Electrical Testing Standards Guide

Megger

Chapter 5: Measuring current

Introduction

Overview

Current represents one of the most serious safety hazards in an electrical circuit, and it must be accurately measured when working on PV systems. These measurements enable technicians to assess the system performance and better identify potential hazards. Field technicians routinely measure current during construction, commissioning, and ongoing maintenance activities.

The presence of direct current (DC) and alternating current (AC) in PV installations presents unique challenges for field technicians. Technicians must accurately measure current values on both sides of the system. On the DC side, technicians must measure for current before opening isolation devices such as touch-safe fuse holders and quick connects. During system operation, measurements on both sides are required to confirm proper production. Digital multimeters (DMMs) that can read both DC and AC are used for these measurements.

Technicians use current measurements to confirm proper system operation, which is covered in the **Performance Verfication** chapter. More commonly, current measurements verify that zero current is flowing and the circuit is safe for interaction. These tests are often the first step in more complicated troubleshooting processes, and will be the focus of this chapter.

Figure 5-1: PV technicians use handheld digital multimeters to measure DC and AC circuits in PV systems.

Electrical current concepts explained

Electrical current quantifies, in units of amperes (A), the flow of electrical charge that is moving through an electrical conductor. To illustrate, imagine a long pipe with water flowing through it. The water flow rate (gallons per second) through the pipe is analogous to the electrical current (charge per second) that is flowing through a conductor. A nonzero current measurement indicates that electrical current is flowing within the conductor.

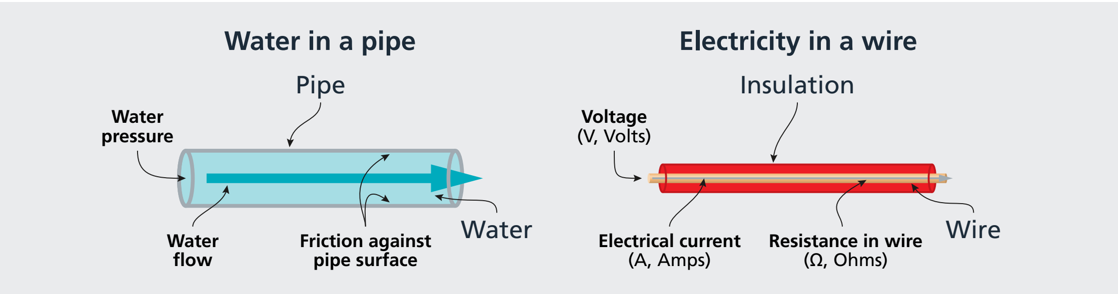


Figure 5-2: Comparison of water flow with electrical current.

Current is closely related to voltage and resistance by Ohm's Law, which states that current is proportional to voltage and is inversely proportional to 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

$I = E \div R$

I = Current in Amperes

E = Voltage in Volts

R = Resistance in Ohms

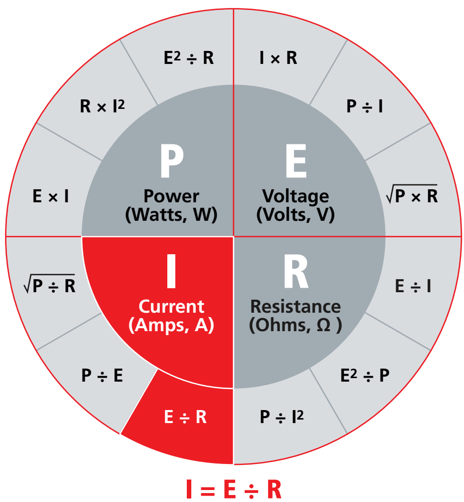


Figure 5-3: While Ohm's Law is typically represented as E(Volts) = I(Amps) X R(Ohms), we can rearrange the formula to solve for Current as I(Amps) = E(Volts) / R(Ohms).

Figure 5-4: A clamp meter measures the current flowing through the conductor or bundle of conductors enclosed within the clamp.

