

Keysight Technologies

# Installation and Maintenance of Solar Photovoltaic Systems

Using handheld and benchtop solutions  
for solar energy applications

Application Note



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## 1. Introduction

This application note introduces the test solutions—comprising Keysight ruggedized handheld and benchtop measuring instruments—for the installation and maintenance of solar photovoltaic (PV) systems. This system is designed to harness solar radiation and to convert it to electricity. Solar radiation is an enormous source of renewable energy. In fact, the Earth receives nearly 4000 kWh of energy from the sun. By harnessing just 5% of this energy, the electricity generated would be sufficient for the current worldwide energy requirement [1].

Solar energy usage is currently growing at an exponential rate, and solar energy could be the world's largest source of electricity by 2050. According to the technology roadmap of the International Energy Agency (IEA), solar PV systems could generate up to 16% of the world's electricity together with solar thermal electricity from concentrating solar power (CSP) plants could provide another 11% by 2050 [2].

The potential for generating electricity from sunlight is enormous, and Keysight is enabling this potential with its range of measuring instruments for the installation and maintenance of solar PV systems.

### Solar power ecosystem

Anyone planning to set up a solar PV system is spoilt for choice when selecting solar components from the many suppliers available. Companies that provide solar components are matured businesses with an end-to-end global supply chain market. These companies provide solar components, which comprise solar panels, cables, interconnects, batteries, battery chargers, inverters, smart utility meters, transformers, electrical safety relays, switches, and more.

### Markets for solar power generation

The following are the markets for solar power generation:

- Residential
- Commercial and Industrial
- Power Providers

### Solar power generation for residential

In the residential market, countries that implement feed-in tariff (FiT) policy programs generally experience tremendous growth. Customers in this market install their solar panels on the roofs (typically sloped roofs) of their homes, and each home usually generates about 1 kW to 10 kW of power.

In urban areas under the FiT policy programs, customers grid-tie their home solar system setup. By doing so, they can either sell all their generated solar power to the utility company or sell only the nett excess solar power (minus internal load usage) to the utility company. Houses in the rural areas tend to add battery storage to their solar PV system setup for their own power usage.

## Solar power generation for commercial and industrial

In the commercial and industrial market, solar PV systems are gaining popularity because they offset business-operating expenses (after breaking even from the cost of setting up the system). By installing solar PV systems in their buildings, companies have the opportunity to be socially responsible and to present themselves as environmentally friendly companies.

The typical setup in this market is to install solar panels on flat or low-sloped roofs. In some setups, the solar panels are turned into carpark shades (see Figure 1). The power generated in this market can range from more than 10 kW to a few multi-MW. The solar PV systems are normally grid-tied to utility companies.



Figure 1. Solar panels at the carpark of Keysight Technologies, Santa Rosa, CA.

## Solar power generation for power providers

In the power provider market, generating solar power is its main business. The power generated typically ranges from multi-MW and more. The solar PV systems are more sophisticated and are normally equipped with advanced monitoring systems, controls, and remote shut-off capabilities. The solar components in the system are large-scale central inverters, complex high-power combiners, switches, and transformers that are connected to the utility grid.

## 2. Components in Solar Photovoltaic Systems

This section briefly describes a typical setup of a solar PV system. A solar PV system comprises the following components, as shown in Figure 2.

- Solar panels to collect solar energy
- Cables and interconnects to route the energy
- Charge controllers and batteries to store the energy
- Solar inverters to convert the stored energy to electricity
- Smart meters, transformers, and ground fault switches to monitor and meter the generated electricity

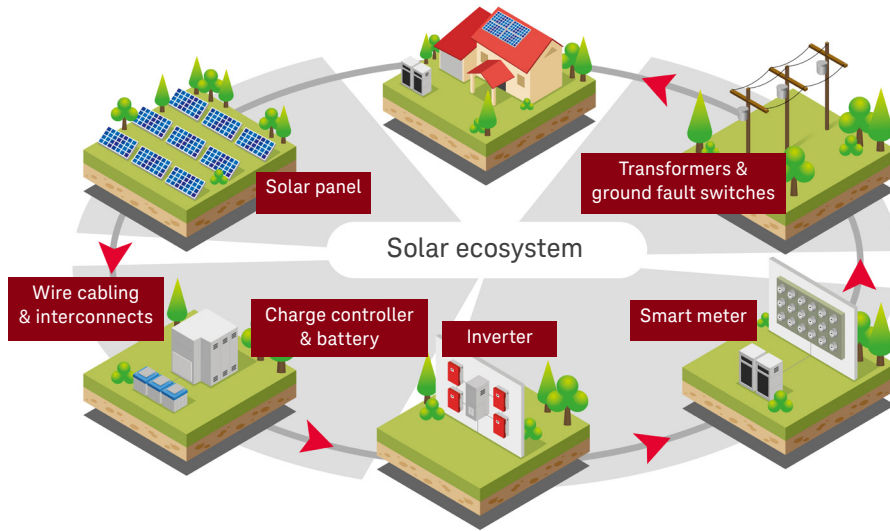


Figure 2. Components in a solar PV system

The installation of a solar PV system does not end with the installation of the components. Solar PV system installers have the challenge of performing continual validation and monitoring of the quality of the power generated. This is to ensure a reliable linkage of the solar PV system to the power grid. Furthermore, in the present and near future, solar power providers may be required to provide a stabilizing effect to the power grid using reactive power control. Figure 3 shows the challenges of validating and maintaining a solar PV system.

