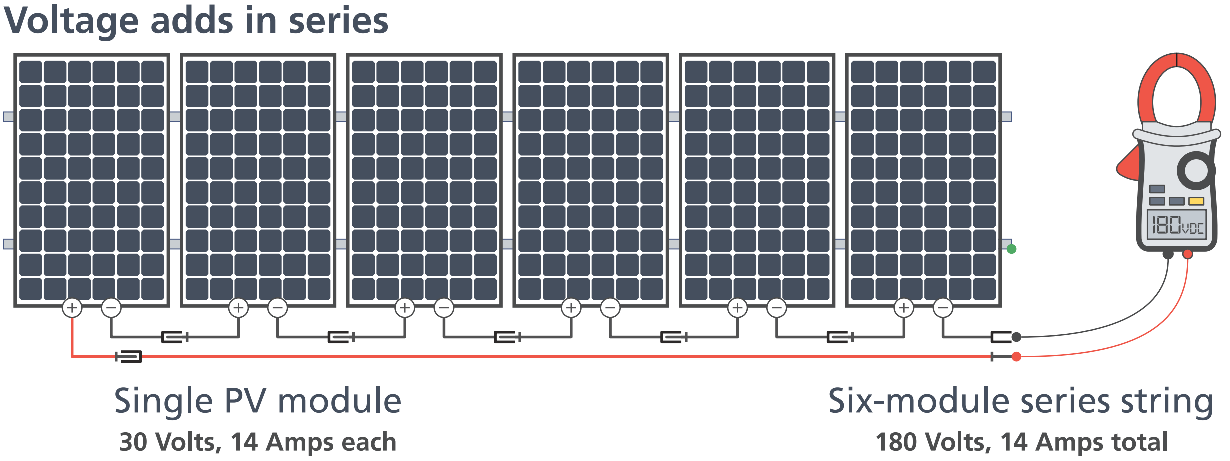


Figure 4-12: Six modules × 30 V / module = 180 volts

Locations to test voltage in PV systems

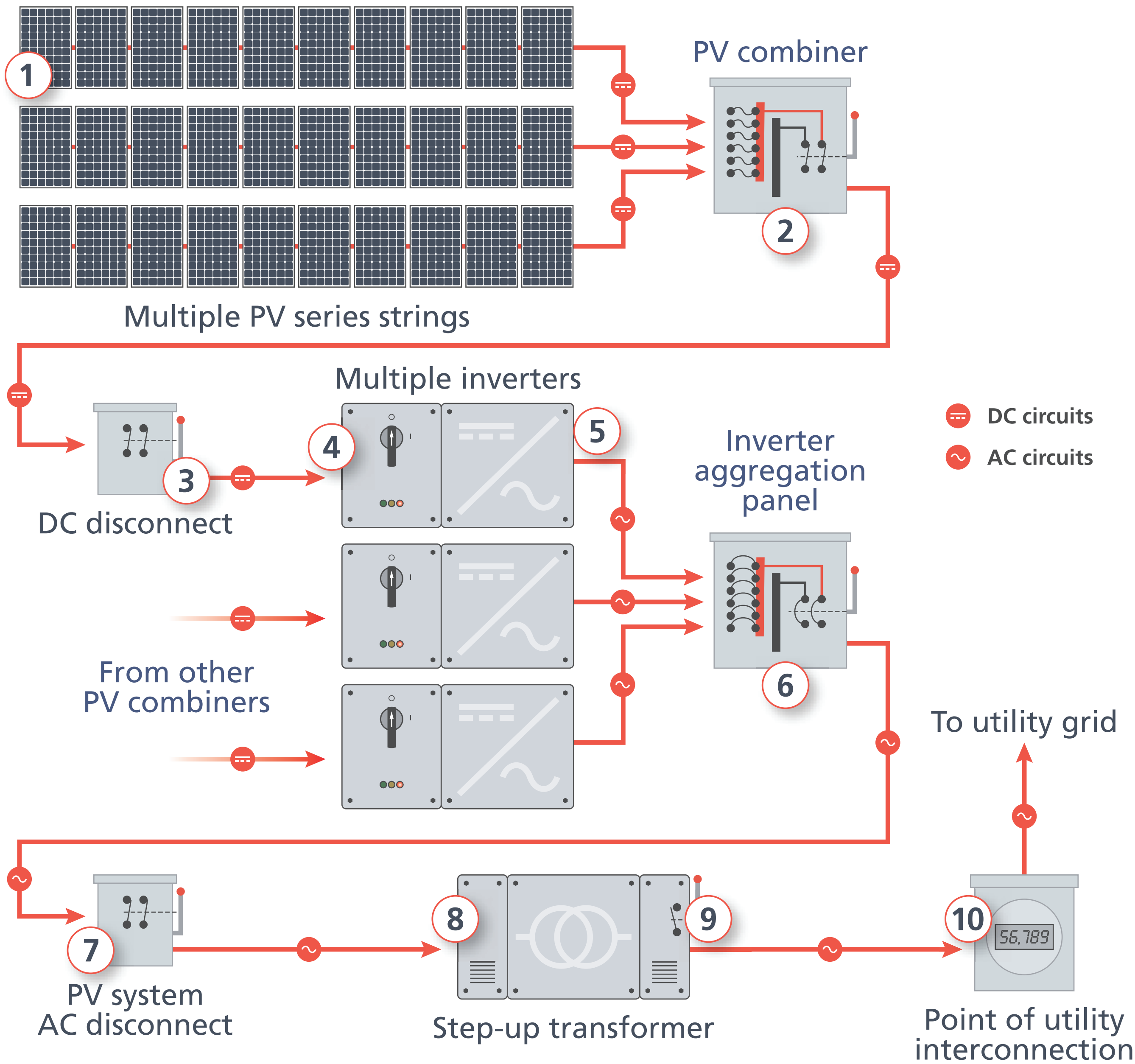


Figure 4-13: Voltage measurements are taken at multiple locations within the PV system.

DC voltage reading locations:

1. **PV module level:** confirms proper output of individual modules.
2. **Combiner box input and output terminals:** verifies proper voltage and polarity. It also confirms the appropriate operation of the combiner box disconnecting means (if present).
3. **Disconnecting means:** verifies proper voltage and polarity. It also confirms the proper operation of the disconnecting means.
4. **Inverter input terminals:** verifies proper voltage level and polarity.

AC voltage reading locations:

5. **Inverter output terminals:** verifies correct voltage at the inverter.
6. **Inverter aggregation panel:** demonstrates proper voltage.
7. **PV system disconnect terminals:** verifies correct voltage.
8. **Secondary side of transformer:** verifies correct voltage for PV inverters.
9. **Primary side of transformer:** verifies correct voltage from utility.
10. **Point of interconnection:** Demonstrates proper utility voltage.

Why measure voltage?

Appropriate testing for PV systems

Voltage measurements are one of the fundamental electrical tests that technicians routinely perform. The presence of voltage helps identify shock hazards and enables technicians to assess potential problems within the system. Technicians take voltage measurements at every stage of a PV installation, through to commissioning and ongoing operations and maintenance.

Codes and standards

Commissioning documents and operations and maintenance documents reference specific codes and standards in the contractual documentation. Applicable codes and standards for voltage tests can include:

Applicable standards for various agencies Figure 14

International Electrotechnical Commission (IEC)
IEC 62446, Sections 6.2, 6.3, and 6.4
IEC 60364-6, Section 6.4
IEC 62109-1, Sections 4.6 and 4.7
IEC 60060-3, Sections 5 through 10
IEC 60904-1
National Fire Protection Association (NFPA)
NFPA 70B (2023) 30.4.5

Contracts between the system owner and the installer dictate the exact tests to be performed. In some cases, the contract references specific standards. In other cases, the agreement may reference only tests without the associated standards.

