# HANDBOOK

## Measurements on PV systems


METREL®

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# Measurements on PV systems

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# 1. Measurements on PV systems

This booklet deals with measurements on PV systems. Two fields of measurements are described: verification of safety and testing of performance of PV systems. Typical problems because of changing test conditions are highlighted. Advantages of the I-V curve measurement are described. Typical problem with PV generators and how they are seen on the I-V curve are shown. Sources of measurement errors are presented and solutions are proposed. Some less known influence factors are described.

## 1.1 Labelling of values

Descriptions and equations in this document refer to different types of data. The labelling is as follows:

**Actual (exact) value of data**: **X** (no subscript)

**Measured value of data: $X_{meas}$**
Value obtained by measurement.

**STC value of data: $X_{STC}$**
STC value calculated on base of measured values. The calculation is based in the standardized electrical model of PV cells. Refer to chapter 4 for more information about STC conditions.

**Nominal value of data: $X_{nom}$**
Value given by the manufacturer. Value is always given for STC conditions.

## 1.2 Safety of PV systems

### 1.2.1 Overvoltage categories in PV systems

PV systems are treated as a part of LV electrical installations. The PV generator is classified as overvoltage category I – no overvoltage and transients are expected to occur on the d.c. side. For standard PV systems the a.c. side is connected as a circuit in the installation and is classified as overvoltage category II and III (see Fig. 1.2.1). PV systems generate high energies – the voltages are up to 1000 V and the current in individual strings can exceed 10 A. Special considerations must be taken when testing PV systems. Measures for work in high voltage environment must be taken, appropriate measuring equipment and accessories must be used etc (see chapter *9* for more information).

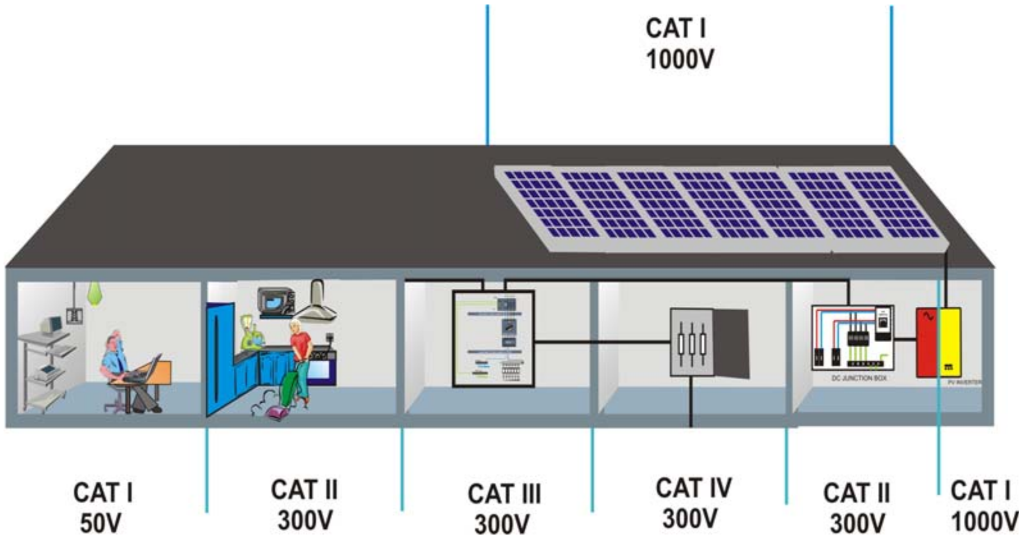



*Fig. 1.2.1: Installation categories in a PV system*

### 1.2.2 Relevant standards

Table 1.2.2 contains a list of main standards that deals with measurements on PV systems.

| ***Standard*** | ***Short description*** |
|---|---|
| **LV / Electrical / PV Installations** | |
| IEC 60364-1<br>Low-voltage electrical installations – Part 1: Fundamental principles, assessment of general characteristics, definitions. | General rules and guidance for installing and inspecting electrical systems. |
| IEC 60364-7-712<br>Electrical installations of buildings - Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems | Describes the protective measures and requirements of the PV system. |
| IEC 60364-6<br>Low-voltage electrical installations - Part 6: Verification | Describes the verification procedure on the a.c. side of the installation. Measurements and verification on d.c. side are partly covered. |
| **Testing / Inspection /Reporting** | |
| IEC 62446<br>Grid connected photovoltaic systems - Minimum requirements for system documentation, commissioning tests and inspection. | Measuring functions for PV systems and verification procedures on the d.c. side are described. Supplements Part 6 of IEC 60364. |

| | |
|---|---|
| IEC 61557 series<br>Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. - Equipment for testing, measuring or monitoring of protective measures.<br>Part 1: General requirements<br>Part 2: Insulation resistance<br>Part 3: Loop resistance<br>Part 4: Resistance of earth connection and equipotential bonding<br>Part 5: Resistance to earthPart 6: Effectiveness of residual current devices (RCD) in TT, TN and IT systems | Describes requirements for measuring equipment. Measurement equipment for PV system must be in accordance with the belonging 61557 standard if it exists. In addition IEC 62446 and IEC 60364-6 must be considered. |
| **T and Irr corrections / STC calculations** | |
| IEC 60891 Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics | Defines procedures for temperature and irradiance corrections to the measured I-V (current-voltage) characteristics of photovoltaic devices. It also defines the procedures used to determine factors relevant for these corrections. |
| IEC 60904 Photovoltaic devices<br>Part 10: Methods of linearity measurement | Describes procedures used to determine the degree of linearity of any photovoltaic device parameter with respect to a test parameter. |

*Table 1.2.2: Relevant standards for testing PV systems*

## 1.3 Specific safety issues in PV systems

This chapter describes some dangers that are specific for PV systems. Dangers caused by electricity are addressed. Other dangers (mechanical strength, works on height etc.) are beyond the scope of this book.

### 1.3.1 PV generator can not be switched off

The high voltage of a PV module / string / array can not simply be switched off. If working by day the installer must be aware that the PV generator is permanently energized down to the d.c. disconnection switch. Installers must strictly consider the safety precautions because some works on the installation must be done under high voltage. Special care must be taken in case of searching and removing faults.

### 1.3.2 DC electric arc

Switching d.c. currents is much more difficult than switching a.c currents.
Whenever a current is flowing a certain amount of energy is stored in the magnetic field of the current loop (Fig. 1.3.2 ①). The magnetic energy is proportional to the inductivity

of the current loop. In a PV generator the inductance of the wiring forms the main portion of the overall inductance. This is why the (+) and (-) conductors must lie in parallel.

$$W = \frac{L \cdot I^2}{2} \qquad \text{Eq. 1.3.2}$$

*W….magnetic energy stored in a current loop*
*L….. inductance*
*I……current*

When a contact is disconnected the magnetic energy can not just disappear and the current can not stop flowing immediately. The magnetic energy initiates an induced voltage. A voltage spike occurs on the contacts as soon as the contact starts disconnecting (Fig. 1.3.2 ②). At the beginning of the disconnection the distance between the switch contacts is small and the induced voltage causes a breakdown between the contacts (Fig. 1.3.2 ②). This enables the current to continue flowing (path is through the air). An electric arc occurs. As the distance between the contacts increases the arc is getting longer (Fig. 1.3.2 ③). A 50 Hz a.c. currents cross zero 100 times per second. While the current is close to zero the arc usually distinguish spontaneously. However the d.c. current has no zero crossover. The arc sustains a low impedance current path and the current doesn't stop to flow until the distance between contacts becomes high enough (Fig. 1.3.2 ④). In d.c. systems with a voltage of several hundred Volts this distance is several centimetres! The energies in large arcs (long distance between contacts, high current) can be in range of kW and can cause damage and fire. There is no simple mechanism to stop this phenomena. Bad contacts, use of improper components and equipment can cause unwanted arcs and consequentially a fire.
It is important that all protective measures on the d.c. side of the PV installation are properly designed and installed. Switches, relays, fuse and other components must be declared for use in PV installation. Measurement equipment should be declared for use on PV systems.

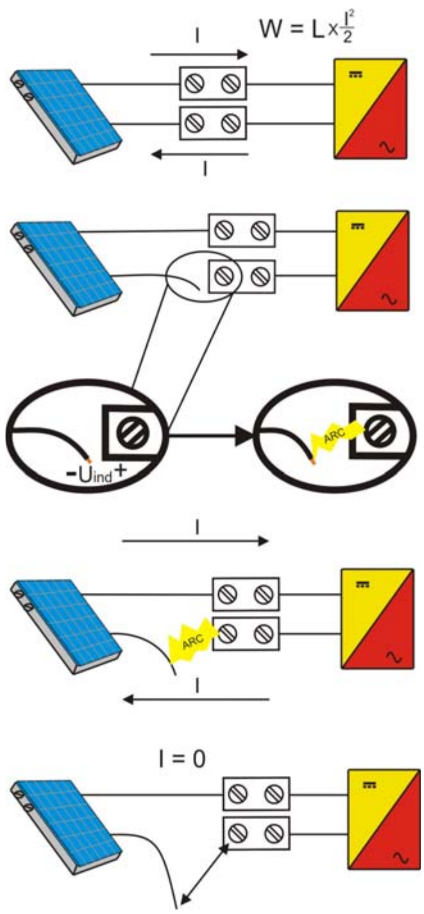


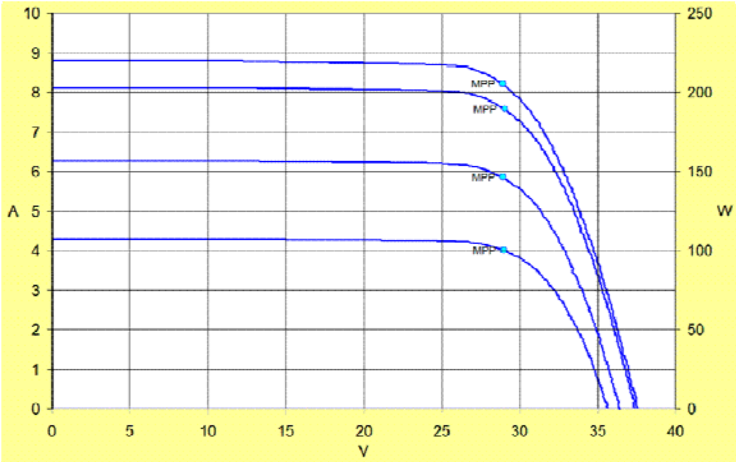

*Fig.1.3.2: The d.c. arc phenomena*

### 1.3.3 The current of PV generator is limited – other function of fuses

A standard a.c. power system is a voltage source with a relatively low serial impedance. In case of a short circuit (short between phase conductors or a short to earth) the fault currents are typically much higher than during normal operation.
The PV generator behaves more like a current source. There is only a small difference between a normal operating and a fault current (short). The maximal operating current strongly depends on the environmental condition (irradiance, temperature, wind). A fault short circuit current in the morning is much lower than the normal operating current at 12 o' clock.

Fig.1.3.3 ① shows measured I-V curves of a PV module at four different irradiance levels. It can be seen:

- that the difference of current size for a 50% change of irradiance is about 50%.
- that the difference of current size for Isc (current that would flow in fault conditions) and $I_{MPP}$ (normal operating current) at same level of irradiance is less than 10%.




| $I_{RR}$ [W/m²] | $I_{SC}$ [A] | $I_{MPP}$ [A] |
|---|---|---|
| 1048 | 8,75 | 8,17 |
| 971 | 8,11 | 7,57 |
| 750 | 6.26 | 5,85 |
| 513 | 4,28 | 4,00 |

*Fig. 1.3.3: PV generator performance at different environmental conditions*

Because of this the overcurrent protection in PV systems doesn't have the same function as in a.c. systems. A fuse will not burn in case of a short between d.c. conductors or a short to earth. The protection against shorts is more based on proper dimensioning of the components of the PV system. In general PV modules, cables, connections must sustain all possible fault currents without damage.

Exception are PV arryas with more strings connected in parallel. In this case the fault current in one string (due to a short or other fault) can exceed the nominal current of the string (Eq.1.3.3).

$$If_{MAX} \le Isc_{STC} \cdot (N-1) \cdot 1.25$$

A fuse with a nominal value of $1.25 \cdot Isc_{STC}$ (of one string) at the output of the string would burn and prevent the system from overheating. Example on Fig. 1.3.3 ② shows a situation with a fault current of $3 \cdot Isc$.

An effective common protection measure is also to place a blocking diode in each string. In strings with a blocking diode the current can not increase above $1.25 \cdot Isc_{STC}$ (of one PV string).

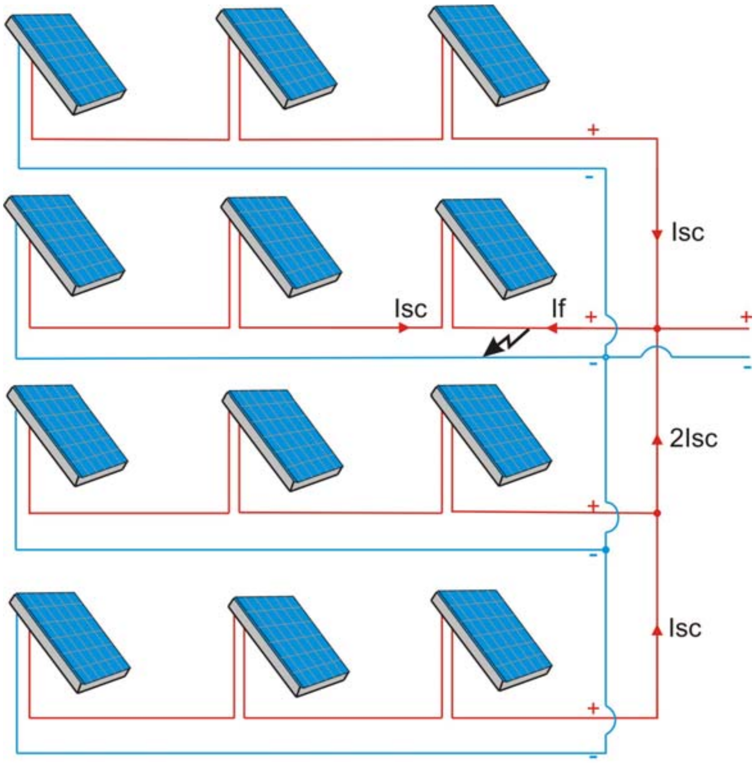



*Fig. 1.3.3: Worst case fault current in one string of a PV array (with no protection elements)*

## 2. Elements of a PV systems

Fig. 2 shows a block diagram of a PV system as defined in IEC 60364-7-712, with all safety relevant components.