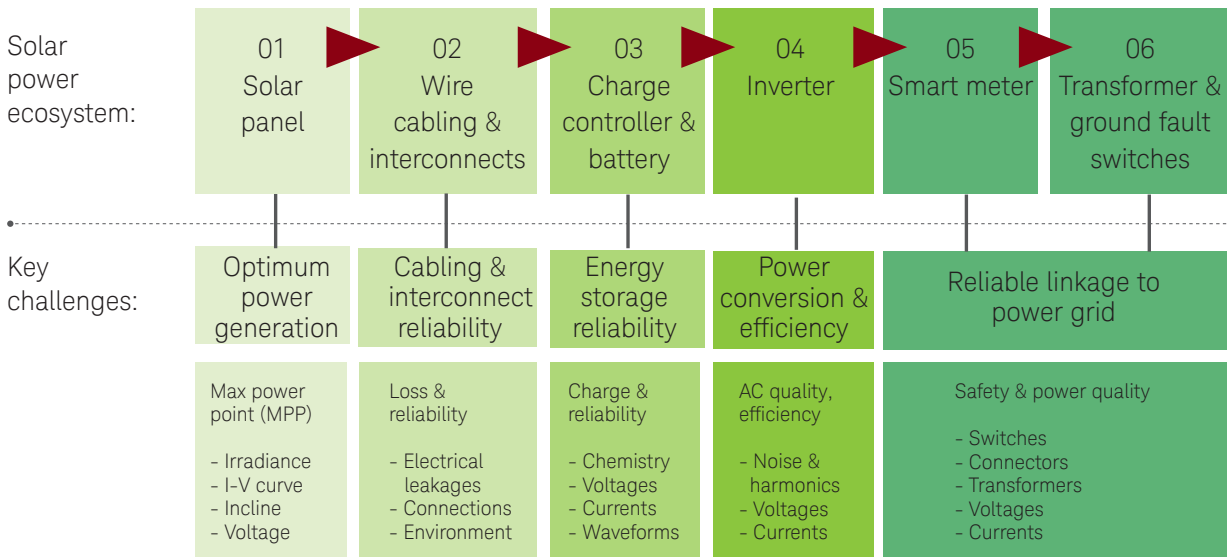


Figure 3. Test challenges in solar power ecosystems

### 3. Solar Panels: Collecting Solar Energy

#### Considerations for installing solar panels

During the pre-installation activities, solar PV system installers calculate the solar panel string sizing and array to maximize the power output. At the same time, they need to ensure their planning meets the allocated budget.

The panel string sizing and array calculation is very important to ensure optimum operation throughout cold and hot weather seasons. Solar PV system installers must ensure their string voltages do not exceed standard electrical guidelines and also do not exceed the maximum voltages of the components in the system.

Here's an example. Inverters normally have a Maximum Power Point Tracking (MPPT) voltage range between 250 V and 500 V. Solar panels have negative temperature coefficients; hence, during very hot summer seasons, the system voltage will drop and may drop below the 250 V Inverter MPPT range. This will cause the solar inverter to turn OFF during a hot summer day with plenty of solar irradiance. Conversely, during very cold winter seasons, the system voltage may peak above the solar inverter MPPT operating voltage range or peak beyond the component operating specifications. Depending on the design of the system, this may cause clipping and results in wasted energy [4].

Electrical measurements that solar PV system installers need to perform during the installation of solar panels normally include Short Circuit Current ( $I_{SC}$ ), Open circuit Voltage ( $V_{OC}$ ), total array voltage, current, and solar irradiance.

#### Tasks for validating and maintaining solar panels

Below are the tasks to validate and maintain the solar panels of a solar PV system.

- Locating faulty PV cells and panels
- Troubleshooting PV panel strings
- Determining the performance of solar cells and panels

#### Locating faulty PV cells and panels

Thermography is an extremely useful method to detect faulty PV cells and panels. Consider the alternative: for a solar farm that is a two or more acres, a solar technician cannot troubleshoot string after string of PV arrays by disconnecting and testing each array one at a time.

Using the Keysight U5855A TrueIR Thermal Imager, the solar technician can do a fast thermal image scan (see Figure 4). Faulty PV cells normally manifest themselves as thermal hotspots because they load up the system. One of the reasons for these thermal hotspots is the degradation of electronic component such as the bypass diodes in the solar panels. This will lead to lower efficiencies in output power. Refer to “*Thermography for Photovoltaic Panel Using the U5850 Series TrueIR Thermal Imager - Application Note*” for details (<http://literature.cdn.keysight.com/litweb/pdf/5992-0719EN.pdf>).