What are ammeters and digital multimeters?

An ammeter measures the current, or amperes, in a circuit. Given the makeup of PV circuits, technicians typically use a digital multimeter (DMM), which can measure both DC and AC. Appropriate DMMs include a clamp meter in their design. The clamp feature makes current measurements as straightforward as possible. Technicians simply close the jaws around a conductor to measure the current that is flowing within it.

Testing PV circuit current with a digital multimeter

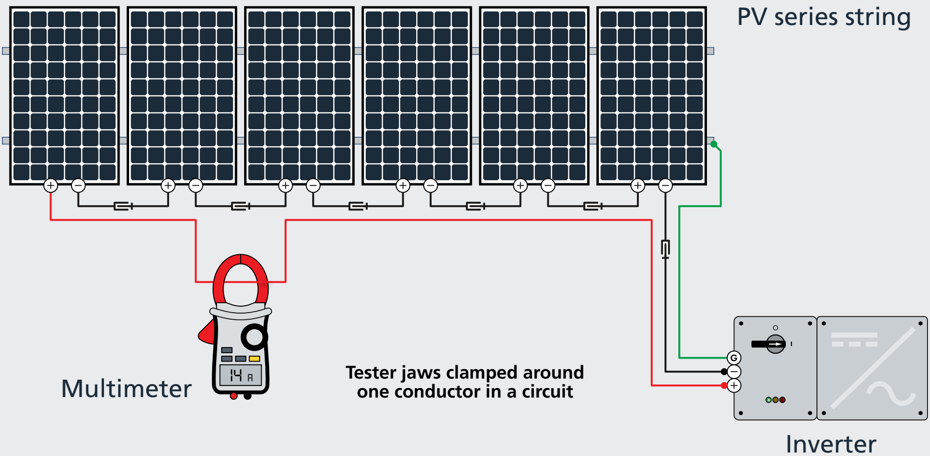


Figure 5-5: A DMM will measure current in a coductor around which the jaws are clamped. DMMs are used throughout PV systems including to measure the PV array string current to the inverter.

Not all DMMs with a clamp meter can measure direct current, however. To read direct current, a specific type of clamp meter, a Hall Effect meter, is required. Conventional alternating current can be measured with either a Hall Effect meter or a current transformer (CT) meter. CT meters are less expensive and are a standard feature for many electrical measurement tools. Technicians should be sure to verify that they have the proper meter type before they measure DC.

Figure 5-6: A handheld DMM with a Hall Effect clamp meter and test leads will be able to measure direct and alternating current, as well as voltage.

Basics of I-V curves

An I-V curve is a graphical representation of the operation of a solar module. The graph visualises the relationship between a module's current (I) and voltage (V), and it is typically included in the module datasheet. Three points along the curve are important to know:

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. Refer to the Safety Considerations section in this chapter.

Open-circuit voltage (Voc) is the point on the curve where 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.

Current at maximum power (Imp) and **Voltage at maximum power (Vmp)** are the points on the curve where the module produces the maximum power. These readings occur during operation.

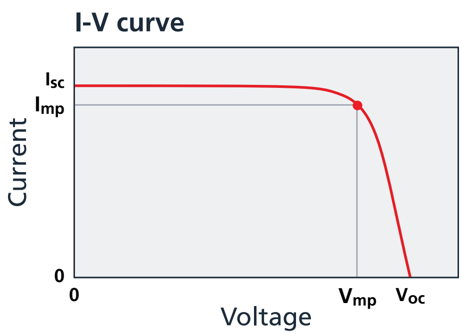


Figure 5-7: A typical PV module I-V curve. The short-circuit current (Isc) is the point along the curve where the current is maximum and the voltage is zero.

Environmental impacts on current testing

An ammeter measures the current that is flowing within a conductor. However, environmental conditions affect the current readings for PV systems. Irradiance, or intensity of the sunlight striking the module, significantly affects the module's current output. As such, technicians must record the irradiance value when they record amperage readings during commissioning and power production verification activities.