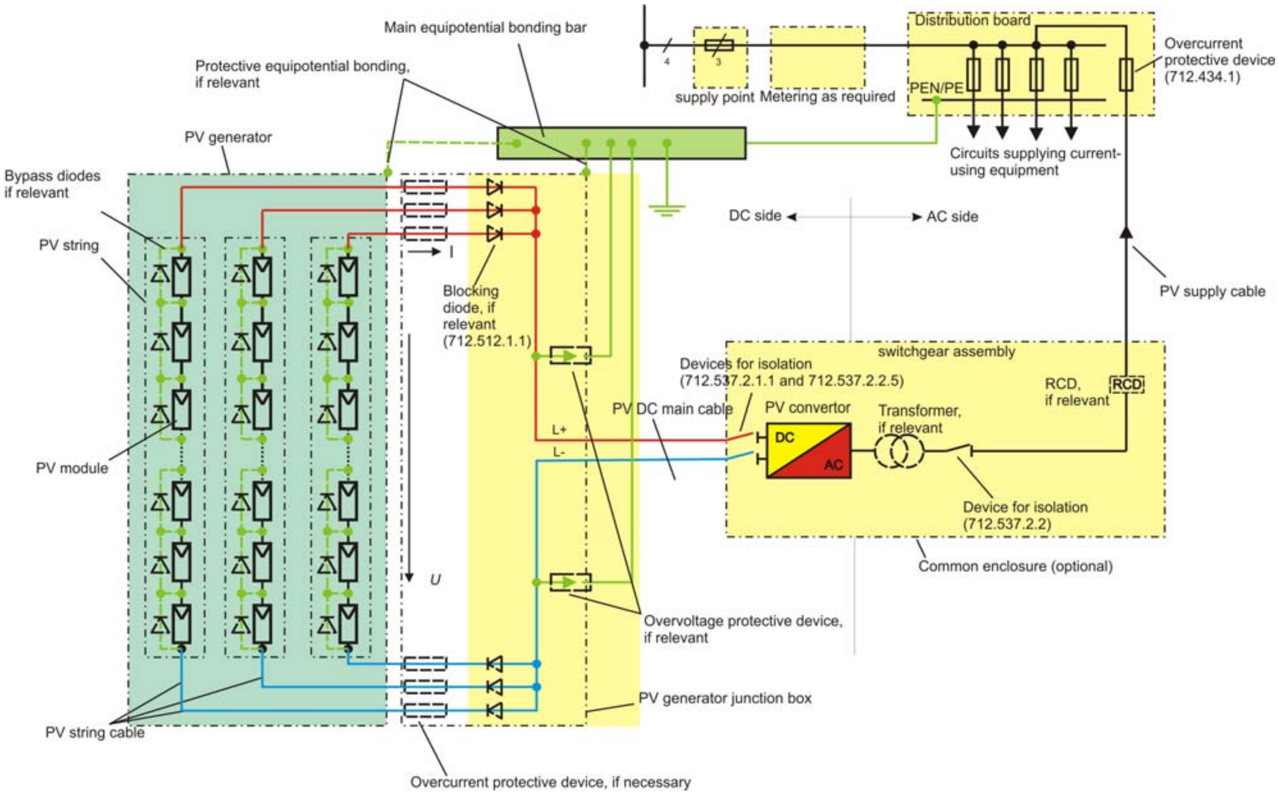



*Fig.2: Schematic of PV installation (according to IEC 60364-712)*

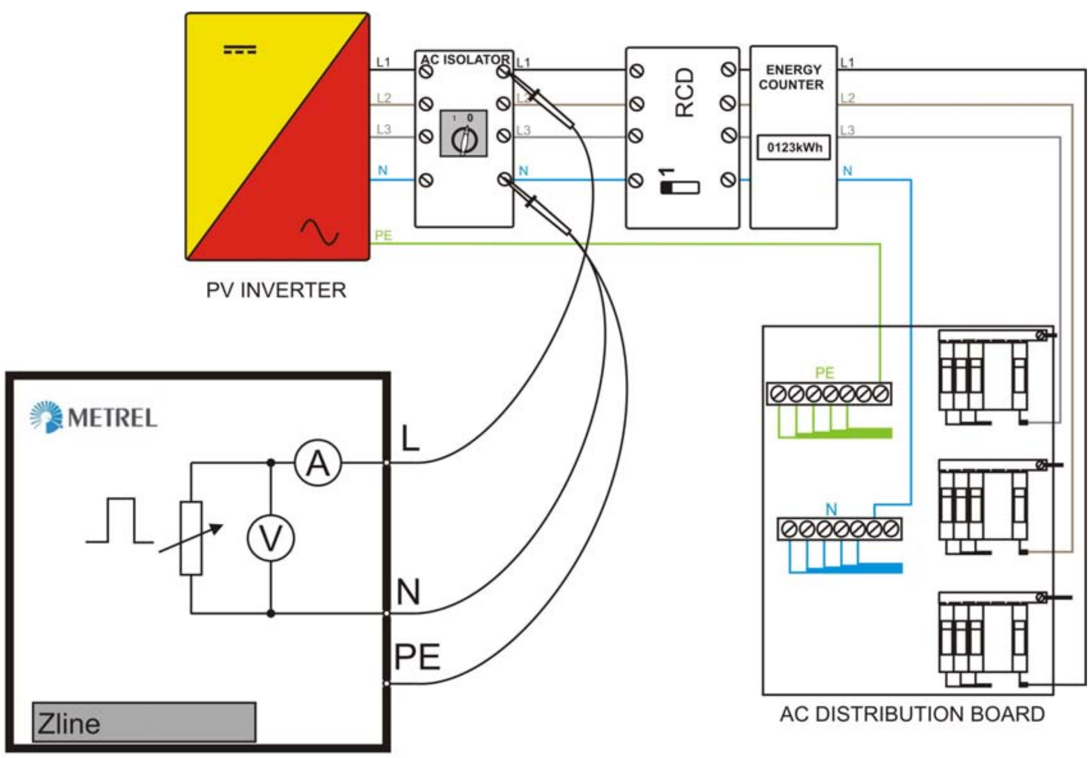
# 3. Measurements of safety of PV systems (acc. to IEC 62446)

## 3.1 AC side of PV system

The a.c. side of PV system is the part between the output of the inverter and the connection point to the power system (usually electrical counter). The voltages and currents (levels, shapes) are the same as in standard a.c. systems. The a.c. output of the PV system is connected to the a.c. installation point as a special circuit of the electrical installation. The fact that the energy is distributed from the inverter to the power system has no influence on the safety principles.

## 3.2 Overcurrent protection

The function of the fuse(s) between the a.c. side of the inverter and connection point (electrical counter) to the power system is the same as of other circuit fuse(s). For verification measurements of line (phase –neutral and phase-phase for three phase circuit) and loop impedances (phase-PE) should be performed. The measuring parameters and limits are to be selected according to the installed fuse(s). The voltage drop can be measured for estimation of wiring losses on the a.c. side (see chapter 8.5). The voltage drop should be as small as possible  because wiring losses decrease the performance of the PV system. Fig. 3.2 shows measuring connection for the Zline and Zloop tests.



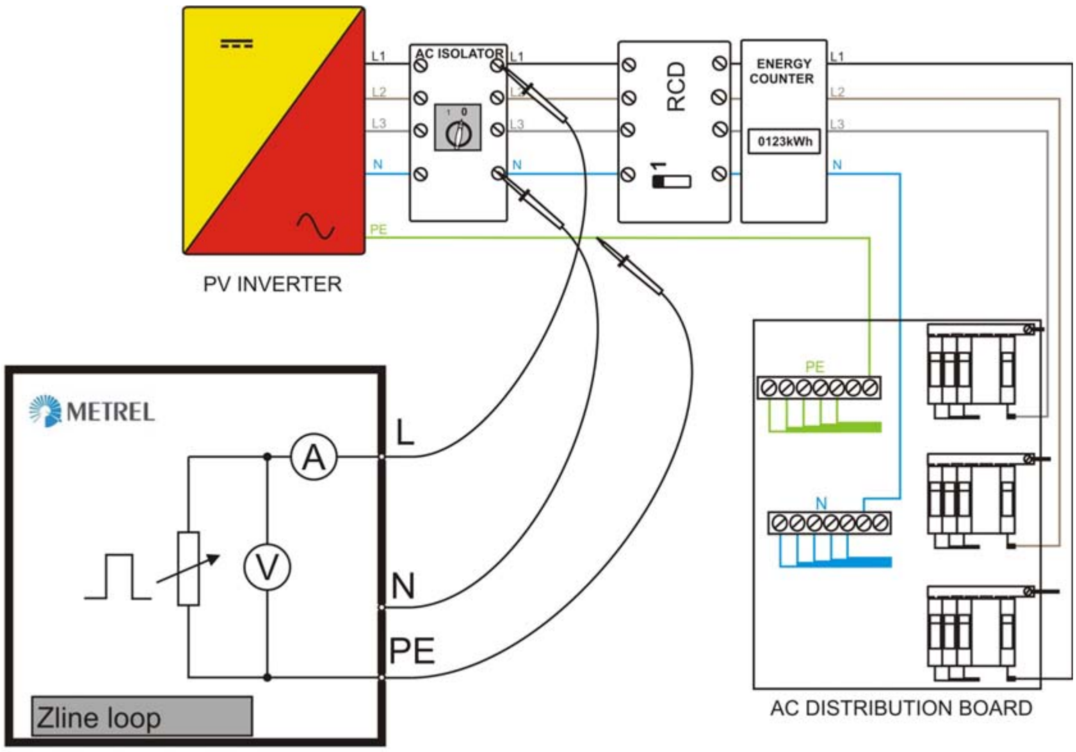



*Fig.3.2: Measurement of Zline, Zloop*

## 3.3 Protection against excessive residual currents

If an RCD is installed on the a.c. side of the PV system it must be tested. The best practice is to perform a complete RCD test (RCD Auto) that includes:

- no tripping test with 0.5x IdN
- tripping time test with 1x IdN and 5x IdN
- tripping current (ramp test)

The measuring instrument should be able to test B type RCD's – there will often be a DC sensitive RCD (B, B+ type) installed. Fig. 3.3 shows measuring connection for the RCD test.

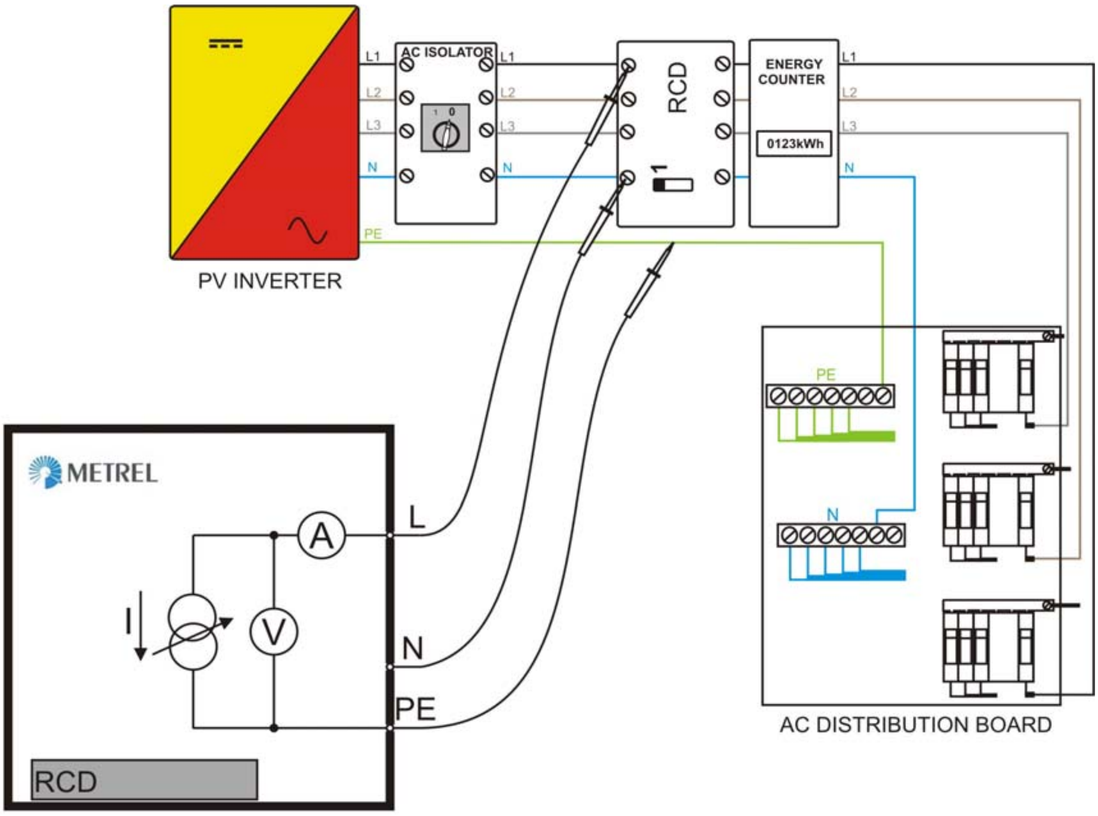



*Fig.3.3: Measurement of RCD*

## 3.4 Insulation between live and earthed parts

Insulation tests between conductors of the a.c. circuit should be carried out (line/neutral, neutral/earth, line/earth for one-phase and additionally line/line for three-phase circuits). The insulation tests should be carried out at disconnected mains and PV generator. The test voltage for 120 V /240 V a.c installations of (phase - neutral voltage) is 500 V and the limit resistance at least 1 MΩ. Fig. 3.4 shows measuring connection for the insulation tests.

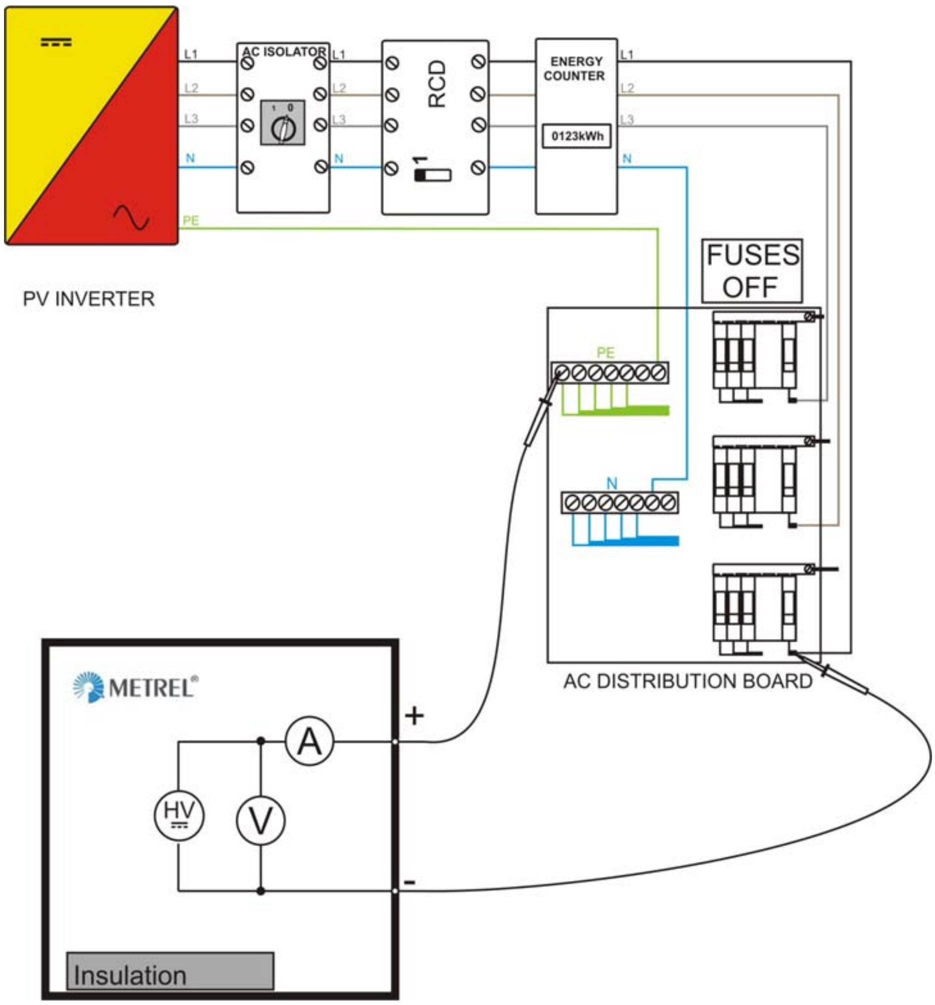



*Fig.3.4: Measurement of insulation*

## 3.5 Continuity of earthing conductor

The connection on the a.c. side between the inverter's PE terminal and main potential equalizer must be verified with a continuity test. The continuity tests are carried out at disconnected mains and PV generator.  The resistance values should correspond to the material, length and crossection of the conductors. In Table 3.7 the resistance of some typical conductors / lengths is shown. Fig. 3.5 shows measuring connection for the Continuity test.

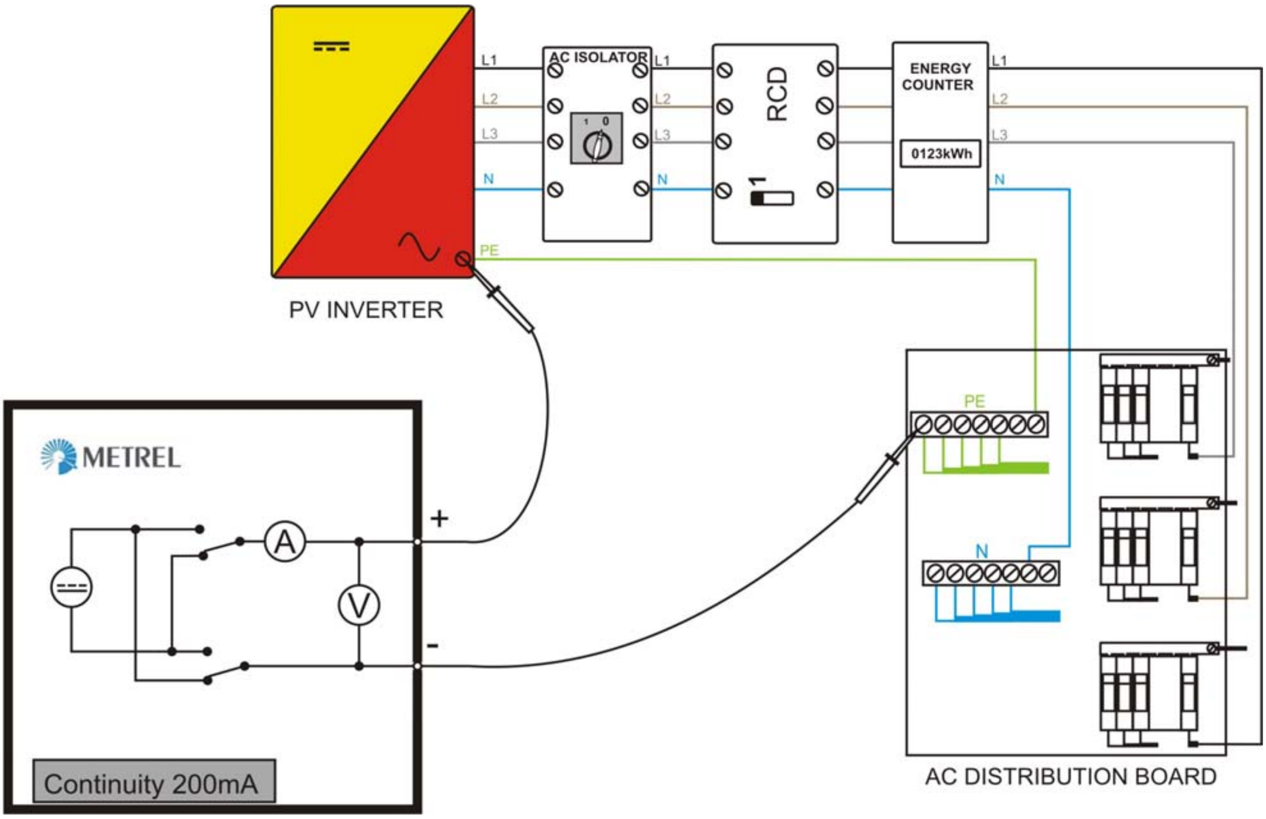



*Fig.3.5: Measurement of continuity on a.c. side of PV installation*

## 3.6 DC side of PV installation

### 3.6.1 Protective measures of PV module/ string/ array

High energies generated in the PV module/ string/ array must be safely distributed to the inverter. There must be a mean for disconnection of DC power. The modules /strings / arrays are often protected with overcurrent and surge protection devices. Protective measures are following:

- cables are double isolated and must be rated to sustain at least 1.25x $Uoc_{nom}$
- cables, connectors, component must sustain at least 1.25x $Isc_{nom}$ without being overheated.
- in case that fault currents (eg. in arrays due to a short in one string ) can exceed the 1.25x $Isc_{nom}$ and the overcurrent protective devices are not installed,  the conductors must be of appropriate (higher) size. The cables and the PV module must sustain the higher current.