Figure 4-15: Technician recording voltage measurements at a PV array combiner box.

Figures 4-16 and 4-17: A field technician uses a DMM to confirm expected voltages and polarity in a PV combiner box.

Confirm proper installation at project commissioning

Performing voltage measurements during commissioning provides benchmark data for future reference and confirms proper installation techniques before turning on equipment. By establishing the voltage and polarity readings, technicians can verify that the modules are correctly wired and that they are ready to connect to the other power electronics in the system.

To safeguard against applying improper array voltages to equipment, technicians should take voltage and polarity measurements before commissioning.

Operations and maintenance (O&M) plans

Routine maintenance tests also require voltage measurements. Similar to tests that are performed at commissioning, measuring voltages during maintenance can help identify performance issues or trouble areas within the array. Voltage is typically measured during O&M activities to help technicians identify any potential shock hazards in the equipment that they are working on and to confirm the components' de-energisation.

Upon completion of O&M activities, the system is recommissioned, and the technicians use voltage measurements similar to the methods for initial commissioning.

Troubleshooting

Voltage measurements help identify multiple failure modes within an array. The measurements can locate DC circuits that are wired backward (or reverse polarity), open circuits, and ground faults. Technicians will typically perform these activities when a known issue arises within the array, and the system is underperforming. The **Ground-Fault Testing chapter** provides more information about ground-fault testing with DMMs.

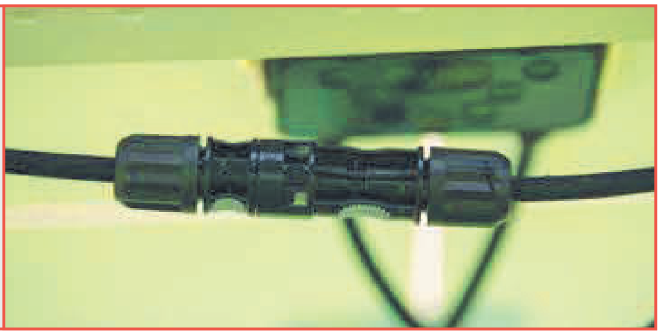
Safety considerations

Voltage safety hazards

PV systems are unique in that AC and DC voltages are present on every job. The PV modules produce DC voltage, and they connect to inverters that use the DC input to generate AC voltage for connection to the utility.

CAUTION!

Before opening any touch-safe fuse holders or PV quick connects, technicians should always verify with a DC-rated clamp meter that no current is flowing in the circuit.



The voltage between two points alone is insufficient to induce the flow of electrical current. A path must form to allow electrons to flow. Thus, voltage-related hazards are most dangerous when:

- **Nonzero voltage is measured between two points, and**
- **A path exists for current to flow between the two points**

It is crucial to note that the path for current to flow does not have to be within the electrical circuit. For example, suppose a technician touches an exposed live wire with one hand and a metallic enclosure with the other. In that case, the difference in voltage between the two points is nonzero, and current can flow from the live wire through the technician and into the metallic enclosure.

Shock paths through the body

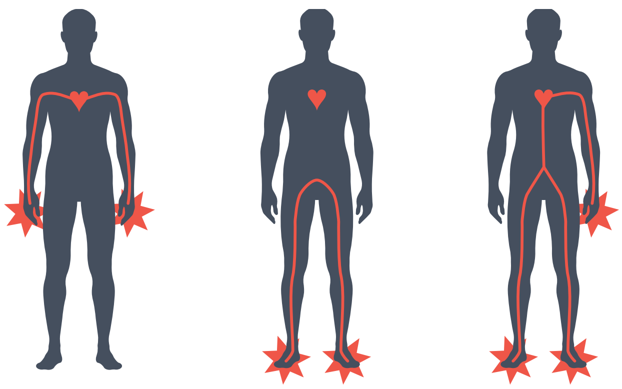


Figure 4-18: A potential shock hazard for technicians is if they complete the current path. The proper use of personal protective equipment (PPE) and voltage measurements helps reduce the risk of shock.