Figure 5-8: Irradiance is read with an irradiance meter placed on the same plane of the PV modules that are under testing. Technicians record the value and use it to calculate the actual current flow against the STC conditions.

Effect of irradiance on PV module current

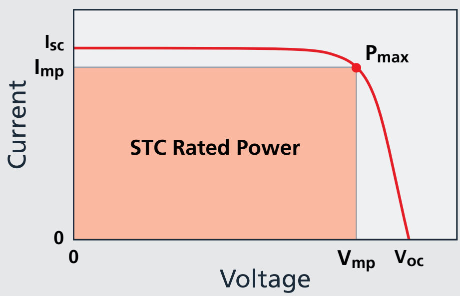
Solar irradiance refers to the power per unit area (W/m²) of electromagnetic radiation from the sun. As you might intuitively guess, irradiance and PV module current directly correlate: Higher irradiance results in higher current output from the module and, therefore, higher power output. This relationship is best illustrated by the module's current versus voltage (I-V) curves, which show increasing module current and power output as conditions become sunnier.

Irradiance is measured with an irradiance meter, and the results are used to adjust the actual measured current to the STC current value. Small atmospheric changes such as water vapor, cloud cover, and elevation can have a significant impact on irradiance. Therefore, technicians must use an irradiance meter to measure the exact values accurately. The meter must be placed on the same plane as the modules that are being tested. Most testing protocols dictate that irradiance values be no less than 500 W/m². Values less than 500 W/m² can result in erroneous readings and may not reflect the actual array production.

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. The value 1000 W/m² is considered "one full sun" and can be imagined as a clear sunny day at sea level at noon.

I-V curve at STC Figure 5-9



Irradiance effects on current

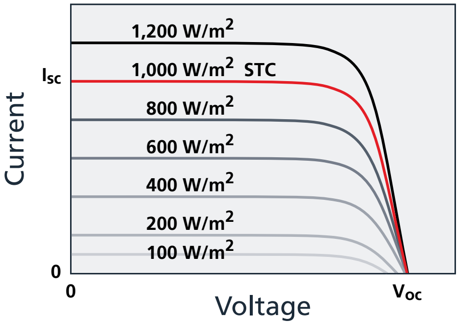


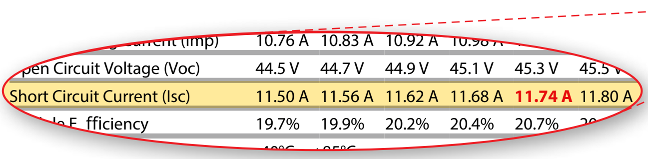
Figure 5-10: A module's Isc is directly proportional to the intensity of sunlight on the module. Note that module current may rise above the Isc value listed on the data sheet, which was measured at STC.

To capture a more accurate snapshot of PV array performance, technicians should measure and record irradiance during tests. Irradiance measurements can be adjusted to STC values to estimate Isc. For example, if irradiance is measured at 850 W/m^2 and the modules are rated for 11.74 A Isc, a technician may estimate the real-world Isc to be around 9.39 A, as shown in the two calculations below:

(measured irradiance) ÷ (STC irradiance)
= (850 W/m^2) ÷ (1000 W/m^2) = 0.85

(irradiance ratio) × (STC-rated Isc)
= (0.85) × (11.74 A) = 9.39 A

PV module spec sheet



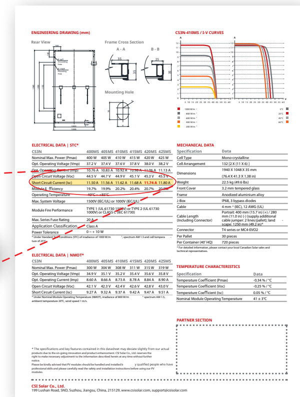


Figure 5-11: The Isc value provided in the module datasheet can be recalculated with onsite irradiance data.