- all connectors and connections must be firm, of low resistance and of proper current rating. An electric arc in d.c. systems is more dangerous than in a.c. installations.
- A list of items to be inspected is given in the IEC 62446 standard. The PV test report in Metrel's PCSW EurolinkPRO also contains the list of visual checks.
- The insulation of the PV generator must be tested with the PV insulation test (see chapter xy). A visual inspection should be made for verification of other protective measure.

### 3.6.2 Lightning protection of PV modules

Except in rare cases PV generators does not increase the probability of a lightning strike. PV systems are usually protected with a lightning protection system anyway. The protection consists of:

- connections between the frames of PV modules (equipotential bonding). All frames are connected to an earthed potential equalizer.
- connections are sometimes connected via earthing electrode(s) to earth.

## 3.7 Continuity and earthing resistance tests

Connections between frames of PV modules and the potential equalizer should be proved with a Continuity test. The resistance values should correspond to the material, length and crossection of the conductors. In Table 3.7 the resistances for some typical conductors / lengths are shown.

| Length of conductor | Material /crossection | | |
|---|---|---|---|
| | Cu 2.5mm$^2$ | Cu 4 mm$^2$ | Cu 6 mm$^2$ |
| 1 | 6.88mΩ | 4.3mΩ | 2.87mΩ |
| 5 | 3.44mΩ | 21.5mΩ | 14.33mΩ |
| 10 | 68.8mΩ | 43mΩ | 38.67mΩ |
| 20 | 137.6mΩ | 86mΩ | 57.33mΩ |
| 50 | 344mΩ | 215mΩ | 193.33mΩ |

*Table 3.7: Resistance for typical PV conductors / lengths*

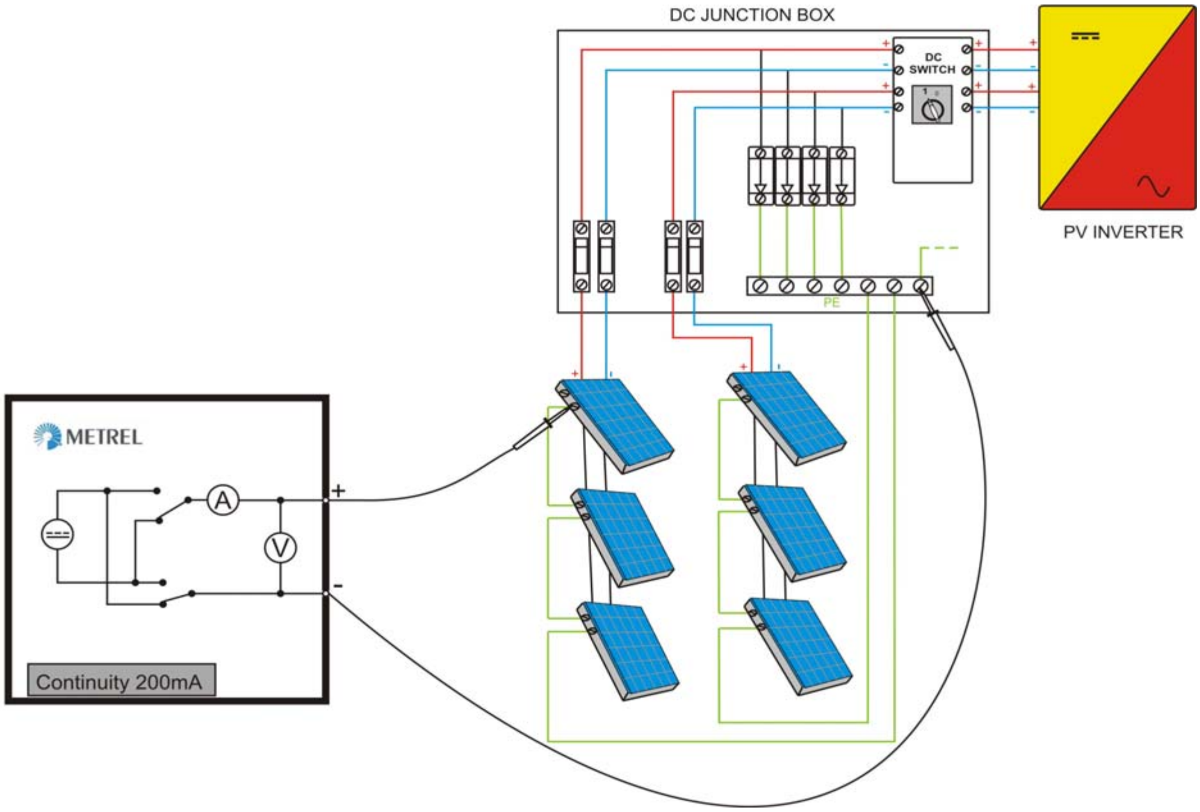
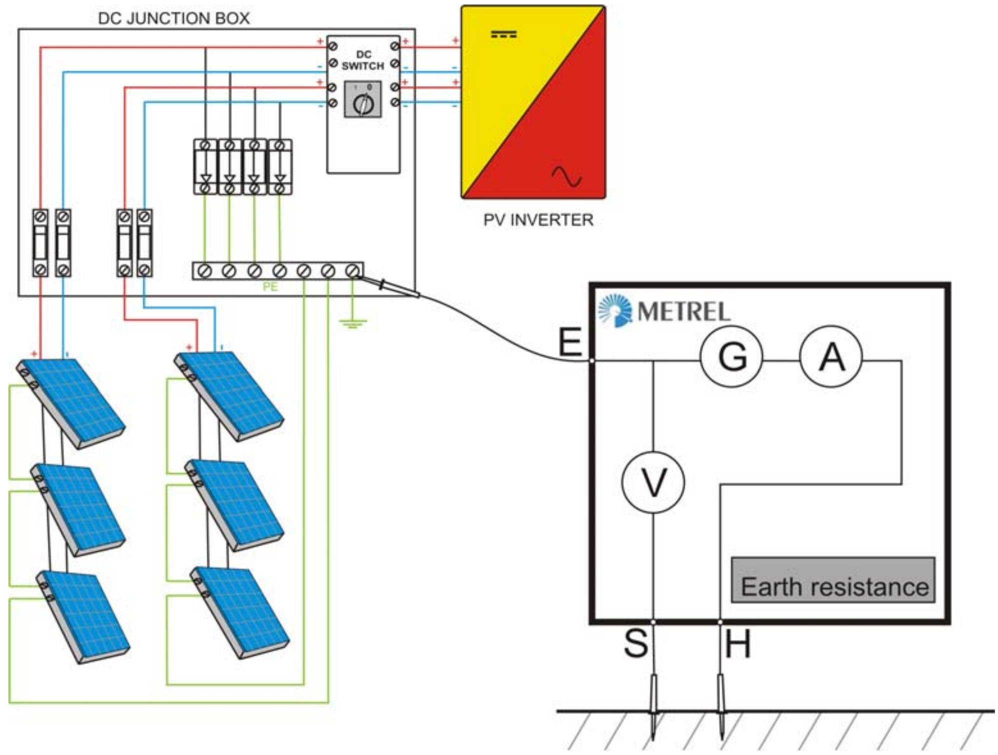



*Fig.3.7 ①: Measurement of continuity on d.c. side of PV installation*

The earthing resistance of earthing electrodes should be measured with an appropriate earth resistance test.
The earthing resistance test with two clamps is a suitable method for measuring resistance if there are more earthing electrodes in parallel. Typical resistance limit for an earthing electrode is less than 10 Ω. Fig. 3.7 ② shows measuring connections for the earthing resistance test. The two clamp earthing resistance test can be performed with several Metrel testers.



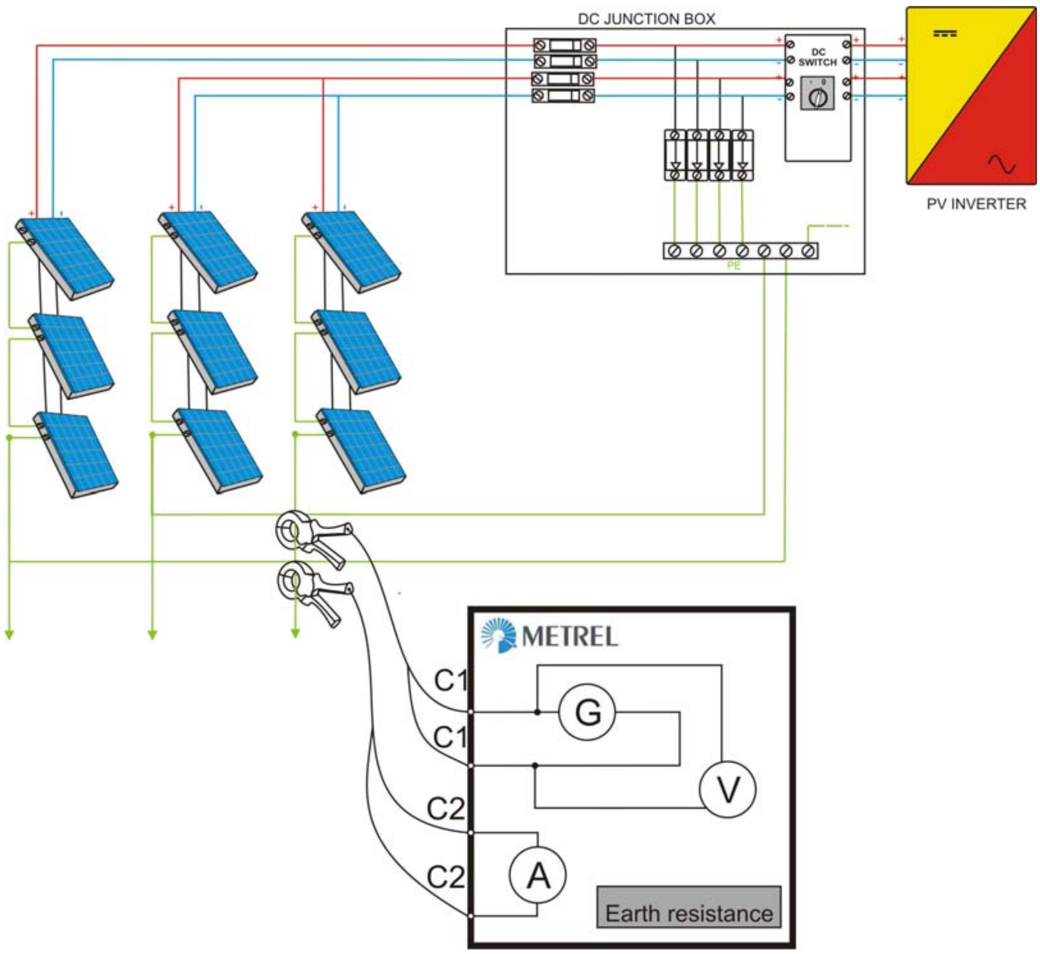




*Fig.3.7 ②: Measurement of earthing resistance of earthing electrodes*

## 3.8 Insulation resistance between live and protective parts of PV generator

The protection by isolation in PV system is at least of the same importance as in standard a.c. installations. Because of the exposure of PV devices and components to high d.c voltages and high risks in case of fire the insulation resistance should be regularly verified.
The insulation resistance between the PV module/ string/ array and PE connection should be measured.

Two possible test methods are defined in IEC 62446:
Method 1: Test between array negative and earth followed by a test between array positive and earth.
Method 2: Test between earth and short circuited array positive and negative.
The advantages of method 1 are:

- no need to make a short circuit of the PV generator's output.
- measurement is carried out with two test terminals. This can be an advantage if the connection points are difficult to access.

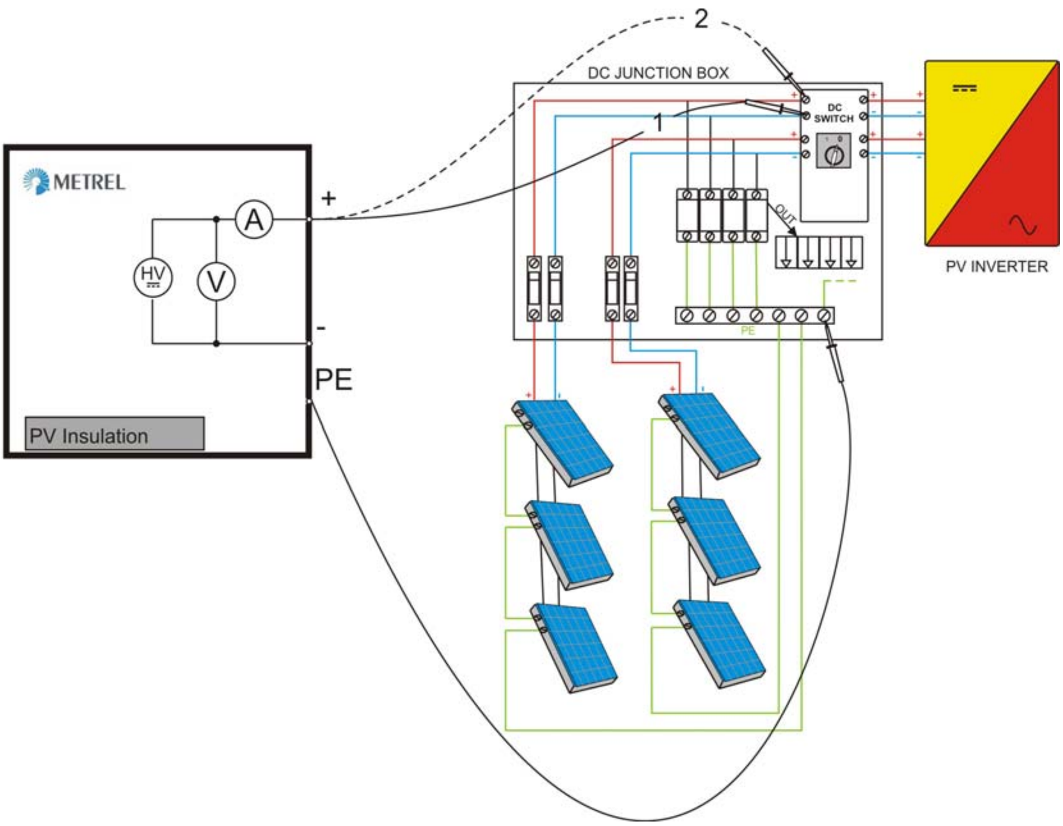
Drawback is that two measurements must be taken to get a valid insulation result.

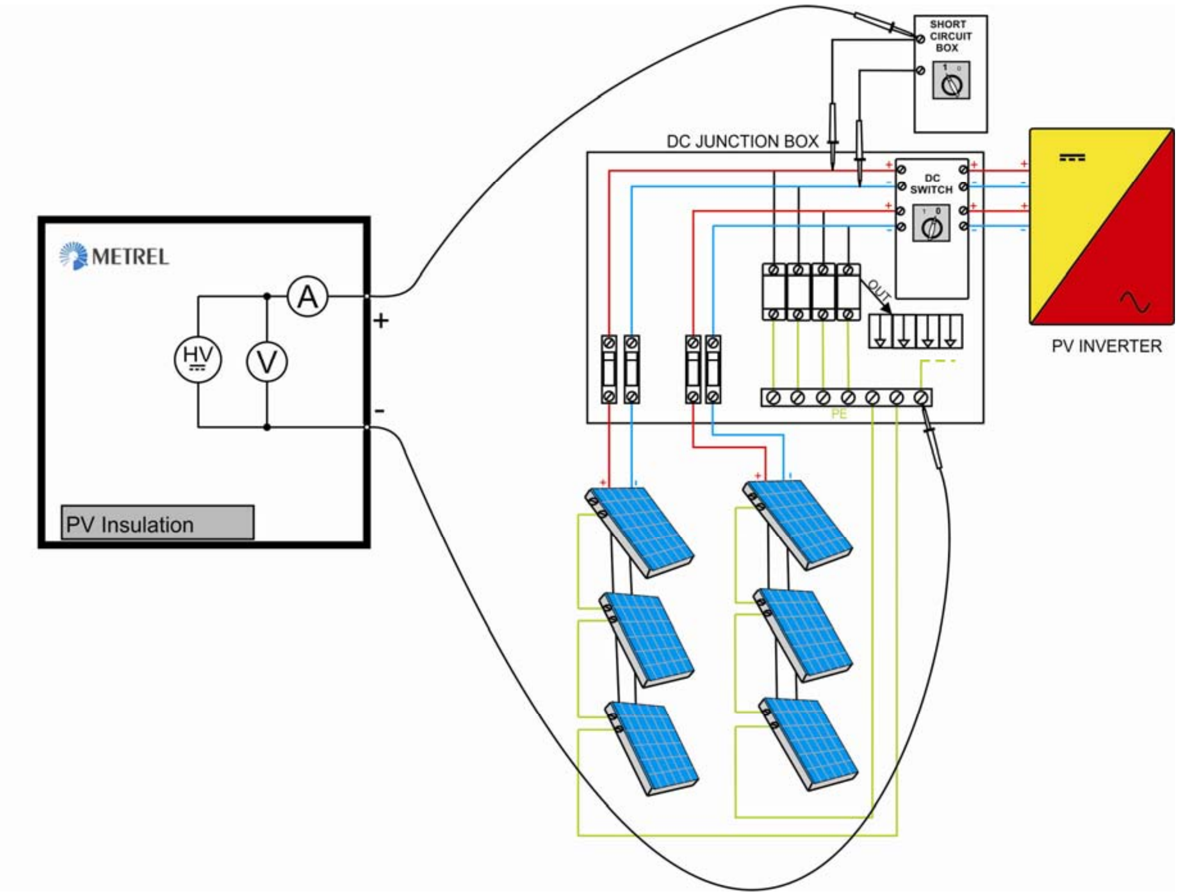
Test voltage and limits (both methods) acc.to IEC 62446:

| 1.25x Uoc of PV system | Test voltage / Limit |
|---|---|
| < 120 V | 250 V / 0.5 MΩ |
| < 600 V | 500 V / 1 MΩ |
| < 1000 V | 1000 V / 1 MΩ |

*Table 3.8: Test voltages and limits for insulation resistance test*

Fig. 3.7 shows measuring connections for the PV insulation test:
first figure shows measuring connection for method 1
second figure shows measuring connection for method 2
last figure shows measuring connection for method 1 with Metrel's PV tester MI 3109.