How to take voltage measurements

Proper planning for and understanding of the required test methods support safe and correct test execution.

When preparing to commission a system, technicians should identify all circuits for testing before arriving onsite. While testing, technicians should use a site map and sequential operation to maintain proper recordkeeping. Collecting data within the tools expedites the process, but technicians must be aware of the data collected and must verify that the measured circuits match the plans. The minimum PPE required when performing voltage measurements include high-voltage safety gloves and safety glasses.

Figures 4-19 and 4-20: Technician wearing appropriate PPE while taking voltage measurements in a PV combiner box.

Step-by-step instructions for DC (PV) circuits

All the steps that are presented here are for open-circuit (non-operating) voltage testing. The Production Verification chapter discusses the testing procedure for maximum power voltage (an operating system).

1. Document environmental conditions

This step is crucial to establish accurate trend lines. The environmental conditions affect the test results. Properly accounting for the environmental conditions better informs the data that is collected. For future reference, document the time, date, ambient temperature, module temperature, and irradiance. You can use the temperature values to normalise the collected data for analysis in trend lines.

2. Shut down and perform lockout/tagout (LOTO)

Place all solar equipment (inverters, DC disconnects, combiner boxes, etc.) in the open (off) position and use LOTO methods to maintain a safe working environment.

PV modules produce voltage whenever ambient light is present. Therefore, until modules are isolated, the supply side of all PV circuits has voltage present even when the connected equipment is in the open (off) position. The load side of the terminals may also have voltage present, depending on the exact configuration of the equipment.

Before opening any PV quick connects or touch-safe fuse holders, use a DMM that can measure DC current on all PV DC circuits (detailed step-by-step instructions are included in the Current chapter). Faults in the wiring or miswired PV modules can result in current on conductors, even when the disconnects are in the open position. Opening quick connects or touch-safe fuse holders in these scenarios exposes you to shock and fire hazards and can damage the equipment.

3. Measure module temperature

By using an infrared thermometer or the temperature probe on a DMM, measure the temperature of a PV module from the array under test. The best method is to take the temperature from the back of a module, near the center. A temperature measurement at this location gives the most accurate reading. Use this value to adjust the voltage reading that is obtained in the following steps. Check temperatures periodically to maintain good data collection.

Figure 4-21: PV module temperature is measured by making direct contact with the backside of the module under test. A thermal camera may be used, or a temperature sensor that integrates with the technician's DMM as is shown in Figure 4-8.

4. Measure PV voltage

Voltage measurements typically begin at the string level in a combiner box or in an inverter's wiring compartment. Insert the meter's leads in the corresponding receptacle (red and black). Select the DC voltage setting on the DMM above the expected voltage at the location based on the system specifications and documentation. Verify that the meter can measure the highest expected voltage for the site.

Place the red lead from the meter to the positive terminal of the string that is being tested, and place the black lead to the negative terminal. The meter displays a voltage measurement. Verify that the reading is within the expected range based on the plans and current temperature.