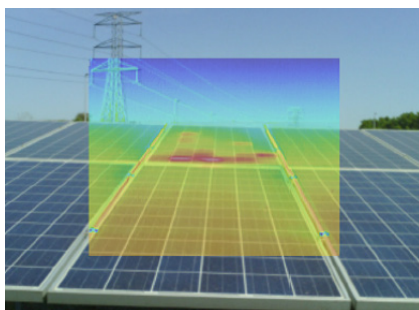


Figure 4b. Picture-in-picture mode (blends IR and visible images) and overheated solar cells

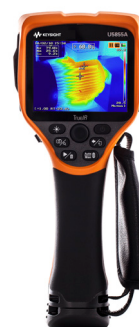
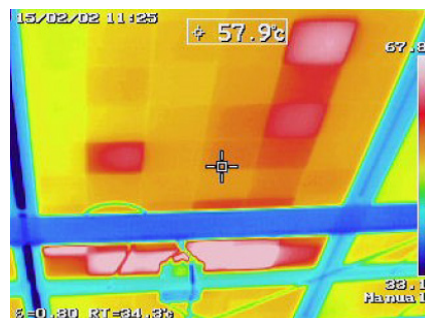


Figure 4a. Keysight U5855A TrueIR thermal imager

## Troubleshooting PV panel strings

Solar PV system designers and installers can use Bluetooth wireless digital multimeters from Keysight to validate or troubleshoot string performance. The wireless remote link feature allows up to four string voltages to be compared simultaneously (see Figure 5).

Measuring up to four string voltages simultaneously has the advantage over measuring one string at a time. It simply removes all the variability of irradiance levels, shadings from moving clouds, and other external effects that will affect the measurement of string voltage.



Figure 5 Photovoltaic string comparisons

## Determining the performance of solar cells and panels

A series of solar cells forming a solar panel normally has the characteristic of a current source in parallel with a diode and is coupled with parasitic shunt and series resistances as shown in Figure 6

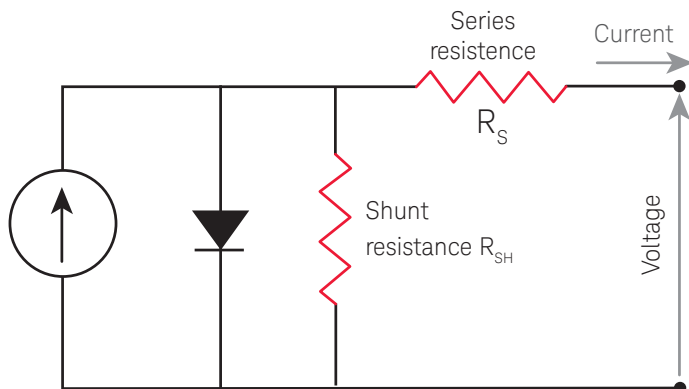


Figure 6 Model of a simple solar cell

The Current-Voltage (I-V) characteristics of a solar cell are shown in Figure 7.

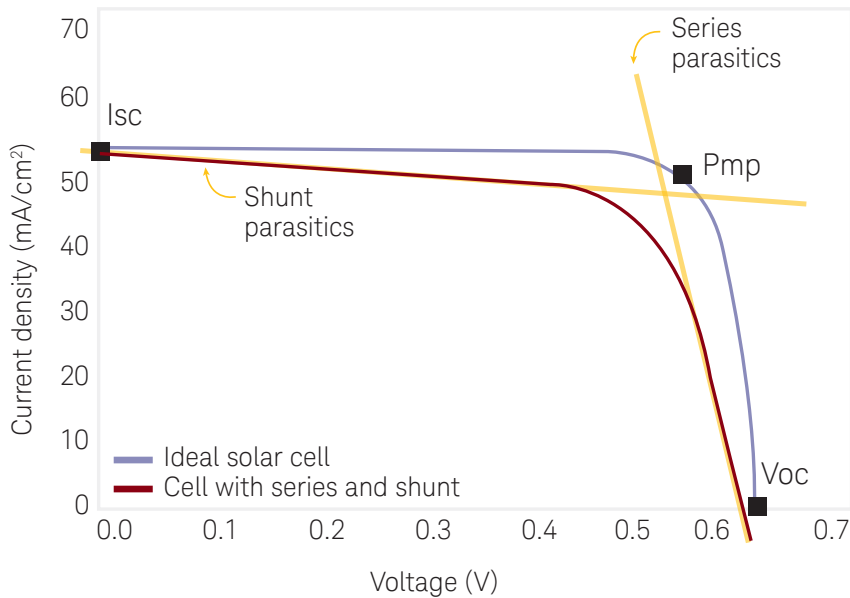


Figure 7 Current-Voltage (I-V) parametric characteristics of a solar cell

Using the Keysight B2900A Series Precision Source/Measure Unit (SMU), key solar cell or solar panel parameters such as the short-circuit current ( $I_{SC}$ ), short-circuit current density ( $J_{SC}$ ), the open-circuit voltage ( $V_{OC}$ ), the maximum power point ( $P_{MP}$ ), and the conversion efficiency ( $\eta$ ) can be measured. The solar cell and solar panel I-V parametric characteristic graph can be easily plotted using the list sweep mode of the Keysight B2900A Series Precision SMU. Refer to “*IV Characterizations of Solar Cells Using the B2900A Series of SMUs - Technical Overview*,” (5990-6660EN) for details.