Effect of temperature on PV module current

PV modules, like all electronics, are sensitive to changes in temperature. At an atomic level, higher temperatures excite the electrons within the semiconductors that make up the PV modules' core. Higher temperature leads to an increase in output current from the module.

However, a slight increase in module current is considered negligible in current readings and is overshadowed by an associated decrease in module voltage. Because power is the product of current and voltage, a slight increase in current and a large reduction in voltage result in an overall decrease in power output. In general, PV modules prefer to operate in cold, sunny conditions.

Types of current tests

DC versus AC

The distinction between DC and AC is essential for technicians to understand, since both forms of current will be present in PV systems. Direct current flows in a single direction. Alternating current flows bidirectionally, oscillating between positive and negative values. DC values have a single component (Amps) while AC values have two components (Amps and frequency of oscillation).

DC and AC waveforms

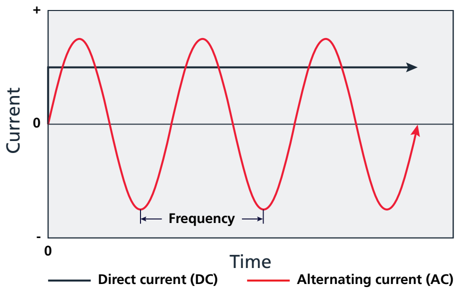


Figure 5-12: Direct currents are constant with respect to time while alternating currents are time-dependent waveforms with a frequency component. The frequency describes the number of complete cycles per second.

Current 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 is most commonly measured on the circuit components that are upstream of the inverter. Technicians are required to measure AC from the inverter all the way to the utility point of interconnection.

Where to take current measurements

Current measurements are typically taken on both the DC and the AC sides of the PV system at locations where conductors terminate. Typical examples are PV combiner boxes, inverter wiring boxes, inverter output connections, and AC distribution equipment. Technicians must measure and record the amperage values at the string and system level level; rarely are measurements acquired at the module level.

Current adds in parallel

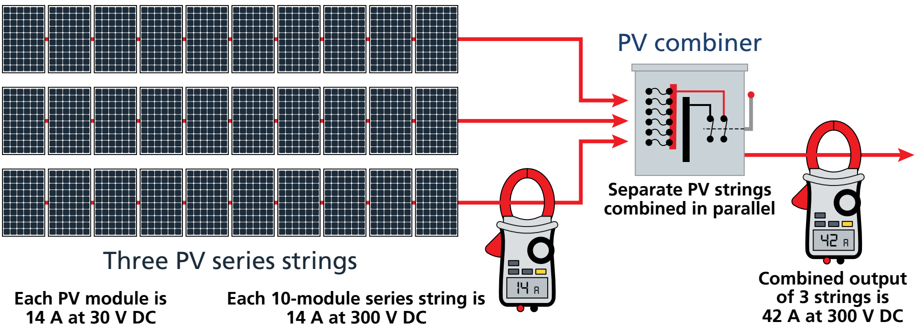


Figure 5-13: Current adds in parallel and voltage adds in series: Three series strings × 14 A each = 42 A combined in parallel.