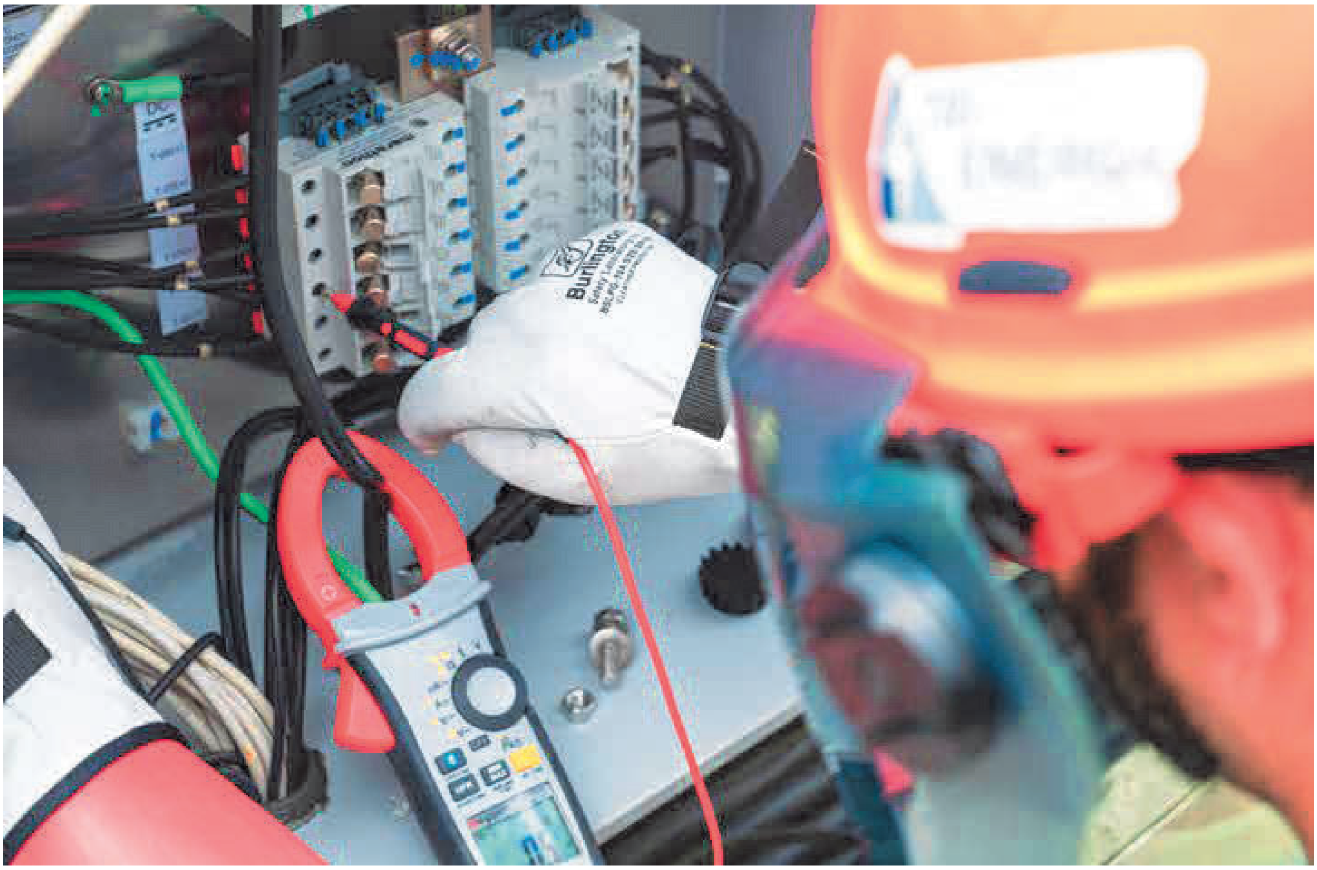
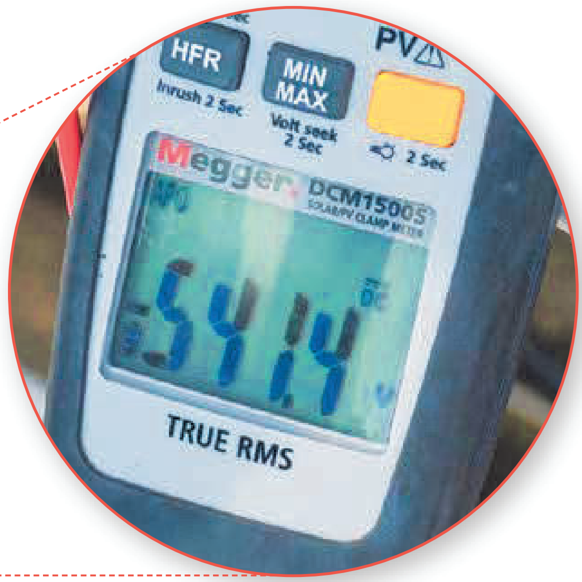


Figure 4-22: By applying the red lead (shown) and black lead (not shown) at different terminals in the PV combiner box, the technician can measure voltage down to the individual string level.