2
1
DC JUNCTION BOX
DC SWITCH
OUT
PE
METREL
A
HV
V
+
-
PE
PV Insulation
PV INVERTER


SHORT CIRCUIT BOX
DC JUNCTION BOX
DC SWITCH
OUT
PE
METREL
A
HV
V
+
-
PV Insulation
PV INVERTER

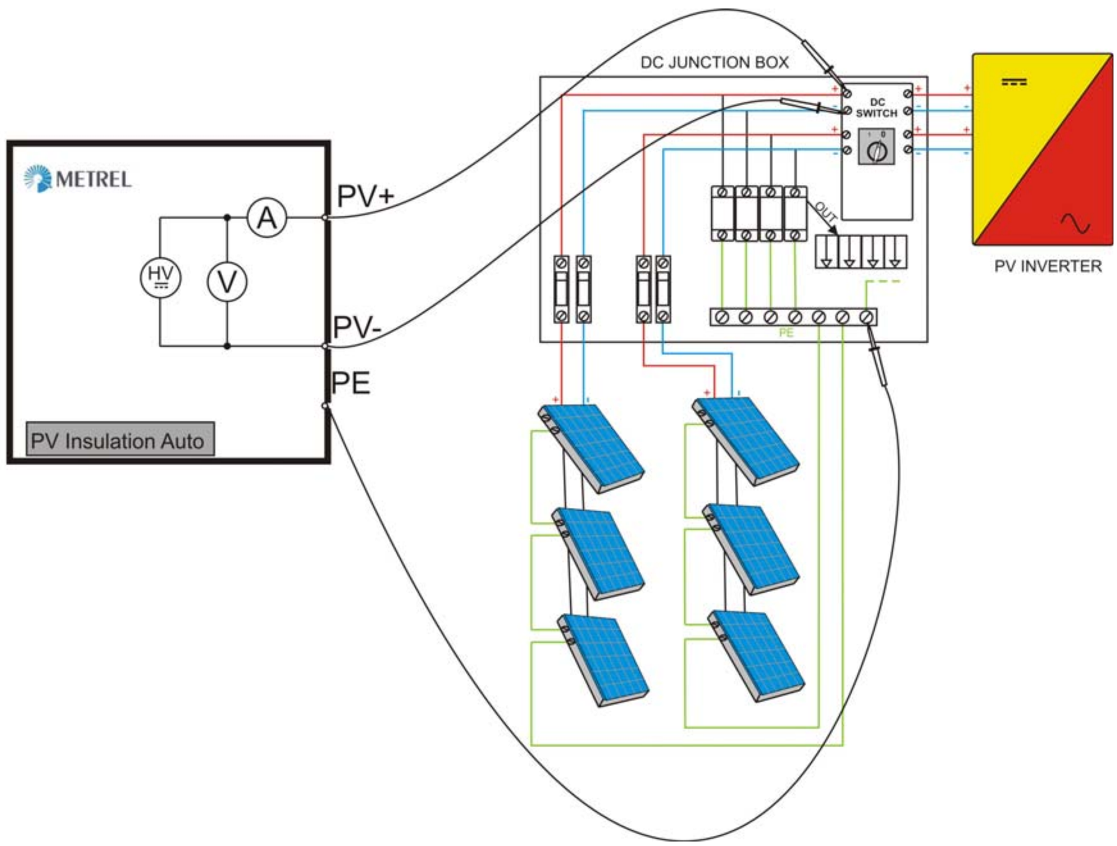
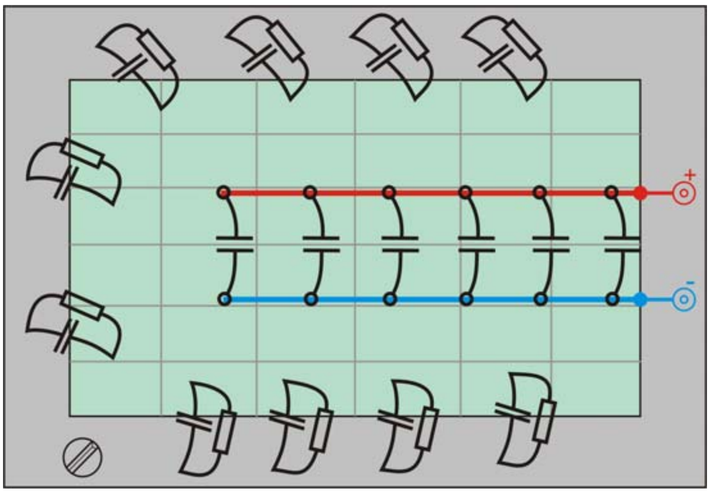



*Fig.3.8: Measurement of PV Insulation (both methods)*

### 3.8.1 Influence of leakage components in PV generator

Acc. to IEC 62446 insulation resistance measuring equipment designed according to IEC 61557-2 is appropriate. However because of the leakage components of PV modules different measuring instruments may show different results. Fig. 3.8.1 shows a model of the PV module with leakage parameters (resistive and capacitive leakage paths).



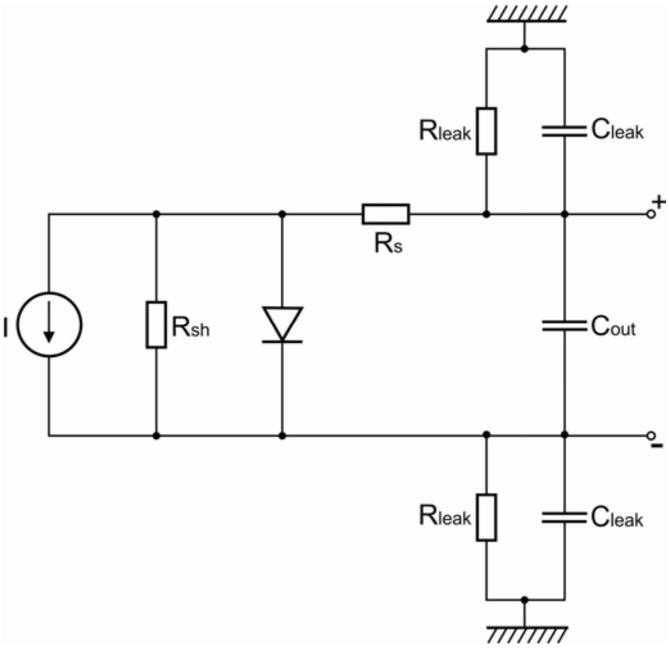



*Fig 3.8.1: Leakage components in PV module*

The size of leakage components is usually unknown and varies with the operating conditions and time of the day. In general the capacitances are proportional to the size of the PV array and are larger at low irradiance. For large arrays the values can increase up to µFs and this can mean troubles for the measuring equipment.
It is important that the inverter and surge protectors are disconnected from the PV module /string / array during the test. Both add additional leakage paths against earth and can influence the results.

### 3.8.2 Interaction of leakage components and measuring instrument:

Because of leakage components in the PV module there will already be (a low energy) high external voltage present on the measured connections before the test. After the tester is connected the size of voltage depends on the size of PV generator's leakage components and the input resistance of tester. If the leakage capacitors are small they will be discharged through the resistance of the measuring instrument and will decrease very fast . If the voltage doesn't drop this means that the PV generator charges the leakage capacitances faster than the test equipment can discharge them or an erroneous connection directly to the PV source.
In case of high leakage capacitances and/or the ability of the PV generator to fast charge the leakage capacitors following problems appear:
The measuring instrument must start the test at high external voltage.
It is likely that the charging currents will interfere with the measuring current and influence the reading.
The level of influence depends on the electrical design of the tester but can not be estimated on base of technical specification of the insulation tester.
Because of the leakage components the result may be different if measuring acc. to method 1 or method 2.

Metrel's testers use method 1 for the PV insulation test. They estimate the leakage parameters in a pre-test before the test. If the measured leakage is too high the measurements will be blocked and a warning will be displayed.

## 3.9 DC voltage and current measurements

The momentary voltage and current on the output of the PV module/string/array are measured in this test.
The output voltage and current depend on environmental conditions and how the inverter adjusts the operating point. The inverter tracker should adjusts the voltage and current to get the maximal available power (MPP point) from the connected PV generator.
If there are more identical strings the results should be compared. According to EN 62446 the difference between strings should be lower than 5%. If the difference between the results lies inside the 5% limits,
it is very likely that there are no graving problems with the performance of the PV installation. If other tests according to EN 62446 pass it is also very likely that the PV generator has no safety problems.
The measured voltage and current results should be compared with the inverter's reading (if they are available). Fig. 3.9 shows measuring connections for the d.c voltage and current test.

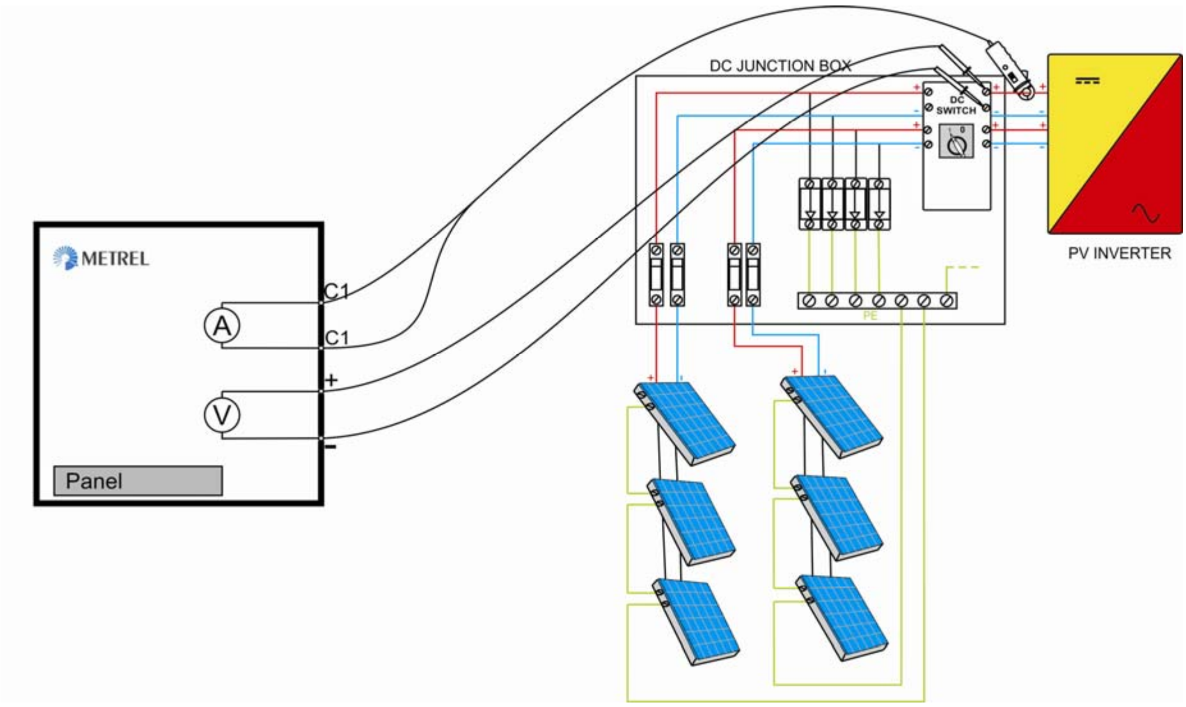



*Fig.3.9: Measurement of d.c. voltage and current*

If environmental data and module data is available the results can be calculated to STC values. STC values give additional and more accurate information about the performance of the PV system (see chapter 8.1 for more information)

$$Ppvgen_{meas} = U_{meas} \cdot I_{meas}$$ *Eq.3.9 ①*

$$Ppvgen_{STC} = U_{STC} \cdot I_{STC}$$ *Eq.3.9 ②*

$$Ppvgen_{STC} \approx Ppvgen_{nom}$$ *Eq.3.9③*

*$U_{meas}$ , $I_{meas}$…… ………..measured output voltage and current of PV generator*
*$Ppvgen_{meas}$……………..measured output power of PV generator*
*$U_{STC}$ ,$I_{STC}$…………………STC voltage and current (calculated)*
*$Ppvgen_{STC}$………………STC power (calculated)*
*$Ppvgen_{nom}$……………nominal power of the PV generator*

$Ppvgen_{STC}$ should be close to the nominal power *$Ppvgen_{nom}$* of the measured module/ string/ array. For strings and arrays with same modules the nominal power can be calculated according to Equation *3.9 ④*. Losses of the wiring can be considered (see chapters 8.2 and 8.5) but are usually neglected.

*$Ppvgen_{nom}$ (of string, array) =* $P_{nom}(\text{of module}) \cdot n \cdot m$ *Eq.3.9 ④*

*$Ppvgen_{nom}$(of string, array)…….nominal power of PV string/ array*
*$P_{nom}$(of module)…………..nominal power of PV module*
*n…………………………………number of modules in series in string*
*m……………………………….number of strings in parallel in array*

Similar $Ppvgen_{STC}$ and $Ppvgen_{nom}$ values gives additional level of confidence that the PV systems performance is appropriate.
For a more complete verification or if the measured power is not similar to the nominal power a further analysis should be taken (on base of I-V measurement).

## 3.10 Open circuit voltage (Uoc) and short circuit current (Isc) tests

Uoc is the output voltage of the PV module/ string/ array in no-loaded condition (I = 0 A).
Isc is the output current of the PV module/ string/ array if the output is shorted (U = 0 V).

In IEC 62446 the Uoc and Isc tests are defined as a check for correct installation of the PV installation. It is noted that this tests are not a performance test of the PV generator. If there are more equal strings the results should be compared and the difference between individual strings should be lower than 5%. Larger differences may indicate a problem.
The minimum testing requirements for testing and interpreting the Uoc and Isc according to the standard IEC 62446 are simple. However there are many arguments for a more complete test. On base of calculation to STC values and measurement of I-V curve a more complete information about the PV system can be obtained.
If environmental values at the time of the Uoc / Isc tests and PV module data are known the results can be calculated to STC values. The measured calculated STC values ($Uoc_{STC}$, $Isc_{STC}$) can then be compared with the nominal values ($Uoc_{nom}$ and $Isc_{nom}$). For strings with same PV modules the nominal values of the string can be calculated according to Equations *3.10 ①* and *3.10* ②. The STC values should be close to the nominal values of the measured string.
Fig. *3.10* shows measuring connections for the Uoc/ Isc test.

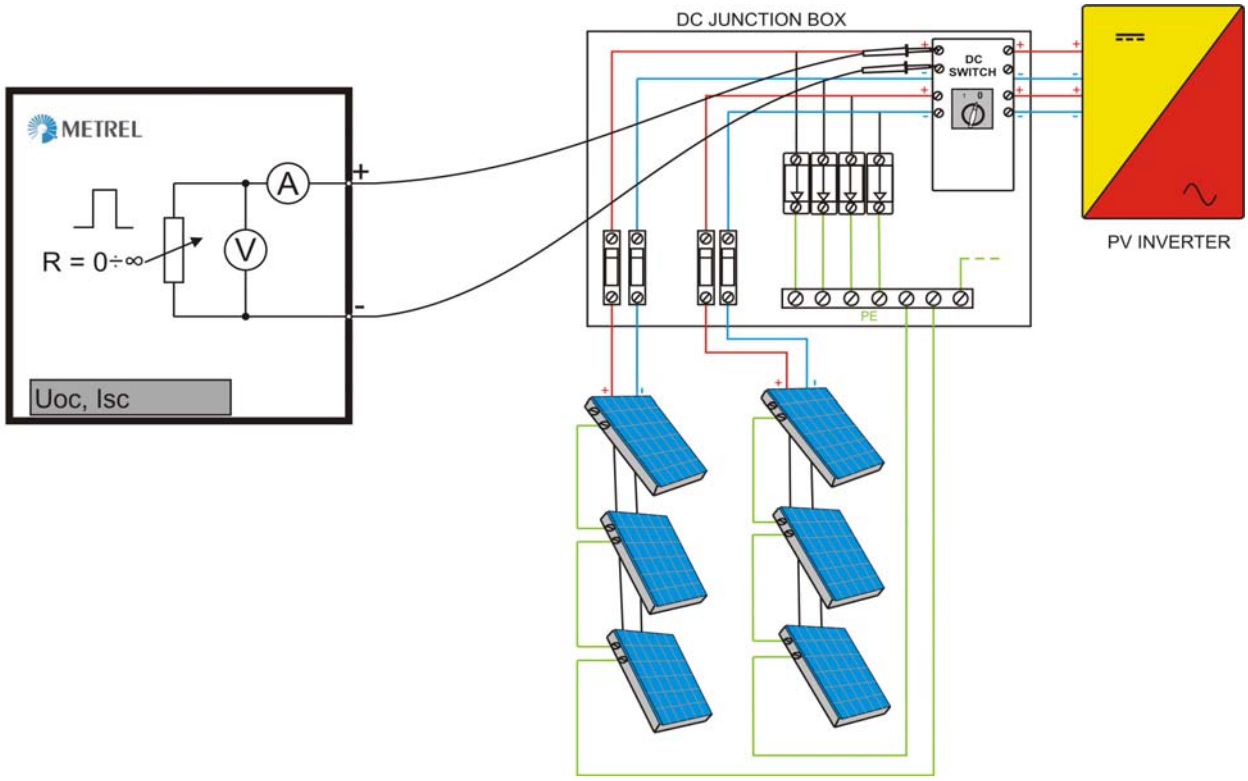



*Fig.3.10: Measurement of Uoc and Isc*

$$Uoc_{nom}(\text{of string, array}) = Uoc_{nom}(\text{of module}) \cdot n \qquad \textit{Eq.3.10①}$$

$$Isc_{nom}(\text{of array}) = Isc_{nom}(\text{of module}) \cdot m \qquad \textit{Eq.3.10②}$$

*$Uoc_{nom}$ (of module), $Isc_{nom}$ (of module)…nominal values of PV module*
*$Uoc_{nom}$ (of string, array), $Isc_{nom}$ (of array)…nominal values of string or array*
*n….. modules in series in string*
*m….modules in parallel in string*

If:
the nominal (on base of manufacturer's data) and STC (on base of measurement and calculation) results are similar,
the difference between results for individual strings lies inside the 5% limits it is likely that there are no graving problems on the PV installation. If other tests according to EN 62446 pass it is also very likely that the PV generator has no safety problems.
With the Uoc / Isc test it can not be confirmed that the PV generator has proper performance. For a more detailed information or if the STC results are not similar to the nominal results further analysis should be taken (on base of the I-V measurement).