One key advantage of the list sweep mode found in the Keysight B2900A Series Precision SMU is that it allows you to specify widely spaced steps in regions where the device characteristics are stable, and to specify closely spaced steps in regions of special interest such as the maximum power point of a PV cell.

In addition, the Keysight B2900A Series Precision SMU comes with an intuitive graphical user interface (GUI) and a free PC-based application software that enables you to produce measurements immediately.

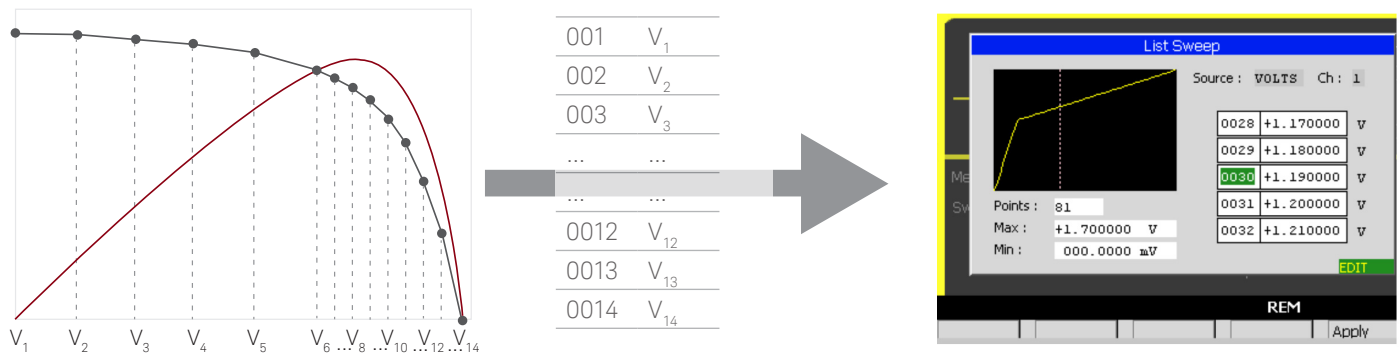


Figure 8 The list sweep mode of the B2900A Series Precision SMU to characterize PV cells in the region of interest



## 4. Cables and Interconnects: Routing Solar Energy

### Considerations for installing cables and interconnects

Cables and interconnects for solar applications are normally designed to withstand long-term exposure to UV light from the sun, endure extreme temperatures from sub-zero cold temperatures to desert hot temperatures, and be resistant to water. Solar PV systems have standard solar interconnects and cable diameter sizes. Furthermore, the cables and interconnects are color-coded, which helps simplify system installations.

During installation, cables and interconnects are subjected to high degrees of flexing, twisting forces, and abrasions as they are routed through tight conduits. There is a possibility that the insulation on the cables and interconnects may be affected. Therefore, electrical tests are required by IEC 62446:2009 to ensure proper commissioning and safety checks. These tests include performing earth continuity and insulation resistance measurements.

### Tasks for validating and maintaining cables and interconnects

Although cables and interconnects for solar PV systems are ruggedized, it is still important to periodically check them for any faults to ensure optimum system operation and efficiency.

Below are the tasks to validate and maintain the cables and interconnects of a solar PV system:

- Locating faulty cables and interconnects
- Verifying the installation of cables and interconnects and checking for performance degradation

### Locating faulty cables and interconnects

In general, faulty cables and interconnects tend to overheat. The Keysight U5855A True/R Thermal Imager is the best tool to scan for hotspots. Excessive heat on cables and interconnects may indicate poor connections or defective connections (see Figure 9).

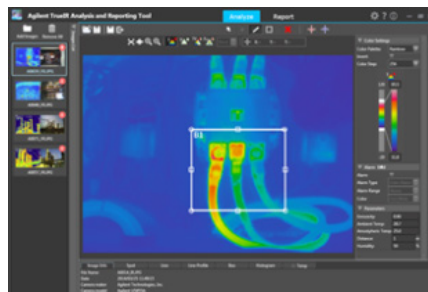
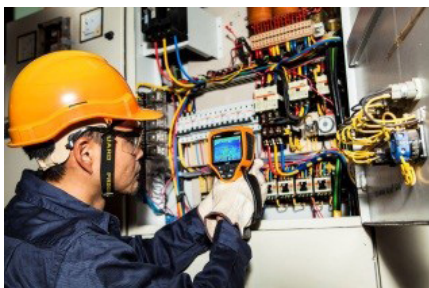
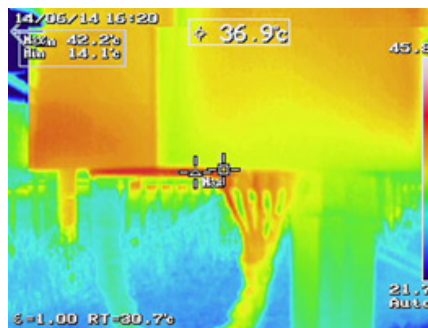


Figure 9a. Thermal scans of wires and interconnects to detect any signs of overheating

Figure 9b. Keysight U5855A True/R thermal imager

## Verifying the installation of cables and interconnects and checking for performance degradation

According to IEC 62446:2009, the cable insulation resistance test is one of the important requirements during the commissioning test and inspection of grid connected PV systems. It is also important to periodically check for faulty cables and interconnects to ensure optimum system operation and efficiency.