Locations to test current in PV systems

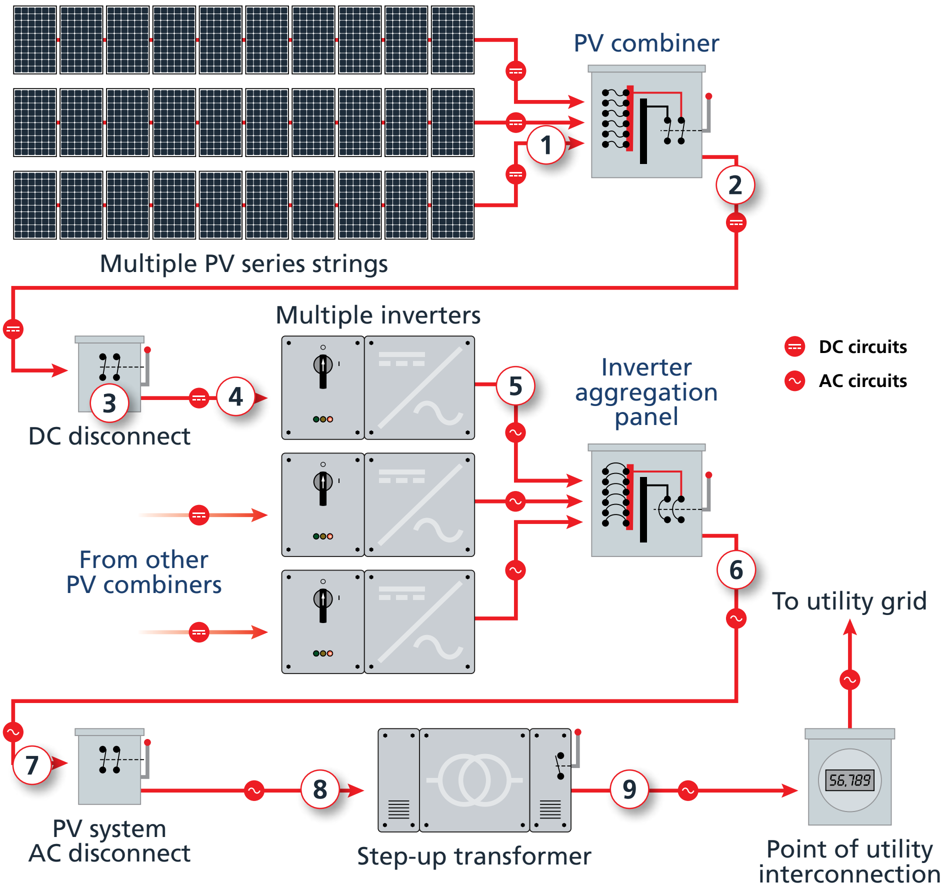


Figure 5-14: Amperage measurements are taken at multiple locations within the PV array and on the utility side of the inverter.

DC reading locations:

1 PV series strings
2 Combiner box output circuit
3 Disconnecting means
4 Inverter input circuit

AC reading locations:

5 Inverter output circuits
6 Inverter aggregation panel output
7 PV system disconnect
8 Secondary side of transformer
9 Primary side of transformer / point of interconnection

Why measure current?

Appropriate testing for PV systems

Current measurements are one of the fundamental electrical tests that technicians routinely perform. Current flow helps identify shock hazards and enables technicians to assess potential problems within the system. Technicians take current measurements at every stage of a PV installation, through to commissioning and ongoing operations and maintenance. The rest of this chapter will focus on taking current measurements to verify that circuits are open (not conducting current) so technicians can safely perform additional troubleshooting tests. The **Performance Verification chapter** overviews the current measurements that are taken on closed, or operational circuits.

Codes and standards

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

Applicable standards for various agencies Figure 5-15

International Electrotechnical Commission (IEC)
IEC 62446, Sections 5.3 and 6.5
IEC 62109-1, Sections 4.6 and 4.7
IEC 60904-1, Sections 3 and 4.1
National Fire Protection Association (NFPA)
NFPA 70B (2023) 30.4.5

Contracts between the system owner and the contractor 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.

Confirm proper installation at project commissioning

Performing current measurements during commissioning provides benchmark data for future reference and confirms proper installation techniques before turning on equipment. As a part of the system checks, technicians should take current measurements to confirm that no current flow is present before switching on the system. This check informs the technicians that no strings were inadvertently shorted to others.

Operations and maintenance (O&M) plans

Current measurements are taken as part of routine maintenance tests to confirm proper power production while the system is operating. Technicians use ammeters during the recommissioning process of O&M operations to verify proper wiring before reenergizing equipment.

Electrical current safety hazards

A common electrical safety saying is "Current kills, not voltage." Current causes sparks and fires, can freeze muscles, and can stop hearts. A minimal amount of current can be deadly.