# 4. STC (Standard Test Condition) values

The performance of PV generators depends on the level of radiance and temperature. Measurements taken at different time can not be directly compared. The calculation to STC (Standard Test Condition) values enables to compare PV measurements that were measured at different environmental conditions and time. Test results measured at standard conditions or calculated to standard conditions are marked as STC values. Standard conditions are defined in the standard IEC 60904:

- Irradiance: G, Irr = 1000 W/m$^2$,
- Cell temperature: $T_{STC}$ = 25°C ,
- airmass factor: AM = 1.5 (corresponds to conditions in Europe)

In Metrel PV testers and PC software the measured values are calculated to STC values acc. to IEC 60891, Ch. 3.3: Correction procedure 2 (see Eq.4 ① to Eq.4 ③):

$$I_{STC} = I_{meas} \cdot (1 + \alpha_{rel} \cdot (T_{STC} - T_{meas})) \cdot (\frac{Irr_{STC}}{Irr_{meas}})$$ Eq. *4* ①

$$U_{STC} = U_{meas} + Uoc_{meas} \cdot (\beta_{rel} \cdot (T_{STC} - T_{meas}) + \alpha \cdot \ln(\frac{Irr_{STC}}{Irr_{meas}})) - Rs_{meas} \cdot (I_{STC} - I_{meas}) - k' \cdot I_{STC} \cdot (T_{STC} - T_{meas})$$

Eq. *4* ②

$$Rs_{meas} = \frac{N}{M} \cdot Rs_{nom}$$ Eq. *4* ③

*$I_{STC}$, $U_{STC}$…….. calculated STC values of current and voltage*
*$I_{meas}$, $U_{meas}$…. measured direct current and voltage on PV generator*
*$Uoc_{meas}$……… measured Uoc*
*$Irr_{STC}$………….. reference irradiance 1000 W/m$^2$*
*$Irr_{meas}$ ………. measured irradiance*
*$\alpha_{rel}$……….….. relative voltage temperature coefficient*
*$\beta_{rel}$………..….. relative current temperature coefficient*
*α……………… irradiance correction factor (typically 0,06)*
*$T_{STC}$………….. reference temperature 25°C*
*$T_{meas}$……….. measured temperature of the module*
*$Rs_{nom}$…….… serial resistance of module*
*k'……….…… temperature coeff. of Rs*
*N………..….. number of modules in serial*
*M…….…….. number of modules in parallel*

The PV module parameters *$\alpha_{rel}$ and $\beta_{rel}$* are parameters that must be given by the manufacturer. The PV module parameter Rs is in most cases not given by the manufacturer but can be obtained from the measurement. Manufacturer's nominal data is always given at STC.

## 4.1 Calculation of Rs

The procedure of calculation of Rs as described in the standard IEC 60891 is difficult to perform. It demands to calculate Rs on base of two measurements at two different irradiance levels while keeping all other parameters unchanged.
For general measurements and STC calculations a value of 10mΩ/cell can be used but for the evaluation of the measurement results an exact value of Rs for each module type has to be determined.
Metrel uses a special algorithm that enables the calculation of Rs on base of one I-V measurement.
The I-V measurements are usually performed near the inverter. This means, that the measurement results are also influenced by the resistance of wiring from the modules to the inverter, contact resistances in the DC junction box and voltage drop on the blocking diode.

**Example:**

*The cable length between modules and inverters is 75 meters; the material of the conductor is Cu with crossection of 6mm$^2$. This brings an additional resistance of (see table 3.7):*

$$R_{cond} = 2 \times 75m \times 0{,}01722\Omega mm^2 / 6mm2 = 430m\Omega$$

*Each additional PV connector brings (according to manufacturers data) approximately 1mΩ, in the same range are also the junctions resistances in DC boxes.*

*The voltage drop on the blocking diode is at the $I_{MPP}$ approximately 1 V*

*If $I_{MPP}$ = 8A the voltage drop on cables and junctions is ≈4V or ≈5V if a blocking diode is used. For a string with 25 modules, which have $U_{MPP}$=30V each, what finally means $U_{MPP}$ = 750V for string, the 5V drop on cables, junctions and blocking diode brings an 0,7% error.*

The example above shows that the additional losses can usually be ignored. However this can drastically change with time if the contact resistances changes. The modules and cables are exposed to extremely different weather conditions and are therefore subject to changes. Different chemical and physical phenomena can influence the contact resistances as well as mechanical stress (rebuilding, adaptations, …).

Higher resistance means less power efficiency of the PV generator and can in extreme cases, because of overheating, also cause a fire.

# 5. Influencing factors on the performance of the PV generator

The sun's radiation and temperature are changing all the time.
The sun's radiation depends on the geographic location, time of the day, period of the year, position and inclination of the PV modules. PV cells give more energy at lower temperatures. For example the performance at 50°C is about 20% lower than at 20°C.

Slow changes
If the sky is clear the irradiance and temperature changes due to the sun's position are predictable. The rate of changes is slow enough that the time of measurement will not cause problems. The irradiation should be at least 600 W/$m^2$ in order to get valid and comparable results. If irradiance and temperature data at the time of measurements are known the results can be calculated to STC values – to make a more accurate comparison.

Fast changes
Non ideal weather causes unstable conditions for testing. If the sky is not clear the sun's radiation strongly depends on the clearness of the sky. Clouds, fog and diffuse lights are lowering the radiation. Especially diffuse light is sometimes difficult to perceive. In such conditions the fluctuations of the irradiation can reach several 10% in seconds. This makes the measurements more demanding or even impossible.
If the sky is partly cloudy the user must also make sure that the complete PV array is equally illuminated. Even a small shadowed part of the module can cause useless results.

The user must be able to estimate if the environmental conditions are appropriate for testing.
the weather at the moment of measurement must be observed. It must be verified that there is no changing diffuse light and that the clouds are not shadowing only a part of the PV generator.
the measured results must be carefully checked. Fast changing of irradiation and sometimes also temperature will most often result in unusable results. If the results are fluctuating they are not really representative. If the STC results are not close to nominal values they are probably wrong.
knowing the environmental parameters at the exact time of measurement is of highest importance. U, I and Uoc, Isc measurement results are subjected to external conditions. Except the environmental parameters there is no additional information that would confirm if the measurement were valid.

**Careful observation of the sky and weather, making sure the PV generator is equally illuminated, logging Irr and T, and analyzing the shape of the I-V curves is the best combination for getting valid results in unstable weather.**

All Metrel's measuring PV instruments include the I-V function. They can also capture and log the irradiance and temperature measurements.

A 1378 EurotestPV Remote

The A 1378 EurotestPV Remote is an independent measuring instrument for measuring environmental conditions and logging of them. It enables to perform environmental measurements on the roof while the PV measurements are taken at the DC junction box below the roof. The instruments can be synchronized after the measurements have been finished to get exact results.

The unit measures irradiance and cell temperature and logs each change of these values together with the time stamp. A time synchronisation prior to the tests has to be performed. After the measurements on PV system are finished, the measurement results on instrument have to be synchronized with the environment data stored in the remote unit and after that, the recalculation of STC results, stored in the instrument, is performed automatically.

# 6. I-V curve test

The performance of the measured PV generator at different loads can be tested with the I-V curve test. Fig. 6① shows measuring connections for the I-V curve test.

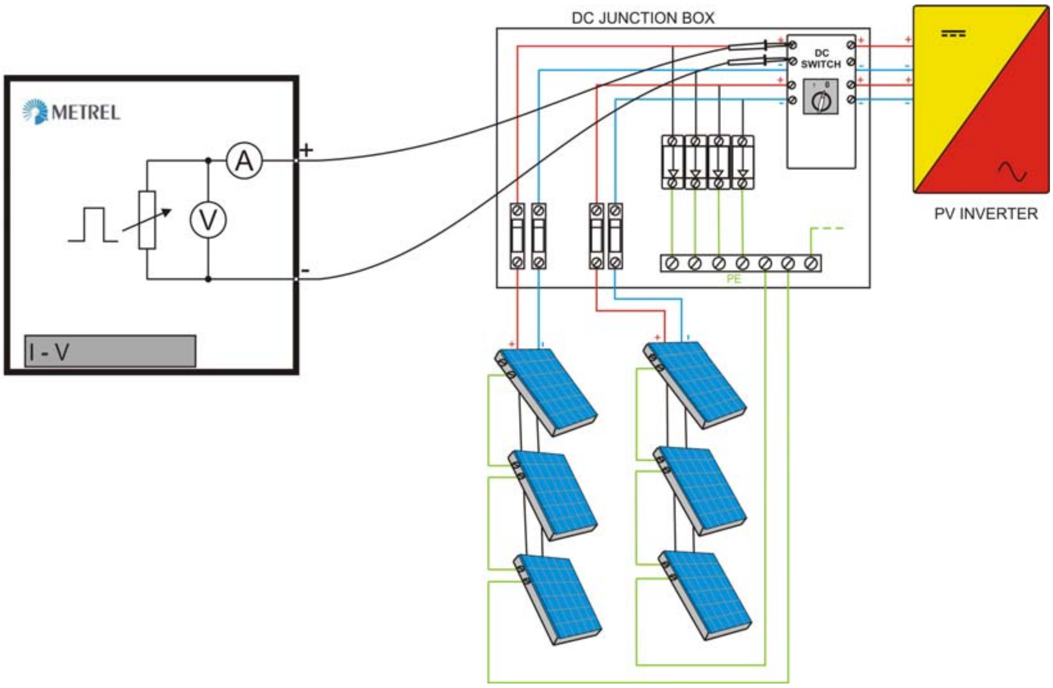



*Fig.6 ①: Measurement of I-V curve*

The I-V curve consists of current / voltage pairs that form the curve. The pairs represent the PV generator's current and voltage at different loads. The pairs are usually presented as I(U) graph or P(U) graph.

Three important current/ voltage pairs are a part of the curve:

- The maximal power point (MPP)
- Uoc (at I = 0 A)
- Isc (at U = 0 V)

If environmental and PV module data are known each voltage / current pair can be calculated to STC voltage / current values that are composing the $(I\text{-}V)_{STC}$ curve. The $(I\text{-}V)_{STC}$ curve can be compared with the nominal $(I\text{-}V)_{nom}$ curve. On Fig.6② (I-V) curves (measured and STC) and Uoc, Isc, MPP points are shown.

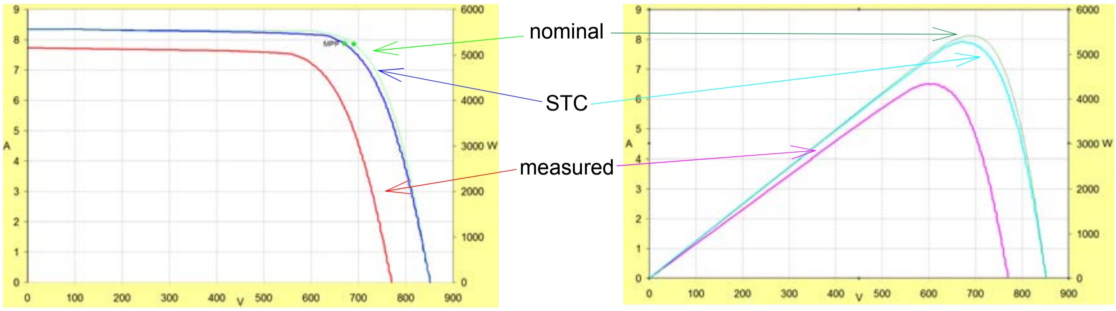



*Fig.6②: measured, nominal and STC U(I), P(I) graphs*

$$(I-V)_{STC} = f((I-V)_{meas}, Irr, T\text{module}, \text{module data})$$ *Eq.6 ①*

$$MPP_{STC} = \max\cdot(U_{STC}\cdot I_{STC})$$ *Eq.6 ②*

$$(I-V)_{STC} \approx (I-V)_{nom}$$ *Eq.6 ③*

$$MPP_{STC} \approx MPP_{nom} = Ppvgen_{nom}$$ *Eq.6 ④*

*$(I-V)_{meas}$…….measured I-V curve*
*$(I-V)_{STC}$………I-V curve at STC conditions (calculated)*
*$(I-V)_{nom}$…….nominal I-V curve of PV generator*
*$MPP_{STC}$……..maximal power point at STC conditions (calculated)*
*$Ppvgen_{nom}$, $MPP_{nom}$……………….nominal power/ MPP of the PV generator*

For equally illuminated PV model/ string/ array the measured and calculated I-V curve should be similar to the nominal curve.
$Uoc_{STC}$, $Isc_{STC}$, $MPP_{STC}$ on the $(I-V)_{STC}$ curve and should be similar to the nominal data.

For strings with same modules the nominal curve data can be calculated from the modules nominal data. Losses are usually not considered.

$$(I-V)_{nom}(\text{of string, array}) = (I-V)_{nom}(\text{of module})\cdot n\cdot m$$ *Eq.6 5*

*$(I-V)_{nom}$(of string, array)….nominal I-V curve of string/ array (calculated)*
*n…..modules in series in string*
*m….modules in parallel in array*

# 7. Typical problems on PV generators and their impact on the I-V curve

## 7.1 Normal I-V characteristic

On Fig. 7 I(U) and P(U) graphs of a normally operating string are shown.

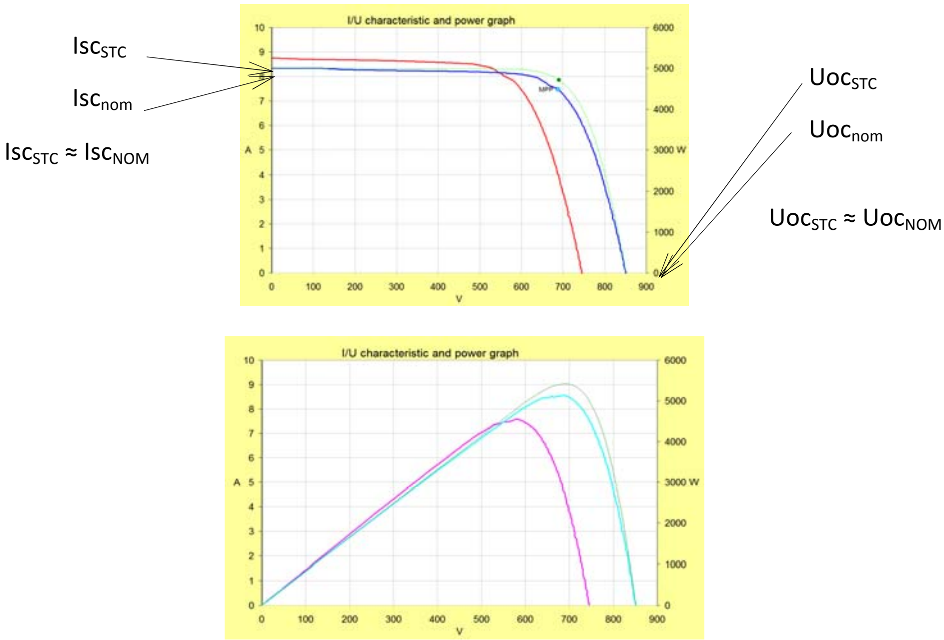



*Fig.7: U(I), P(I) measured and STC graphs of a string*

Typical problems on PV generators are:

- shadows
- dirt
- failures of individual PV cells
- wiring losses
- ageing
- malfunction of inverter

All problems result in a lower MPP point. Most of problems on the PV generator are visible as anomalies on the I-V curve.

## 7.2 Measurement errors

Testing of I-V curves is subjected to different errors. A check on measurement errors has always to be done before further analysis of results.
Typical measurement errors are:

- wrong module data: Uos, Isc, Umpp, Impp, Pmpp, α, β, missing Rs
- wrong number of modules in string

- wrong temperature
- changing irradiation
- These errors are indicated in:
- Too low or too high Uoc
- Too low or too high Isc
- Anomalies (bump) in the form of the I-V characteristics

Metrel's PCSW PVAnalyse tool enables later change of module and environemntal data (to correct values). Tests don't need to be repeated.