The Keysight U1450A/60A Series Handheld Insulation Resistance Testers are effective preventive maintenance instruments to detect early defects on cables and interconnects. These testers are capable of sourcing insulation test voltages up to 1000 V and insulation resistance range up to 260 GΩ.

Insulation resistance testing is carried out by applying a constant voltage to the equipment under test while measuring the current flow. High DC voltages are used, which cause a small current to flow through the insulator surface. The total current consists of three components: capacitance charging current, absorption current, and leakage current (see Figure 10). The leakage current, shown in green, is dependent on the material and will stay constant over a period of time. Refer to “Preventive Maintenance Test with Insulation Resistance Test - Application Note,” (5991-4026EN) for details.

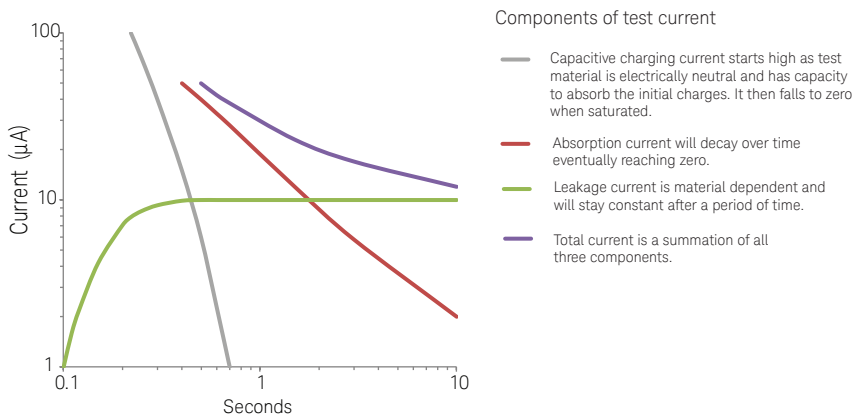


Figure 10b. Keysight U1450A/60A series handheld insulation resistance tester (U1452A)

Figure 10a. Chart of typical leakage current in insulation material over time

Periodic insulation testing will help reveal material degradation over time, as shown in Figure 11. The chart illustrates a scenario where a measurement is made every six months, and changes in the measurement are reflected in the changes that occur to the solar PV system.

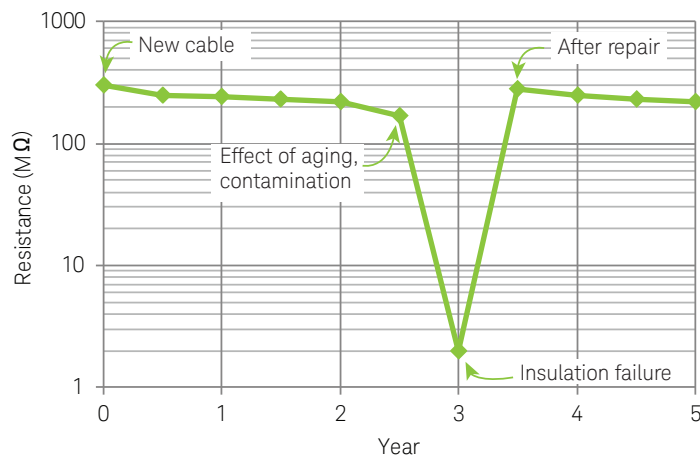


Figure 11. Periodic trend measurements

## 5. Charge Controllers and Batteries: Storing Solar Energy

### Considerations for installing charge controllers and batteries

Energy storage using batteries will increasingly play an important role in residential and commercial markets. It provides uninterrupted power supply and also conditioning of power to household and industrial loads.

Charge controllers and batteries for solar applications are designed differently from conventional applications. For example, solar batteries usually have 'deep cycle' charging capabilities, whereby it can discharge most of its capacity (up to 80%) during use. The lifespan of a battery depends on how it is charged, maintained, stored (ambient temperature condition), and other factors. Solar charge controllers have MPPT hardware and software designed to dynamically match the PV voltage to the battery storage voltage and to maximize the charging to the battery.

### Tasks for validating and maintaining charge controllers and batteries

Below are the tasks to validate and maintain the charge controller and battery:

- Inspecting, monitoring, and testing the battery
- Testing the solar charge controller

#### Inspecting, monitoring, and testing the battery

Solar energy storage has always been useful for rural areas where there is a lack of a power grid connection. It provides electricity during periods when there is no sunlight.

In a typical battery maintenance program, there are physical maintenance and electrical maintenance measurement activities.

The physical maintenance measurement activities are as follows:

1. Visually inspect batteries for leakage, corrosion, deformation, plate discoloration, and electrolyte level
2. Torque checks for connector binding integrity
3. Environmental temperature checks and, in some cases, battery temperature checks

Electrical maintenance measurement activities are as follows:

1. Isolate the battery bank from the solar inverter
2. Isolate the individual battery
3. Test open (no load) voltage
4. Test 100 A loaded voltage
5. Record and track each battery for predictive maintenance trending

Figure 12 shows an example of a battery storage room and of Keysight instruments to perform the electrical maintenance measurement activities.