Returning to Ohm's Law, however, the current does not flow on its own. Voltage must be present to induce current flow, and the resistance level determines the current's exact value. For example, if the voltage between two points is measured at 100 V and the electrical resistance is measured at 10 ohms (Ω), the current flowing between the two points is 10 A. If resistance increases to 1,000 Ω, the current decreases to 0.1 A.

It is crucial to note that the path for current to flow does not have to be within the electrical circuit. For example, suppose that a technician touches an exposed live wire with one hand and a metallic enclosure with the other hand. The difference in voltage between the two points is nonzero, and current flows from the live wire through the technician and into the metallic enclosure. The amount of resistance dictates the amount of current that flows in the path—in this case, the resistance of the technician and their clothes. Technicians who are wearing personal protective equipment (PPE) have higher resistance to electrical current, and therefore the potential for shock hazard is reduced.

Shock paths through the body

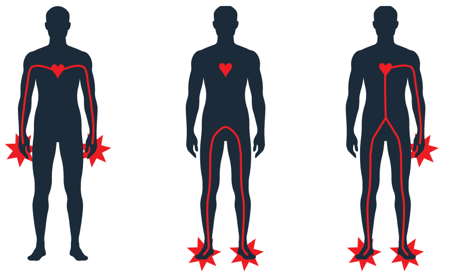


Figure 5-16: Three pathways for current through the human body. Current passing through one hand travels through the heart and lungs. Currents above a certain threshold, described in Figure 5-17 below, may cause the muscles in a technician's hand to freeze in place, forcing the technician to hold onto the live wire until the source is turned off.

Effects of electrical current on the human body Figure 5-17

Bodily effect	Direct current (DC)	60 Hz AC	100 KHz AC
Slight sensation felt at hand(s)	0.6 – 1.0 mA	03 – 0.4 mA	5 – 7 mA
Threshold of pain	3.5 – 5.2 mA	0.7 – 1.1 m	8 – 12 mA
Painful, but voluntary muscle control maintained	41 – 62 mA	6 – 9 mA	37 – 55 mA
Painful, unable to let go of wires	60 – 76 mA	15 – 16 mA	63 – 75 mA
Sever pain, difficulty breathing	60 – 90 mA	15 – 23 mA	63 – 94 mA
Possible heart fibrillation after 3 seconds	—	500 mA	100 mA

To understand how much electrical current may be dangerous, it is essential to know the risks that are associated with specific amperages. Figure 5-17 shows approximate current values and their effects on the human body. Amperages above 6 milliamperes (mA) are considered hazardous and can result in painful shocks and loss of muscle control. Most individual PV modules produce more than 10 A (10,000 mA), and downstream components such as string combiner boxes regularly operate under currents as high as hundreds or thousands of amps.

Muscle mass, body chemistry, clothing, and the presence of moisture all affect the values in Figure 5-17. For example, a 130-pound (60 kg) technician wearing PPE on a cloudless day will experience a different shock hazard than a 225-pound (100kg) technician working on the same circuit during a steady rainfall will.

"Test before you touch" should be the mantra of any technician who is working on any electrical system, but especially on PV systems. Because the PV array is expected to produce power as long as the sun is shining, it is even more critical for technicians to be familiar with testing procedures.

CAUTION!
Before opening any PV quick connects or touch-safe fuse holders, use a DMM to measure DC on all PV DC circuits. 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.