### 7.2.1 Too low or too high Uoc

Possible reasons:

- Wrong temperature: check how the temperature sensor is fixed. If needed correct the mounting of the sensor and repeat the measurement(s). See Fig. *9.3.8* for how to mount the temperature sensor.
- Wrong module data: check the values Uoc and β and enter the correct values into the fields within PVAnalyse tool. No need to repeat the test.
- Incorrect number of modules in the string: check the project documentation and the actual situation and correct the number if needed. No need to repeat the test.

### 7.2.2 Too low or too high Isc

Possible reasons:

- Wrong irradiation: check the mounting of the pyranometer, if the irradiation is too low, the recalculation to STC is not performed. If needed, correct the mounting or wait for higher irradiation. See Fig. *9.3.7* for how to mount the irradiance sensor.
- The irradiation has changed during the measurement: the irradiation at the beginning and at the end of the measurement is not the same. Repeat the measurement at stable environment conditions.
- Wrong module data: check the values Isc and α and enter the correct values into the fields within PVAnalyse tool. No need to repeat the test.

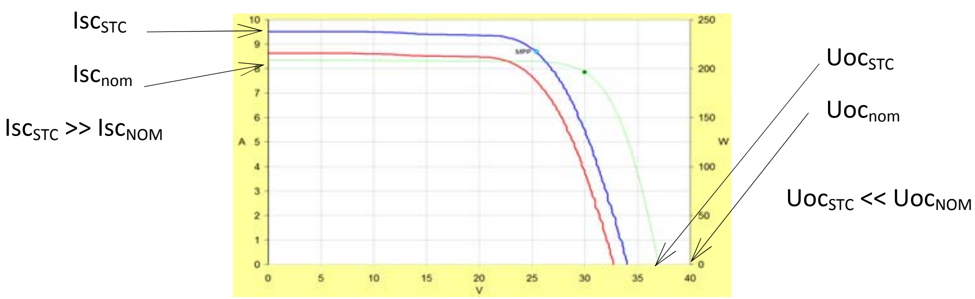



*Fig. 7.2.1: Measurement errors on module*

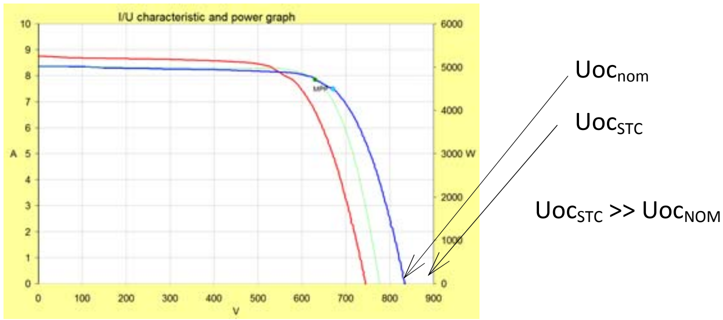



*Fig. 7.2.2: Wrong number of modules in string*

### 7.2.3 Anomalies (bump) in the form of the I-V characteristics

Possible reasons:

- Short change of the irradiance during the measurement of the I-V curve: Repeat the measurement at stable environment conditions.

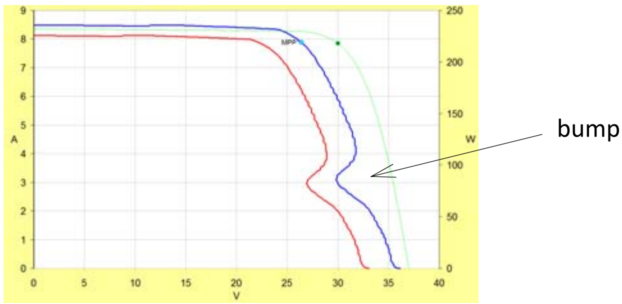



*Fig.7.2.3: Changing irradiance during the test*

## 7.3 Errors on PV modules and strings

If, after the measurement errors were removed, the anomalies in the I-V curve are still present then further analysis of the I-V characteristic is needed.

Error indications and possible reasons:

- Isc too small
- Uoc too small
- Anomalies (concaves) in the I-V characteristic

### 7.3.1 Isc too small

Possible reasons:

- evenly spread dirt or
- a diffused shadow from far obstacle have the same influence as lower irradiation
- ageing

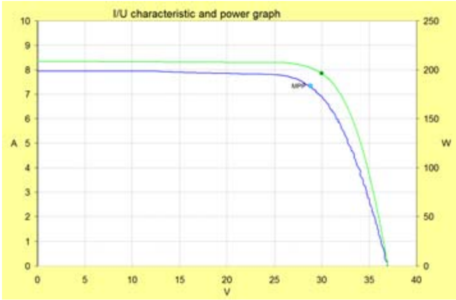



*Fig 7.3.1: Dimmed module*

### 7.3.2 Uoc too small

Possible reasons:

- fully shadowed or damaged modules (by-pass sectors)

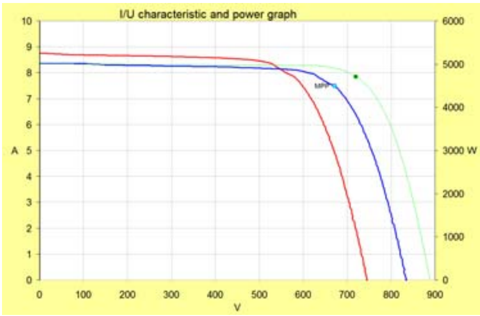



*Fig. 7.3.2 Fully shadowed or damaged modules (by-pass sectors)*

### 7.3.3 Anomalies (concaves) in the I-V characteristic

The I-V curve is not uniform and has one or more concaves. MPP point is significantly lower. Even small shadows have large influence.

Possible reasons:

- partially shadowed module or string
- bird droppings
- obstacle near to modules
- diffuse light – fog, high clouds influencing only on part of the string
- dust on part of the module or string
- mechanical changes on PV modules (blurring of glass)
- mechanical damage on PV modules (hail)

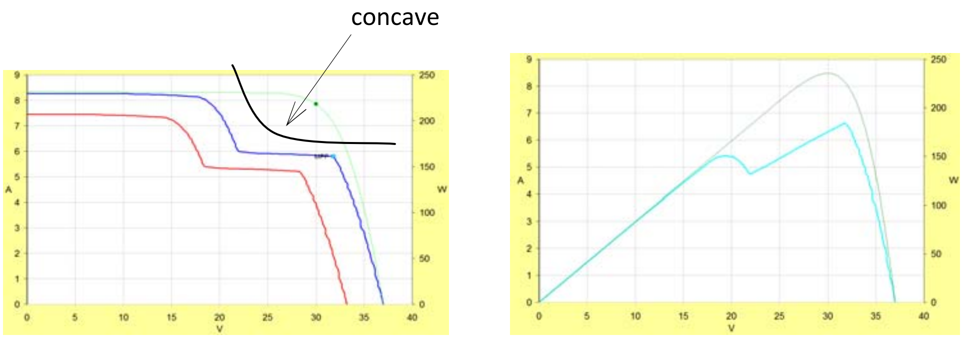



*Fig. 7.3.3: Partially shadowed string*

### 7.3.4 Anomalies in the I-V characteristic

Possible reasons:

- obstacle completely covers a part of PV module. No light or diffuse light reaches one part of the PV generator beneath the obstacle.

Figure 7.3.4 shows influence on a PV module with one bypass sector fully shadowed.

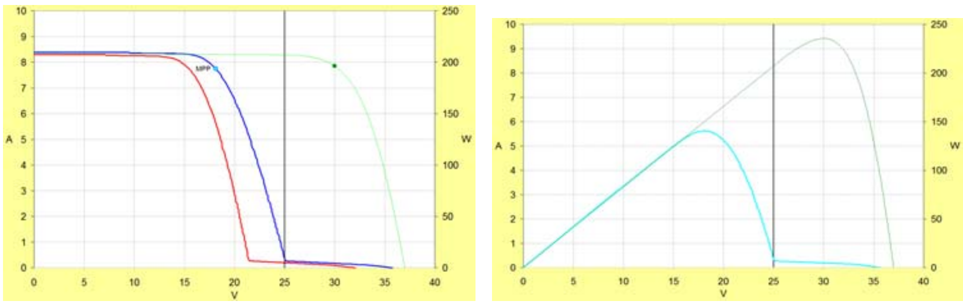



*Figure 7.3.4: I-V and P-V curves of shadowed PV module*

Figures 7.3.5 shows influence of fully and partially shadowed modules on a PV string with 23 modules.

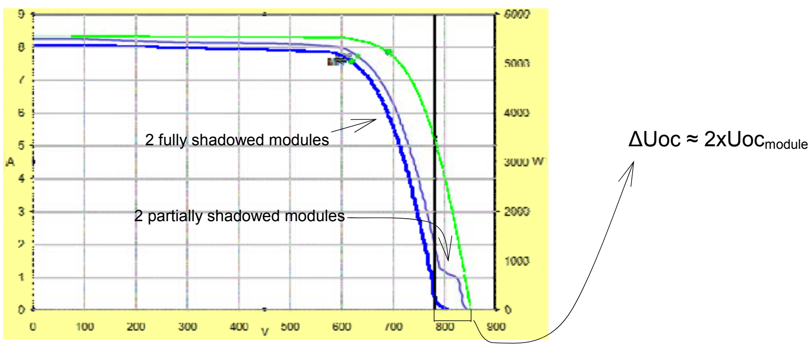



*Figure 7.3.5: I-V curve of PV string with two shadowed modules*

### 7.3.5 MPP too low

Possible reasons:

- Additional serial resistances in string due to wiring losses, contacts etc.
- bad contacts
- connection problem in PV module
- corrosion
- under-dimensioned cables

$$Rloss = \Delta U(\mathrm{Impp_{STC}})/\mathrm{Impp_{STC}}^2 = (U_{nom}(\mathrm{Impp_{STC}}) - Umpp_{STC}) / \mathrm{Impp_{STC}} \qquad Eq.7.3.5$$

*Rloss…….additional serial resistance*
*ΔU……….voltage difference between measured STC and nominal voltage at measured Impp*
*Impp…..measured mpp current at STC conditions*
*$U_{nom}$……nominal voltage at measured Impp*
*Umpp…measured mpp voltage at STC conditions*

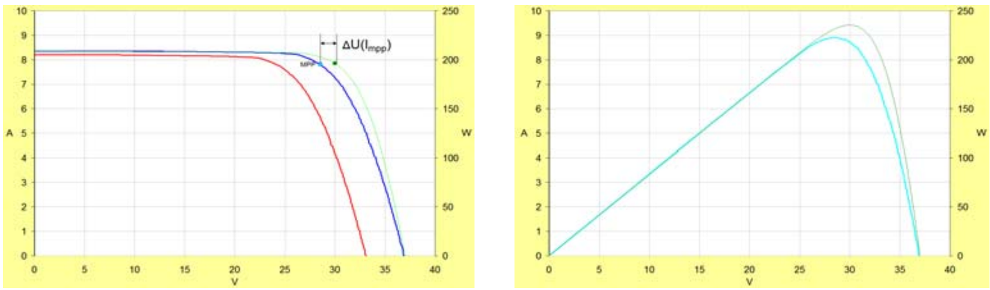



*Fig. 7.4: influence of additional serial resistance*

<u>Influence</u>
Energy is lost inside in string's wiring and other serial resistances instead of delivering to the inverter
Higher impact on the constant current part of the curve. MPP point is slightly lower.

# 8 Performance and efficiency of PV systems

PV systems should provide the specified amount of energy over a long period. The expected lifetime of PV systems is at least 20 years. Even a small decrease of performance results over a longer period in significant losses of money and prolongs the time of the return of the investment. Therefore it is recommended to verify the performance of the PV system by measurements after installation. Later periodic verifications of performance supported with measurements should be performed regularly. Comparison with previous results should be made during periodic verifications.
This chapter describes the procedures for verification of the efficiency.

Main factors that decrease the performance of the PV generator:
- Non-optimal position of the PV generator. The projecting and installation of the PV generator is beyond the scope of this booklet.
- Efficiency of the PV generator (efficiency of conversion of sun's to electrical energy).
- Losses on d.c. side. They consist of wiring losses, contact losses, losses on serial components from PV modules down to the input of inverter.
- Correctness of the set MPP point (proper tracking of the inverter).
- Efficiency of the inverter (losses caused by conversion of d.c. to a.c. energy).
- Losses on a.c. side. They consist of wiring losses, contact losses, losses on serial components and devices between inverter and connection point to power grid.

Except connection points ageing of components shouldn't be a big problem. The producers of PV modules usually specify that the power stays within 95% of the nominal power within at least 20 years. The inverter is an electronic device and its performance will not change until there is no failure. Fig.8 shows a PV system and most important points for defining the efficiency.

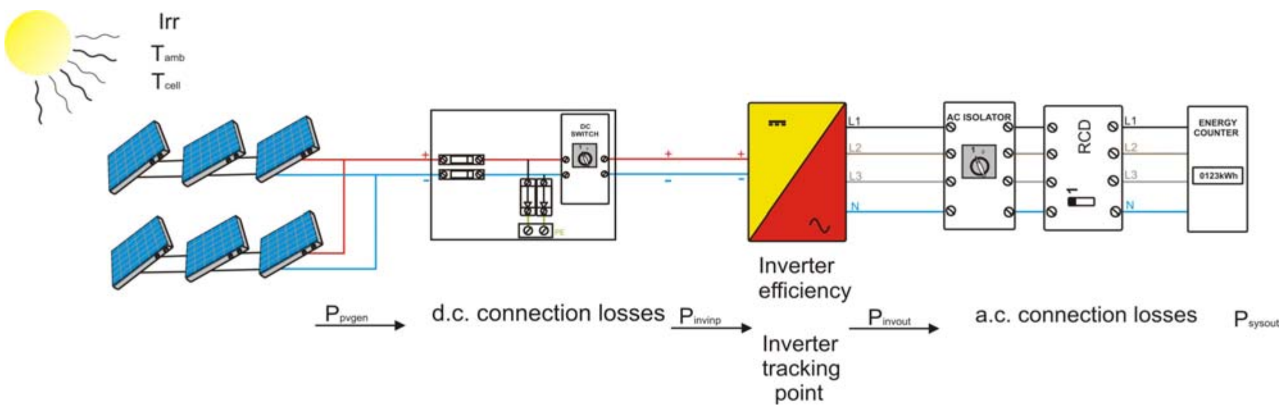



*Fig. 8: Performance of a PV system*

## 8.1. Verification of performance of PV module / string/ array

This verification is to check proper performance of the PV module / string/ array.
Procedure is as following:

1. Check environmental condition before performing tests. Irradiance should be as high as possible (at least 600 W/m$^2$, best above 800 W/m2) and stable to get more accurate results.
2. Perform the I-V curve test. The PV generator must be disconnected from the inverter during the test. The shape of the curve should not show any unexpected anomalies.
3. Calculate the STC values.
4. Compare calculated STC and nominal values.

Results of +0% and -5% for MPP are typical for properly working modules. See chapter xy for information about possible reasons for degradation of performance.

$$(I-V)_{STC} = f((I-V)_{meas}, Irr, T\text{module}, \text{module data}) \qquad \textit{Eq.8.1} \text{ ①}$$

$$MPP_{STC} = \max\cdot(U_{STC} \cdot I_{STC}) \qquad \textit{Eq.8.2} \text{ ②}$$

$$\eta\text{pvgen} = \frac{\text{MPP}_{\text{STC}}}{\text{Ppvgen}_{\text{nom}}} \qquad \textit{Eq.8.3} \text{ ③}$$

*(I-V)$_{meas}$….measured I-V curve*
*(I-V)$_{STC}$………I-V curve at STC conditions (calculated)*
*MPP$_{STC}$…………. maximal power point at STC conditions*
*Ppvgen…………. nominal output power of the PV generator*
*ηpvgen………….efficiency of the PV generator*

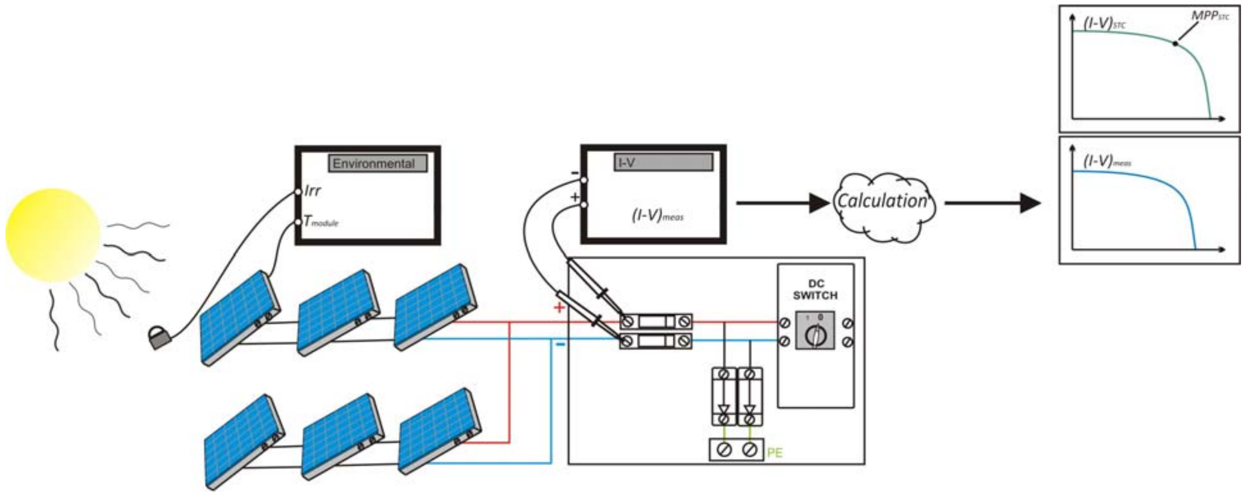



*Fig.8.1: Example of verification of performance of a PV string*

Metrel offers a PC software application for comparison of measured, measured_stc and nominal data.