Figure 12a. An example of a battery storage room and Keysight instruments for electrical maintenance measurement activities

### Testing the solar charge controller

Solar charge controllers have MPPT devices built-in for more effective charging of batteries from solar power sources.

The testing of the MPPT devices comprises the following:

1. The electrical efficiency of the MPPT device: This test can be performed by comparing the output power and the input power using the Keysight PA2201A IntegraVision Power Analyzer (see Figure 13).
2. The tracking effectiveness of the MPPT device: This test is performed by monitoring the power demanded by the MPPT device as compared to the dynamically changing solar module power due to changing solar irradiance. The Keysight U12xxA Series Handheld Digital Multimeters and the Keysight U119xA or U121xA Series Clamp Meters (see Figure 13) are effective instruments for troubleshooting the setup and for tracking effectiveness of the MPPT device.

Both of these tests are included in the DIN EN 50530 standard: Overall efficiency of grid connected photovoltaic inverters.



Figure 12b. (1) Keysight U1115/7A remote link solution; (2) Keysight U12xxA series handheld digital multimeter; and (3) Keysight U5855A True/R thermal imager

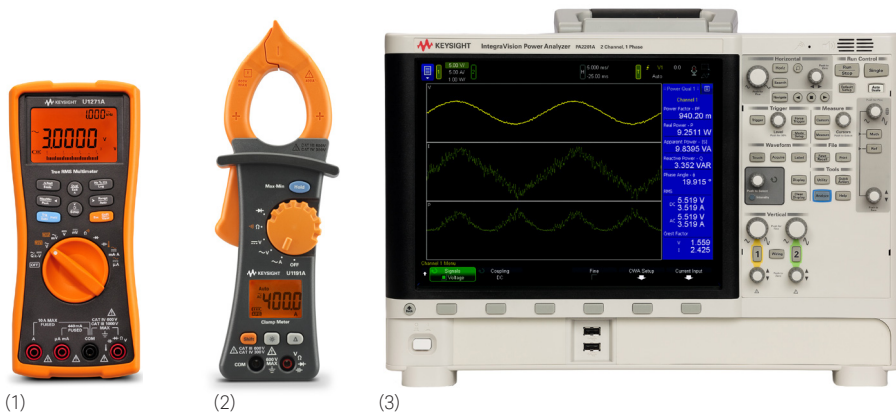


Figure 13. Keysight instruments for testing the solar charge controller. (1) Keysight U12xxA series handheld digital multimeter; (2) Keysight U119xA and U121xA series clamp meters; (3) Keysight PA2201A IntegraVision power analyzer

## 6 Solar Inverter: Converting Solar Energy

### Considerations for installing solar inverters

The main function of a solar inverter is to convert DC power from the solar panel into AC output power. Solar inverters can have these features built-in:

1. An MPPT device to determine the dynamic conditions of solar string and array output and to maximize the power conversion output of the solar inverter.
2. Grid Tied Inverter (GTI) provides proper solar inverter output power that is synchronized with the power grid from the utility company
3. Anti-islanding device that detects 'islanding' whereby the surrounding power line or grid loses power and the device quickly triggers a shutdown of the solar inverter

The quality and efficiency of solar inverters for power conversion are important factors when setting up a solar PV system. Solar inverter manufacturers normally quote the maximum efficiency specification. However in reality, input voltages from solar panel setups fluctuate for many reasons. In light of this, European countries have standardized a weighted average conversion efficiency calculation method ( $\eta_{EU}$ ). In turn, the United States California Energy Commission (CEC) has its weighted efficiency calculation method ( $\eta_{CEC}$ ) as well. Examples of the weighted average conversion for European countries and the US are shown in Figure 14.

California Energy Commission (CEC) weighted efficiency:

$$\begin{aligned}\eta_{CEC} &= 0.04 \cdot \eta_{10\%} + 0.05 \cdot \eta_{20\%} + 0.12 \cdot \eta_{30\%} \\ &+ 0.21 \cdot \eta_{50\%} + 0.53 \cdot \eta_{75\%} + 0.05 \cdot \eta_{100\%}\end{aligned}$$

European weighted efficiency:

$$\begin{aligned}\eta_{EU} &= 0.03 \cdot \eta_{5\%} + 0.06 \cdot \eta_{10\%} + 0.13 \cdot \eta_{20\%} \\ &+ 0.10 \cdot \eta_{30\%} + 0.48 \cdot \eta_{50\%} + 0.20 \cdot \eta_{100\%}\end{aligned}$$

Figure 14 Examples of CEC and EU Inverter Weighted Conversion Efficiency methods [3]

### Tasks for validating and maintaining solar inverters

The output power of the solar inverter, whether it is in single phase or 3-phase, will be required to have very good quality output power for connecting to the utility power grid or for household use.

Issues caused by poor quality output power from the solar inverter may include the following:

- If the AC sinusoidal output power has a lot of harmonic pollution, it will cause extra stress to the power network and will make the overall system run inefficiently.
- A load imbalance resulting in excessive voltage imbalance will cause stress to other loads in the same power network.
- Fast voltage variances will cause lights to flicker.