5. Check polarity

A best practice is to confirm polarity by then placing the DMM leads in opposite locations from the initial reading. Place the black lead on the positive terminal and the red lead on the negative terminal. The DMM displays the same voltage as before, but there should be a negative sign on the display, indicating reverse polarity. Perform this test to confirm the correct polarity by looking for the negative symbol.

Figure 4-23: Verify correct polarity by swapping the lead locations and re-measuring voltage. The DMM should display the same voltage as the initial reading but with a negative sign.



6. Record data

Record the voltage value as measured by the DMM. The results should be collected and stored for future reference.

7. Evaluate results in the field

Take a moment to review the readings and verify that the readings are within reason. Many installation issues are identified by a voltage reading, and you can identify and fix problems in real time. Problems that are commonly encountered include:

- **The voltage reading is lower than expected by a few percentage points.** Verify the temperature reading of the module and the anticipated change in voltage. Modules can continue to heat up, and if the temperature measurement is not accurate, the voltage readings may not correspond to expectations.

- **The voltage reading exceeds expectations, or the DMM reads "OL" (over limit).** Verify that the measured string does not have too many modules wired in series.

- **The voltage reading shows reverse polarity.** This situation is potentially dangerous. Strings that are wired in reverse polarity may short out the other connected strings or damage power electronics. This condition is unlikely to damage any modules, but the risk of electrical arcing appears when you disconnect the strings from each other. Exercise extreme caution in this scenario. Refer to the Electrical Safety chapter for additional information.

- **The voltage reading shows zero volts.** This reading should cause an immediate pause and a call for caution! A zero reading can be caused by a blown fuse, or it could mean that a short is in the circuit and current is flowing in the conductors. Before you open any touch-safe fuse holders or PV quick connects, you must verify that no current is flowing through the circuit. Refer to the Electrical Safety and Current chapters for additional information.

Figure 4-24: In field data evaluation is important to confirm safety and performance.

Step-by-step Instructions for AC circuits

All the steps that are presented here are for AC voltage testing in PV systems. These circuits are tested similarly to the methods that are used for typical AC circuits.

1. Document environmental conditions

Record the conditions observed, such as time, date, temperature, and the general state of the equipment that is under testing. This documentation will be necessary when comparing against future test results to better evaluate the system's condition. The AC voltage readings are not affected by temperature the way that PV readings are, but it is good practice to document the conditions for these tests.

2. Shut down and perform lockout/tagout (LOTO)

Place all solar equipment (inverters, DC disconnects, combiner boxes, etc.) in the open (off) position and use LOTO methods to maintain a safe working environment.

3. Measure AC voltage

Test the PV system's AC connections in the same manner as other AC circuits. This includes measuring and documenting all phase-to-phase, phase-neutral, and phase-ground measurements within inverters, overcurrent devices, and disconnects.

4. Take additional AC measurements

Repeat AC voltage readings for all connections, up to and including the AC interconnection point.

5. Record data

Record the voltage value as measured by the DMM. The results should be collected and stored for future reference.

6. Evaluate results in the field

Take a moment to review the readings and to verify that the readings are within reason. Many installation issues are identified by voltage readings, and you can identify and fix problems in real time.

Figure 4-25: AC voltage measurements must be recorded at all connection points from the inverter output to the utility point of interconnection.

Page intentionally left blank.