## 8.2 Verification of wiring losses (on the d.c. side)

The wiring losses are losses in cables, junctions and serial components. Parallel components and leakages can usually be neglected. This verification is to estimate if the wiring losses are acceptable.

### 8.2.1 Calculation of losses of serial components

The losses can be calculated according to Eq. 8.2.1 ① to 8.2.1③. Conductors length, material and cross-section must be known (see also Table 3.7). The voltage drops of serial blocking diodes (if installed) is < 2 V.

The voltage drop of a fuse is usually < 0.3 V at nominal current. Good contacts have usually a neglectable voltage drop.

$$Ploss\_dc = Rlosscond \cdot I_{nom}^2 + Udiode \cdot I_{nom} + Ufuse \cdot I_{nom} + Ucontact \cdot I_{nom}$$ *Eq.8.2.1* ①

$$Rloss\_dc = \frac{Ploss\_dc}{I_{nom}^2}$$ *Eq.8.2.1* ②

$$Rlosscond = \frac{\rho \cdot l}{(\pi \cdot \frac{d^2}{4})}$$ *Eq.8.2.1* ③

*Rloss_dc……….. ..loss resistance on the d.c. side*
*Rlosscond……….. ..loss resistance of conductors on the d.c. side*
*ρ………………… ……specific resistance of copper*
*d……………………....diameter of conductor*
*Udiode……………..voltage drop on blocking diode*
*Ufuse………….......voltage drop on fuse*
*Ucontact…………voltage drop on contacts*
*$I_{nom}$…………… ……nominal current of PV generator*
*Ploss_dc…………lost power because of wiring losses on d.c. side*

### 8.2.2 Calculation on base of Rs result

An alternative is to estimate the wiring losses on base of the Rs result.

Procedure is as following:

1. Check environmental condition. Irradiance should be as high as possible (at least 600 W/m$^2$, best above 800 W/m2) and stable in order to get more accurate results.
2. Perform the I-V curve test. The PV generator must be disconnected from the inverter during the test. The shape of the curve should not show any unexpected anomalies.
3. The Rs value can be calculated with help of Metrel's PCSW EurolinkPRO. The calculated Rs result is the sum of Rs's of PV modules and loss resistances on the d.c. side.

4. The calculated Rs presents the sum of Rs of PV generator and wiring losses Rloss_dc . If Rs of the PV module is known it is possible to calculate the losses.

$$Rs_{meas} = Rs(\text{of module/ string /array}) + Rloss\_dc$$ *Eq.8.2.1* ①

$$Rs(\text{of module/ string /array}) = Rs(\text{of module}) \cdot \frac{n}{m}$$

*Eq.8.2.1* ②

*Rs(of module)……nominal Rs (producer's data or previously known)*
*$Rs_{meas}$………………...measured Rs (obtained on measurement of I-V curve)*
*Rs(of module/ string/ array)………overall Rs of combination of PV modules*
*Rloss_dc……………wiring losses*
*n…………………….... modules in series in string*
*m……………………...modules of parallel strings in array*

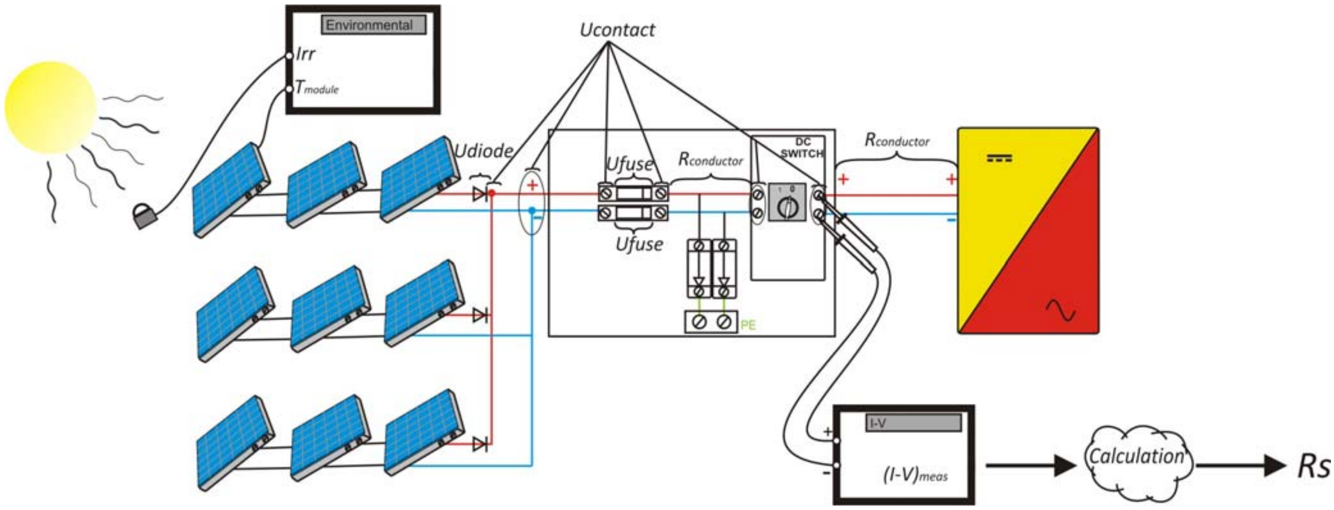



*Fig.8.2.1: Example of verification of d.c losses on base of I-V curve test and known Rs of PV module*

## 8.3 Tracker efficiency (verification of proper MPP point)

This verification is to check if the inverter's tracker sets the optimal operating point at momentary conditions.

### 8.3.1 Calculation on base of comparison of measured I-V curve test and d.c. measurements

The following measuring procedure is based on base of comparison of the MPP point on U(I) graph and d.c. measurements.

Procedure is as following:

1. Check environmental condition. Irradiance should be as high as possible (at least 600 W/m$^2$, best above 800 W/m2) in order to get more accurate results.
2. Measure the momentary voltage and current on the input of the inverter.
3. Disconnect the inverter from the PV generator.
4. Perform the I-V curve test. The PV generator must be disconnected from the inverter during the test. The shape of the curve should not show any unexpected anomalies.
5. Reconnect the PV generator back to the inverter.
6. Compare the measured power $MPP_{meas}$ on the I-V curve and the momentary measured power $P_{meas}$ (Eq.8.3.1).

$$DiffMPP = (\frac{1 - P_{meas}}{MPP_{meas}}) \cdot 100 \qquad \textit{Eq.8.3.1}$$

*DiffMPP …….difference in percents of set and optimum working point*
*$P_{meas}$……..measured power into inverter*
*$MPP_{meas}$….available maximal power into inverter*

A difference of less than 5% means that the inverter has properly set the MPP point. If the I-V curve has not an ideal shape or if the irradiance is low the inverter may have problems to set the proper MPP point.

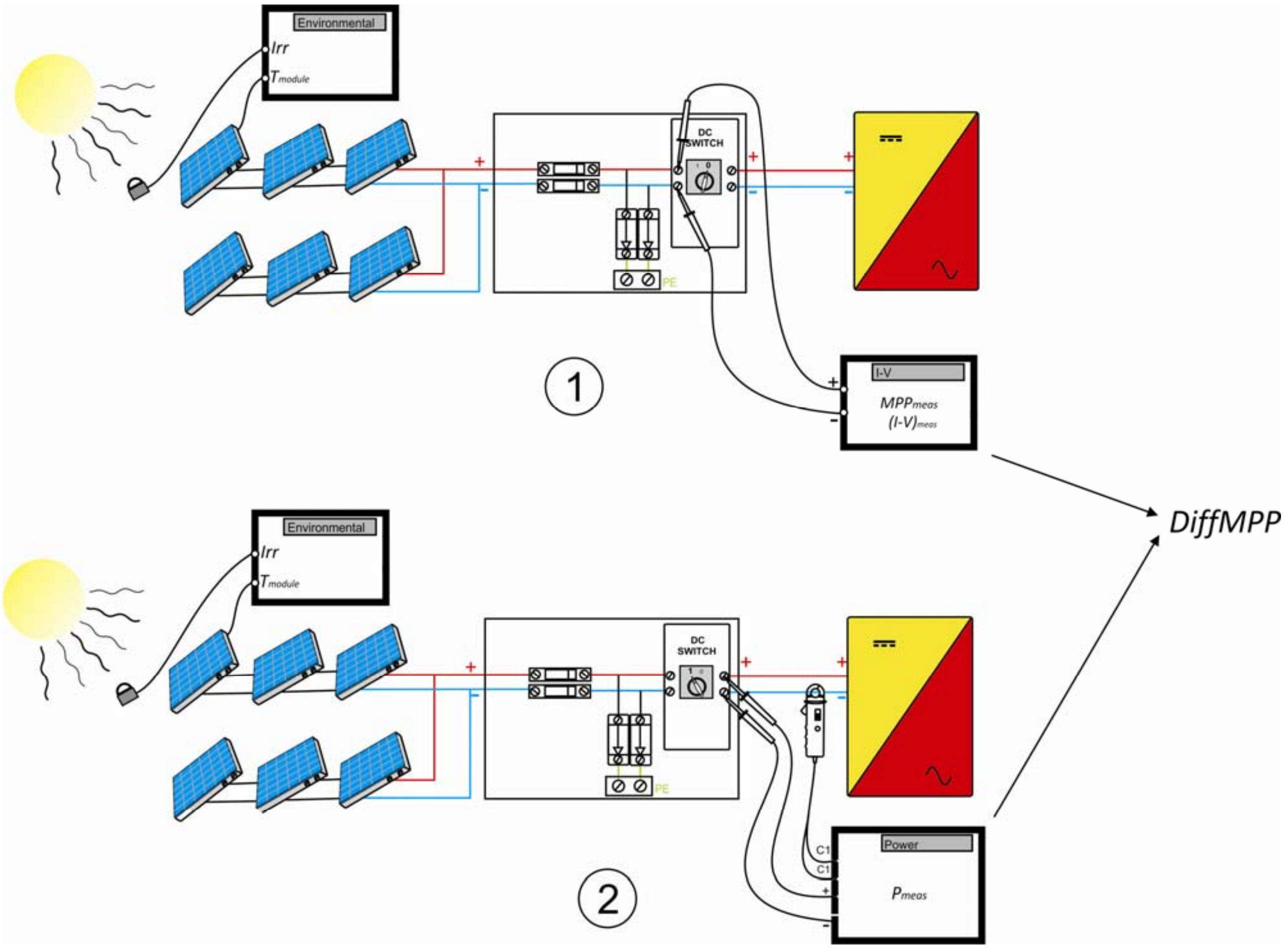



*Fig.8.3.1: Example of verification of tracker efficiency*

This measuring method is subjected to a high measuring error if the environmental conditions are not very stable (for at least 5 minutes). An another problem is that the values to be compared are measured with two different test methods. Therefor the accuracy of this test is lower than the accuracy of individual measurements.

### 8.3.2 Calculation on base of measured I-V curve test and d.c. voltage measurements

An another method for tracker verification can be performed with Metrel PVAnalyse tool. The described method has a higher accuracy than the method decribed in chapter 8.3.1. The procedure is as following:

1. Check environmental condition. Irradiance should be as high as possible (at least 600 W/m$^2$, best above 800 W/m2) in order to get more accurate results.
2. Perform the I-V curve test. The PV generator must be disconnected from the inverter during the test. The shape of the curve should not show any unexpected anomalies.
3. Measure the momentary voltage $U_{meas}$ on the input of the inverter. To get best results store irradiance and temperature data at the time of voltage measurement.
4. Reconnect the PV generator back to the inverter.
5. In Metrel PVAnalyse tool enter irradiance and temperature values stored in step 3 and modify the measured I-V curve.
6. Find $U_{meas}$ on the modified I-V curve and define the belonging d.c. current I. The ($U_{meas}$,I) pair on the modified I-V curve is the operating point set by the tracker.
7. Compare the MPP on the modified I-V curve and power of pair ($U_{meas}$,I) on the modified I-V curve.

$$DiffMPP = (\frac{1 - U_{meas} \cdot I}{MPP_{meas}}) \cdot 100 \qquad \textit{Eq.8.3.2}$$

*DiffMPP …….difference in percents of set and optimum working point*
*$U_{meas}$……..measured voltage at the inverter's input*
*I……………current that belongs to $U_{meas}$*
*$MPP_{meas}$….available maximal power into inverter*

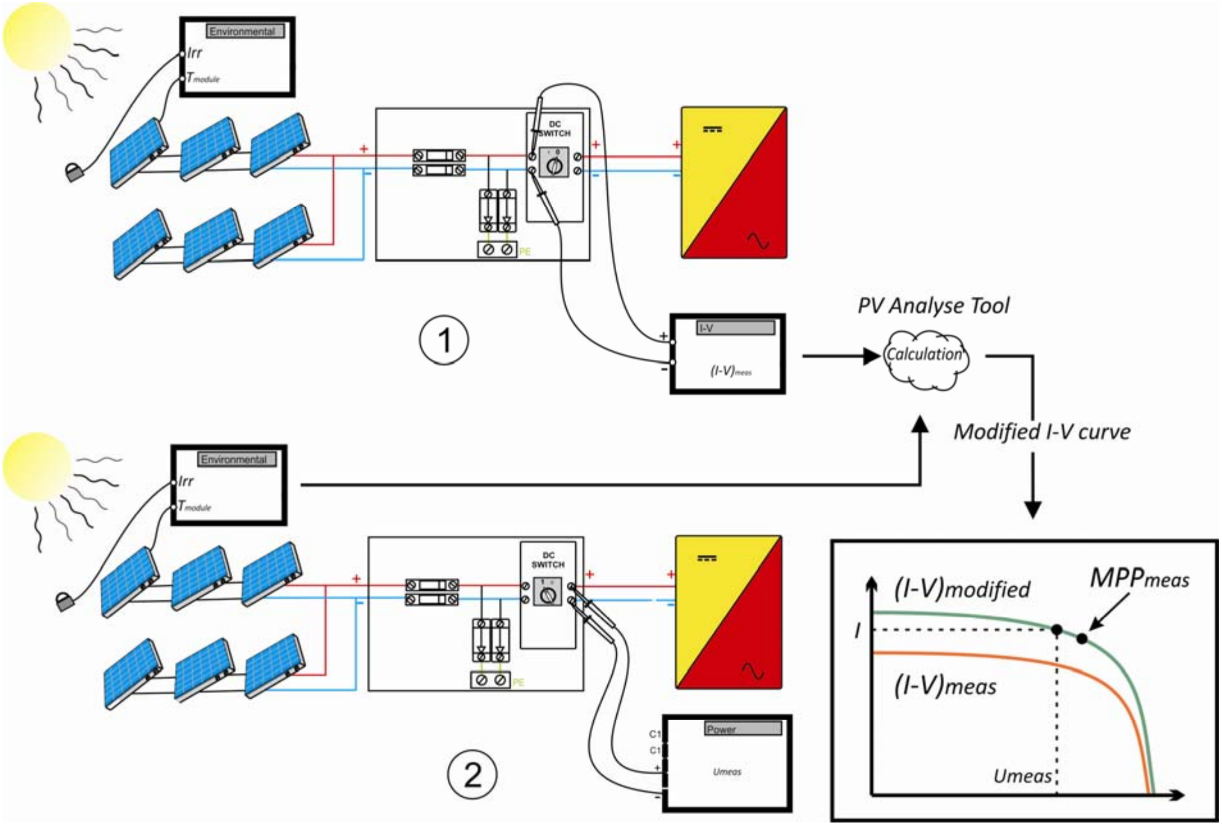



*Fig.8.3.2: Example of verification of tracker efficiency*

The accuracy of this test method is higher because d.c. current clamps are not needed and the I-V curve can be modified to exact environmental parameters.

## 8.4 Verification of efficiency of inverter

This verification is to check the efficiency of the inverter at momentary conditions. Procedure is as following:

1. Check that environmental condition are stable. Irradiance should be as high as possible (at least 600 W/m$^2$, best above 800 W/m2) to get more accurate results.
2. Measure the momentary d.c. voltage U and current I on all inputs of the inverter.
3. Measure the momentary a.c. voltage U and current I on all outputs of the inverter.
4. Calculate the efficiency acc. to Eq. *8.4* ① to Eq. *8.4* ③ and compare it with inverters specification.

$$Pinp = SUM_1^N \cdot (Uinp_N \cdot Iinp_N)$$ *Eq.8.4* ①

$$Pout = SUM_1^N \cdot (Uout_N \cdot Iout_N)$$ *Eq.8.4* ②

$$\eta inv = \frac{Pout}{Pinp}$$ *Eq.8.4* ③

*Pinp…………..measured power on the input of inverter*
*Pout………… measured power on the output of inverter*
*ηinv…………..efficiency of the inverter at momentary conditions*

The inverter's efficiency is typically 95% or higher.