The cost of poor power quality can result in unexpected power outages, equipment failure, equipment overheat (leading to a reduction in useful lifetime of the equipment), electronic communication interferences, and more [5].

Below are the tasks to maintain the solar inverter:

- Measuring the quality of the power produced by the solar inverter
- Monitoring and troubleshooting the operation of the solar inverter

## Measuring the quality of the power produced by the solar inverter

A key electrical measurement for a solar inverter is the efficiency of the DC to AC power conversion. This can be measured using the Keysight PA2200 Series IntegraVision Power Analyzer. Manufacturers usually quote peak efficiency; however, weighted average efficiencies set by CEC and European standards are more accurate in reflecting the actual use case efficiency.

The Keysight PA2200 Series IntegraVision Power Analyzer can measure key power quality parameters such as watt, VA, VAR, power factor, phase angle, and voltage/current crest factor. It also measures voltage harmonics, current harmonics, and power harmonics up to 250th order. These features make the Keysight PA2200 Series IntegraVision Power Analyzer an effective instrument for measuring the efficiency of the solar inverter’s power conversion (see Figure 15).

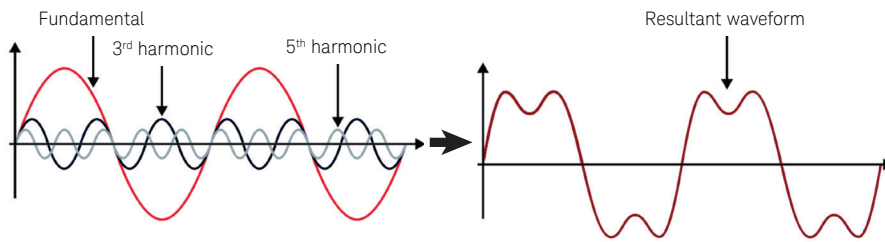


Figure 15. The graph shows the resultant waveform of a sine wave with the presence of third and fifth order harmonics

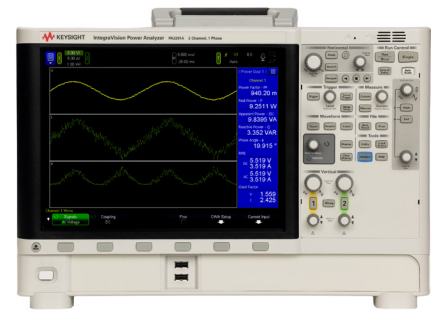


Figure 15b. Keysight PA2201A IntegraVision power analyzer

For instances when benchtop instruments are not suitable, Keysight has a range of handheld devices—for example, the Keysight U12xxA Series Handheld Digital Multimeter and the Keysight U119xA Series Clamp Meter—that are useful for performing quick setup checks or troubleshooting activities. To understand troubleshooting harmonic issues with Keysight handheld digital multimeters, refer to “*Detecting Harmonics in an AC Signal – Application Note*,” (5989-7687EN).

The graph in Figure 16 shows the DC/AC power conversion efficiency versus power. A good efficiency range is typically above 90%. Therefore, as you can see in the graph, there is an optimal power range a particular inverter can operate to achieve good conversion efficiency.

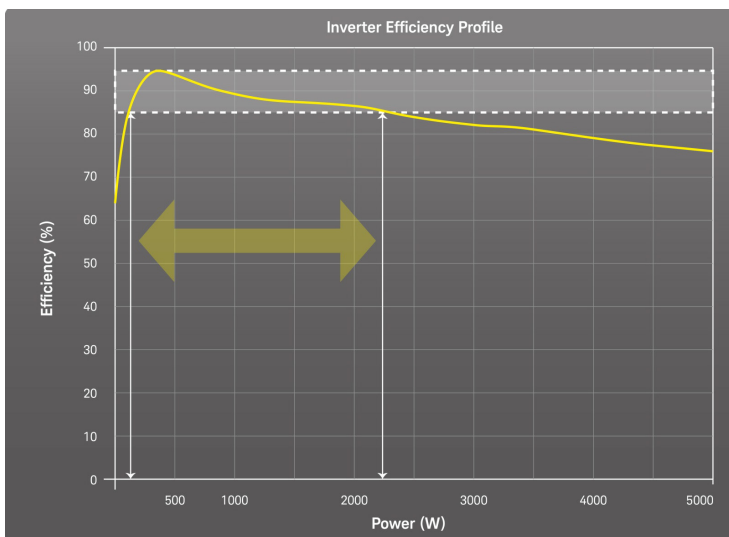


Figure 16a. Solar inverter efficiency versus power



Figure 16b. (1) Keysight U12xxA series handheld digital multimeter; (2) Keysight U119xA and U121xA series clamp meters

## Monitoring and troubleshooting the operation of the solar inverter

Overheating is an early indication of a fault. An effective way to detect abnormal operating temperature is to use a thermal imager. With the Keysight U5855A TrueIR Thermal Imager, you can perform a quick scan of the solar inverter (see Figure 17) and ensure it is operating normally.