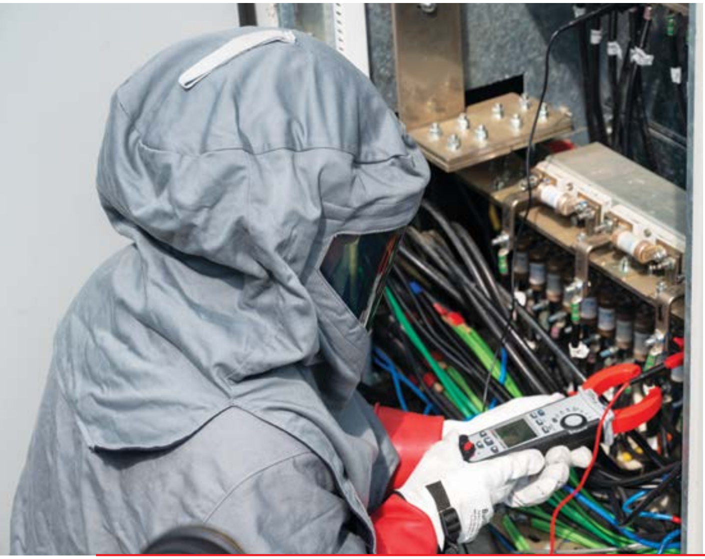


Figure 5-18: PV systems can operate at dangerously high amperages. Technicians should be aware of the risks associated with the expected system current and voltage, and should wear appropriate PPE.

How to take current measurements

Proper planning for and understanding of the required test methods support safe and correct test execution. These tests go hand in hand with the voltage measurements that are described in the **Voltage and Polarity** chapter.

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. As a minimum for PPE, the technician needs a clamp meter to perform the tests, high-voltage safety gloves, and safety glasses.

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

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 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

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, and module temperature. You can use the temperature values to normalise the collected data for analysis in trend lines.

Figure 5-19: Measurements taken without context are less useful in the long run. Technicians should document the environmental conditions present during every site visit.

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. When you are testing PV circuits, only open load-break-rated disconnects. Do not open touch-safe fuse-holders or PV module quick connects..

3. Measure and document irradiance

Use an irradiance meter to measure the sunlight intensity. When you are measuring operating conditions, ideally, the irradiance is stable and above 500 W/m^2. If the irradiance conditions are variable, to obtain accurate readings, you must record the irradiance and current values simultaneously.

Figure 5-20: PV module current is directly proportional to the irradiance striking the module. The irradiance meter should be used at the same angle as the modules to improve measurement accuracy.

4. Measure amperage of individual circuit conductors

PV circuits must be measured individually to obtain accurate readings. When you measure multiple conductors simultaneously, the current is additive if it is in the same direction. If the current flows in opposite directions, the meter reads the difference between the two. Therefore, for circuits that produce equal but opposite amperage, the reading is zero, which may cause you to believe that there is no current flow.

Figure 5-21: Conductors may be tightly bundled inside the combiner box or inverter. Technicians should be careful to isolate each conductor one at a time to avoid cross-currents that could impact measurement accuracy.

Figure 5-22: Technicians should record and store all measurement data. Keep detailed notes on any environmental conditions or equipment damage that may impact the data.

You must perform this step before you open non-load break isolation devices, such as touch-safe fuse holders and PV quick connects. If you fail to confirm zero current flow and open these devices, an arc is pulled, producing a shock hazard, a potential fire, and inevitable equipment damage.

5. Record data

Record the current and irradiance values as measured. 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 an amperage reading, and you can identify and fix problems in real time. Problems that are commonly encountered include:

- The amperage reading is lower than expected. Verify the irradiance reading of the module and the anticipated change in current. Changes in irradiance can have a significant impact on the current values.

- The current reading exceeds expectations. Verify that only a single string was measured.

- Current is measured on a circuit that is expected to have none. This situation is a huge concern and must be treated with care. If multiple PV strings are shorted out, the only safe way to disconnect them is with a load break device or to wait until nighttime when no current or voltage is present.

- The current reading shows zero amps. Depending on the scenario, this situation may be expected as verification that the PV system is not in operation. If current flow is expected, this reading indicates a break in the circuit, and further investigation of the circuit conductors is required.

Step-by-step instructions for AC circuits

All the steps that are presented here are for AC testing in a PV system. 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 amperage readings are not affected by temperature the way that PV voltage 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 amperage

Test the inverter's AC connections like you do for other AC circuits. Document all phase-to-phase, phase-neutral, and phase-ground measurements.

4. Take additional AC measurements

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

5. Record data

Record the amperage 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 current readings, and you can fix problems in real time.

Figure 5-23: Current measurements should be verified at the PV system AC disconnect.