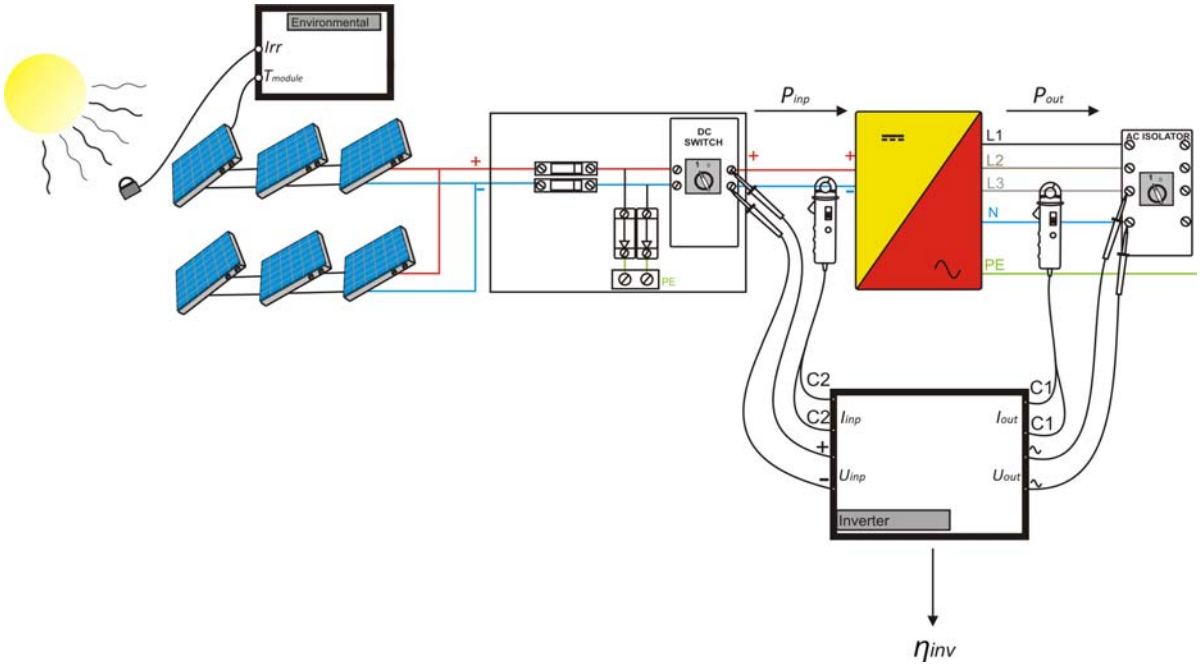



*Fig.8.4: Example of verification of efficiency of inverter*

## 8.5 Verification of wiring losses (on the a.c. side)

### 8.5.1 Calculation of losses of serial components

The wiring losses are losses in cables and junctions and serial components on the a.c. side. This verification is to estimate if the wiring losses are acceptable.
The losses can be calculated according to Eq. xy. Conductors length, material and cross-section must be known (see also Table 3.7). Good contacts have usually a neglectable voltage drop.

$$Rloss\_ac = \frac{\rho \cdot l}{(\pi \cdot \frac{d^2}{4})} + \frac{Ucontacts}{Iinvout}$$ *Eq.8.5.1 ①*

$$Ploss\_ac = Rloss\_ac \cdot Iinvout^2$$ *Eq.8.5.1 ②*

*Rloss_ac……….. loss resistance on the a.c. side*
*ro………………… specific resistance of copper*
*d…………………..diameter of conductor*
*Ucontacts……..voltage drop on contacts*
*Iinvout…………… nominal output a.c. current of PV inverter*
*Ploss_ac………..lost power because of wiring losses on a.c. side*

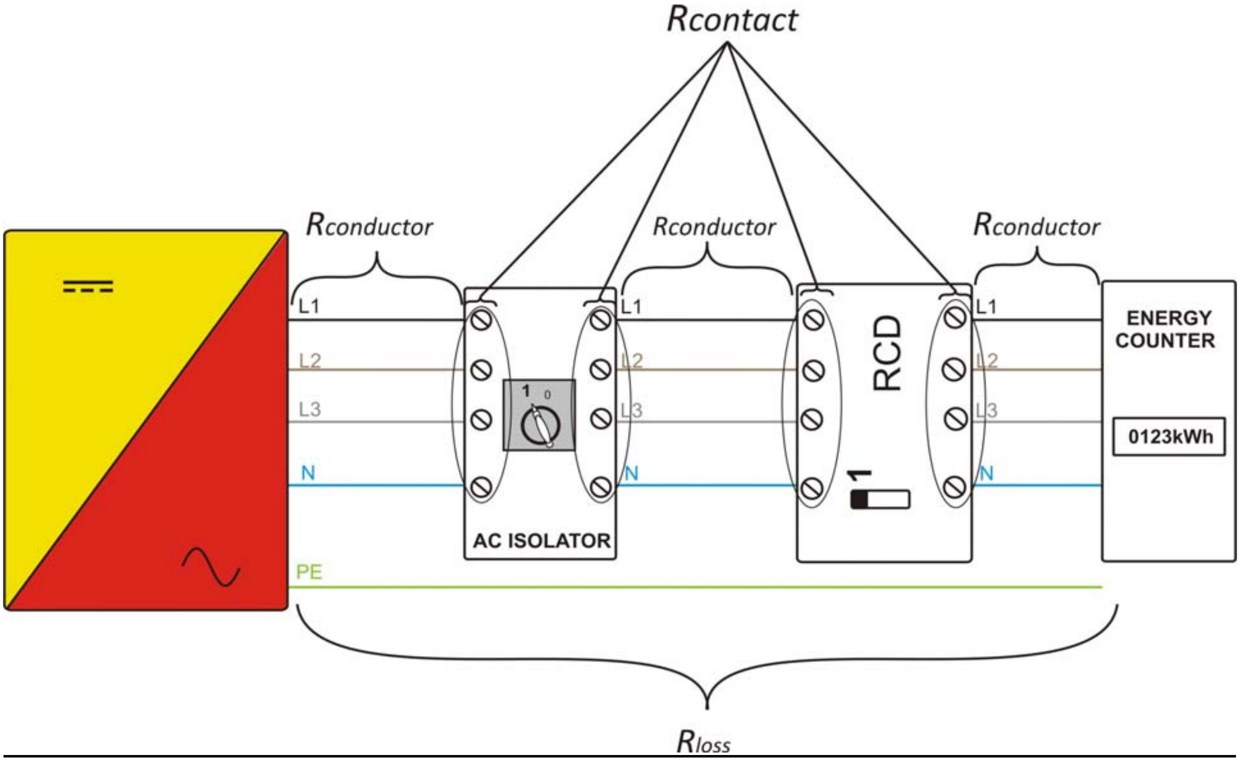



*Fig.8.4: Example of verification of a.c. losses*

### 8.5.2 Calculation on base of voltage drop test

An alternative is to estimate the wiring losses with a Voltage Drop test. The voltage drop is calculated on base of impedance measurements at the beginning (connection point of the PV system to the a.c. installation, electrical counter) and the end of the circuit (a.c. output of the inverter), see Eq. *.8.5.2* ①. For the voltage drop calculation the nominal current of the circuit's fuse is considered. For the loss calculation the nominal output current of the PV system should be considered instead of the nominal current of the fuse.
Losses on the a.c. side can be calculated on base of Eq.xy

$$Voltdrop = \frac{(Zline\_end\ of\ line - Zline\_beggining\ of\ circuit)}{\ln} \qquad \textit{Eq.8.5.2 ①}$$

$$Ploss\_ac = VoltDrop \cdot (\frac{Iinvout}{\ln}) \cdot Iinvout \qquad \textit{Eq.8.5.2 ②}$$

*VoltDrop…….voltage drop of circuit on a.c. side*
*Zline_end of circuit…..measured Zline at the inverter*
*Zline_beggining of circuit……measured Zline at the circuit fuse*
*In………nominal value of circuit fuse*
*Ploss_ac…… lost power because of wiring losses on a.c. side*
*Iinvout…………… nominal output a.c.current of PV inverter*

# 9. PV measuring equipment

## 9.1 Safety

### 9.1.1 Measuring category

Safe design and high protection of the measuring equipment is important. A lot of PV systems generate voltages of close to 1000 V d.c and are connected to a.c. installations of up to 440 V (phase - phase voltage). The minimum requirement for PV test instrument's measuring categories is:

- d.c. 1000 V CAT I
- a.c. 300 V CAT III

All Metrel's PV testers have a higher measuring category - 1000 V CAT II for d.c. and 300 V CAT IV for a.c.

A higher protection degree means a better robustness of the equipment. Please refer to Metrel's article *Electrical installation testers: CATIII or CATIV* for more information about advantages of using measuring equipment with higher measuring category.

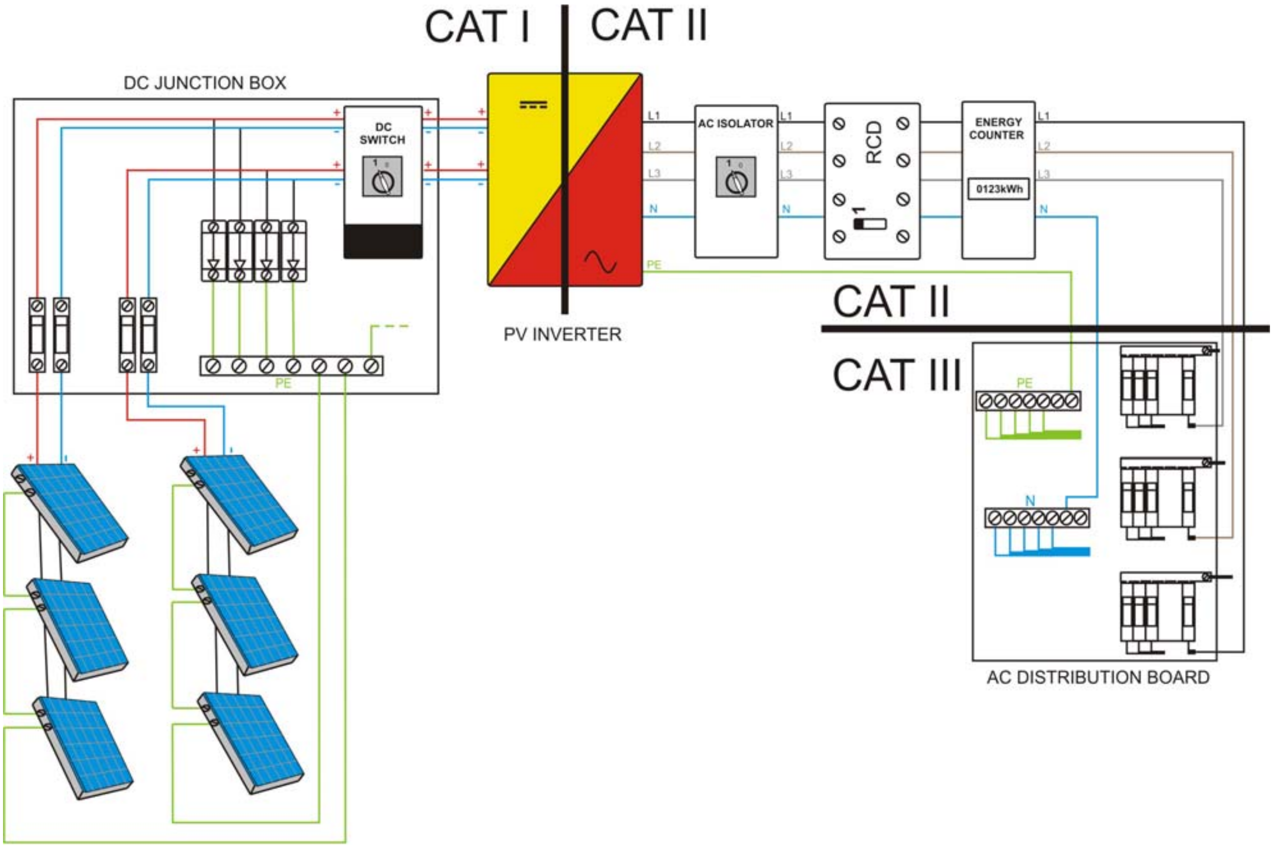



*Fig. 9.1.1: Installation categories in a PV system*

### 9.1.2 PV safety probe

The measuring equipment makes the short during Isc test and loading during the I-V test with semiconductors. The semiconductors are stressed during these tests. If the semiconductor fails during the measurement a permanent short circuit will occur. Pre-tests are of no help as the semiconductors typically fail while they are stressed. Despite of the fact that the PV instruments are designed to safely sustain the permanent short circuit a strong arc can occur when the test leads will be removed. The energy of the arc depends on the voltage and current being disconnected. It can cause additional damage of the connection points and test leads and can jeopardize the user. Therefore it is a good practice to use a disconnection switch between the test instrument and measured point of the PV system.

Metrel's A1384 PV safety probe can safely disconnect the PV installation from the installation in case of a permanent short circuit. It is an electronic replacement of a mechanical d.c. switch. Switching on and off is performed automatically. The disconnection is made with a robust high voltage relay. Its advantage is simple connection to the PV tester and that no switching on / off is needed.

*Fig. 9.1.2 : PV safety probe will safely disconnect the instrument from the PV system in case of a failure*

## 9.2 Performance

### 9.2.1 Current and Power range of the I-V test

During I-V tests the measuring equipment loads the PV generator with a very high power (up to more than 10 kW !) for a short time. The voltage, current and power capability of the I-V test of the measurement equipment should be considered.
Metrel equipment uses high quality PowerMOSFETs that are specially designed for this type of application.
The current capability is declared as 1000 V / 15 A / 15 kW, with a safety margin of at least 25%.

## 9.3 Accuracy

### 9.3.1 Voltage and current measurements

The accuracy of measurement of electrical parameters (a.c. and d.c. voltage U, a.c. and d.c. current I, voltage Uoc, current Isc…) is usually high. Most of measuring instruments measure a.c. and d.c. voltage and current values with a basic accuracy of less than 2%. If d.c. current clamp is used for the current measurement the producer's specification about the current clamp error should be checked.

### 9.3.2 I-V curve measurement

Because of the short time of measurement the voltage and current measurements in the I-V measurement are demanding. It is more difficult to achieve a similar measuring accuracy than for standard voltage and current measurements.
In addition, influence of capacitances and inductivities of the PV system can seriously impair the measurements. Some PV modules have high capacitances and the wiring has always a certain inductivity (see chapter *3.8*). This can cause distortion of the measuring pulses and can result in a high measuring error. This error might be much higher than the declared basic accuracy. In general longer test pulses are less susceptible to this problem. If the test results are suspicious, especially if test always fail on same types of PV modules, it is recommended to check if the pulse distortion could be a problem.
Metrel's instruments use relatively long test pulses – they can afford this because of the use of high quality power transistors. If the distortion of the pulse because of C's and L's still occur the measuring circuit detects this and can eliminate this problem.

### 9.3.3 Insulation resistance measurements

The maximum operating error acc. to IEC 61557-2 is 30%. Most of modern testers have a much higher accuracy.

### 9.3.4 PV Insulation resistance measurements

The maximum operating error acc. to IEC 61557-2 is 30% . Most of modern testers have a much higher operating accuracy. In chapter*3.8* issues that can influence the measurement are described but are not considered in IEC 61557 and IEC 62446.

### 9.3.5 Continuity measurements

The maximum operating error acc. to IEC 61557-4 is 30%. Most of modern testers have a much higher accuracy.

### 9.3.6 Error of calculation to STC values

The STC calculation adds some new errors that must be considered:
error of the given module's PV parameters. The parameters should be obtained from a reliable source.
the error is higher if the environmental conditions differ more from the reference environmental (STC) conditions.

### 9.3.7 Error of irradiance sensor

The irradiance is the highest influencing quantity in the STC model (see chapter *4*). The accuracy and placement of the irradiance probe are therefore of high importance. For a typical PV module:

a 10 % error of irradiance measurement will result in a ca 0.5 % error of Ustc and ca 11 % error of Istc at MPP point.

a 5 % error of irradiance measurement will result in a 0.3 % error of Ustc and 5 % error of Istc at MPP point.

a 2 % error of irradiance measurement will result in a 0.1 % error of Ustc and 2 % error of Istc at MPP point.

Use of irradiance sensor (reference cell or pyranometer) with an accuracy of better than 3% is recommended. The irradiance sensor should be regularly and traceably calibrated. It is a good practice to perform the measurements at high illuminance level.

The inclination of the irradiance sensor must be exactly the same as of the PV module.
a 10° difference will result in a 0.5 % error of Ustc and 10 % error of Istc at MPP point.
a 5 % difference will result in a xy % error of Ustc and xy % error of Istc at MPP point.
a 2 % difference will result in a xy % error of Ustc and xy % error of Istc at MPP point.
The sensor should not cover the PV cells. Even a small covered surface can significantly lower the performance of the PV generator.

*Fig. 9.3.7: Example of correct and wrong placement of the irradiance probe*

### 9.3.8 Error of temperature sensor

The influence of temperature measurement error is about 1% / °C. The accuracy of the temperature sensors is usually better than 1°C.

A much higher measurement error will occur if the sensor on the PV module is not placed properly.

The sensor must have a good thermal contact to the modules surface. All parts exposed to the air must be well isolated (see Fig. 9.3.8).


*Fig. 9.3.8: Examples of correct and wrong placement of the temperature probe*

# 10. Databases of module parameters

The module parameters of most commercial PV modules are collected in different databases.

Some of them are payable and some are free of charge. Below are links to some most popular PV module databases:

http://www.photon.info/photon_site_db_solarmodule_en.photon
http://www.solarpanel-directory.net/
http://www.posharp.com/photovoltaic/database.aspx
http://www.photovoltaikforum.com/database_dir.php

METREL d.d.
Measuring and Regulation Equipment Manufacturer
Ljubljanska c. 77, SI-1354 Horjul
Tel: + 386 (0)1 75 58 200  Fax: + 386 (0)1 75 49 226
E-mail: metrel@metrel.si   http://www.metrel.si