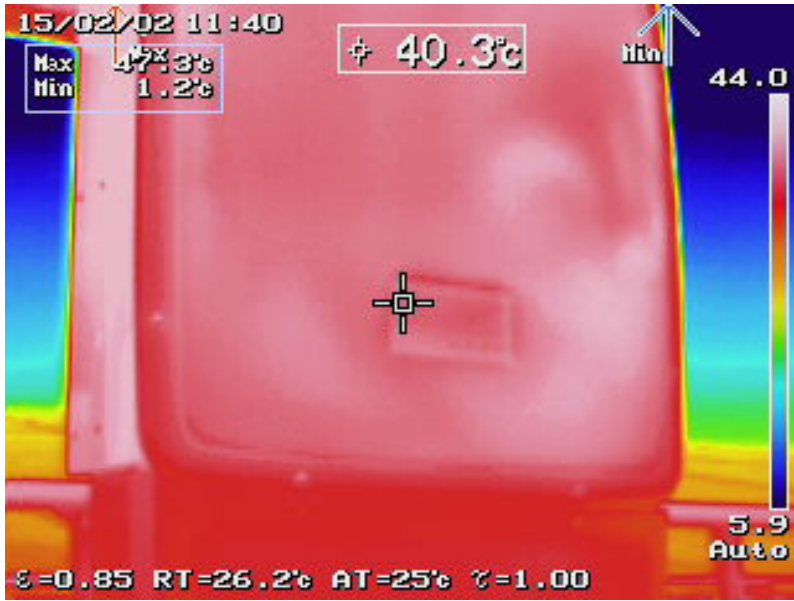


Figure 17a. Thermal image of a solar inverter in operation



Figure 17b. Keysight U5855A TrueIR thermal imager

## 7. Smart Meters, Transformers, and Ground Fault Switches: Monitoring and Metering the Generated Electricity

### Considerations for ensuring safe, reliable, and dependable operation of solar PV systems

During periodic maintenance checks of solar PV systems, it is important to ensure proper connector integrity and transformer winding insulation integrity. In addition, smart meters and ground fault switches should be checked to ensure they are functioning properly. Any faults in these components may cause the solar PV system to shut down and result in aggravating and labor intensive troubleshooting efforts. Furthermore, these faults create a dangerous work situation for the technician maintaining the solar PV system.

### Tasks for validating and maintaining smart meters, transformers, and ground fault switches

Excessive overheating usually indicates the likelihood that a failure has occurred or will soon occur. A safer and convenient method is to use a thermal imager, such as the Keysight U5855A TrueIR Thermal Imager, to capture thermal images of high-power connections and transformers (see Figure 18). With this handheld thermal imager, you can quickly ensure no components are overheating.

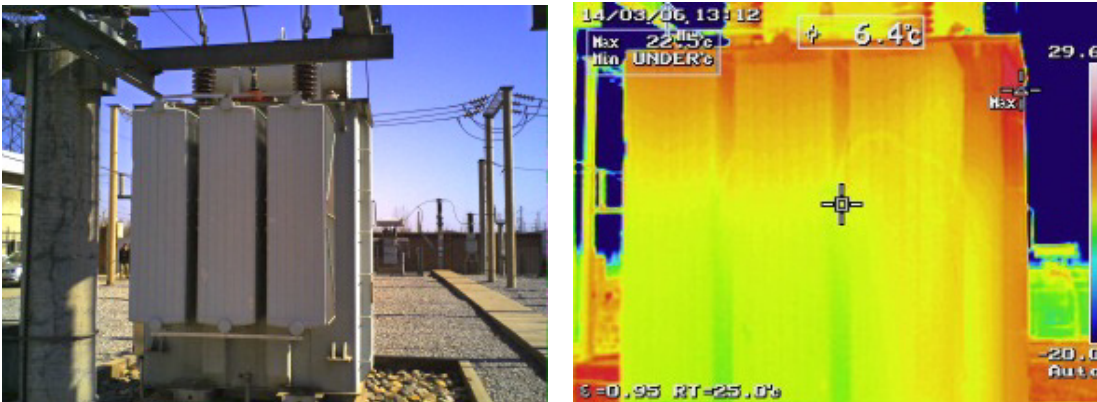


Figure 18 Thermal imagery of transformers in operation

## 8. Conclusion

Keysight Technologies has a comprehensive handheld solution that will meet all your solar power installation and maintenance test needs.



For more information on Keysight Technologies handheld tools, please visit: [www.keysight.com/find/handheld-tools](http://www.keysight.com/find/handheld-tools)





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LAN eXtensions for Instruments puts the power of Ethernet and the Web inside your test systems. Keysight is a founding member of the LXI consortium.



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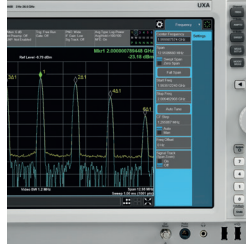
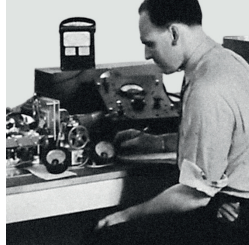
PCI eXtensions for Instrumentation (PXI) modular instrumentation delivers a rugged, PC-based high-performance measurement and automation system.

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## From Hewlett-Packard through Agilent to Keysight

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