DERlab round-robin testing of photovoltaic single-phase inverters

Omar Perego, **Paolo Mora** & **Carlo Tornelli**, ERSE, Milan, Italy; **Wolfram Heckmann** & **Thomas Degner** (DERlab coordinator), IWES, Kassel, Germany

This paper first appeared in the eighth print edition of *Photovoltaics International* journal.

ABSTRACT

Interconnection of inverters to the electrical grid is a key issue for the widespread integration of distributed energy resources, especially when the scenario surrounding international standards is so unclear. As a pre-normative research step, a round-robin test of two small-scale photovoltaic inverters was performed by nine DERlab laboratories during 2009. The test activity was focused on the verification of individual test procedures, common interpretation of standards and requirements, and determination of problems related to the equipment and facilities involved in conducting round-robin tests. Compilation of test results and first conclusions of this activity will be presented in this paper.

DERlab consortium

The activities described in this article are a result of studies carried out by the DERlab team. DERlab is a European Project funded by the EC in the sixth Framework Programme (FP6, n. 518299), armed with the mission of constituting a Network of Excellence (NoE) of DER Laboratories for Pre-Standardization activities.

The main objective of the DERlab NoE is to support the sustainable integration of renewable energy sources (RES) and distributed energy resources (DER) in the electricity supply, by developing common requirements, quality criteria, as well as proposing test and certification procedures concerning connection, safety, operation and communication of DER components and systems. The NoE also acts as a platform for the exchange of current knowledge between the different European institutes and other groups.

> "During the data collection, each laboratory highlighted problems and difficulties occurring during these inverter tests."

In order to establish a durable network of DER laboratories, the members of the DERlab Consortium, together with other important European laboratories and research centres, founded the DERlab Association (DERlab e.V.) in September 2008. The test facilities of the DERlab members (with some relevant additions) are offered, free of charge, to European researchers for activities funded by the EC in the FP7 Research Infrastructures DERri Project (Distributed Energy Resources Research Infrastructure, FP7, n. 228449).

The DERlab Consortium (see Fig. 1) has 11 members: IWES from Germany (coordinator); ARSENAL from Austria; KEMA from The Netherlands; INES-CEA from France; ERSE from Italy; LABEIN-Tecnalia from Spain; University of Manchester from UK; NTUA-ICCS from Greece; RISOE-DTU from Denmark; TU Sofia from Bulgaria; and TU Łódź from Poland.

Round-robin motivation

One of the objectives of DERlab is to support the development of European and international standards by executing exemplary research activities on specific topics and by initiating new research activities, which aim to provide the required technical information and input to the standardization bodies.

The organization's main focus is not on the single, isolated device, but on the DERs integrated in an electrical network to highlight interface conditions. As most DER electrical interfaces to the grid are realized through inverters, this paper answers the need for particular attention to be paid to the testing procedures for these kinds of devices. In order to define a field of application that can be faced, considering also the large diffusion of these devices, this investigation has been focused on single-phase photovoltaic inverters of up to 6kVA of rated power that are connected to the PV field and intended for functioning in parallel to the grid.

This activity is not intended to overlap or to substitute the work being undertaken by standardization bodies. Its purpose is to verify the applicability of the existing

Figure 1. DERlab Consortium members [1].

standards, identifying lacks, explaining difficulties and problems in test conditions and specifying testing equipment by collecting data in an inter-comparison ('round-robin') approach among DERlab members.

Appropriate and well-defined 'PV inverter testing procedures' (related to performance, grid interface and safety) have been prepared by DERlab experts as a basic prerequisite for the round-robin test. This document defines some steps and guidelines to which each laboratory must adhere in testing PV inverter characteristics. During the data collection, each laboratory highlighted problems and difficulties occurring during these inverter tests. The main purpose of such a data collection study is to collect suggestions from the various experts in the field and transfer this experience to the standards committees.

In fact, the analysis of the results and of the notes and suggestions collected during the test phase can be automatically forwarded to the relevant active standardization groups, where the engineers involved in the data collection for this paper are also directly involved in assessing and writing International and National Standards. This round robin will help in assessing, verification and modification of existing and proposed test procedures in order to fill the gaps, to harmonize, and to clarify.

Round-robin activities

The data and information for the round robin were collected during 2008 and 2009, Fig.2 shows moments of test execution; the final analysis, the definition of recommendations and the dissemination of the results are currently in progress.

In brief, a team of experts from DERlab partners has compiled a document for 'PV inverter testing procedures,' related to performance, grid interface and safety. This document has been submitted and shared among all DERlab partners, together with a template of the test reports. This document – which should not be considered a 'standard procedure to test PV inverters' because it is not produced by standard committees – defines some steps that nine DERlab laboratories have to follow to test two PV inverters within the remit of the round robin. Two inverters were circulated among these laboratories, and tested according to the indications of the procedures. The team of DERlab experts and technicians involved in the tests filled in the test reports with the results of these tests. At the end of the round robin, they reported their observations and suggestions in a questionnaire circulated in September 2009, which were then collected and analysed by a team of DERlab experts, who took on board the observations and suggestions on how to improve the test procedures in order to transfer this experience to relevant active standardization groups.

DERlab experts had the opportunity to share their experiences during the round-robin timeline. Some experts visited partner laboratories, working in collaboration with local technicians, yielding data that were collected, compared and analysed by the consortium meetings with the intention of collecting observations and improving the procedure steps.

PV inverters

The investigation focused on single-phase inverters up to 6kVA that are connected to a PV field in parallel to the grid. The two inverters that were circulated among DERlab laboratories were the Aurora Power-one PVI-3.0-OUTD-IT and the SMA SunnyBoy 4000TL, the main characteristics of which are displayed in Table 1.

Tests

The aim of the tests is to assess if the PV inverters are suitable for properly functioning in parallel to the grid and to measure the performances and characteristics of these inverters in different operative conditions. Some tests are identified as mandatory because they refer to problems related to the electrical interconnections of DER (grid compatibility and safety); the other tests are identified as optional, because they measure the performance characteristics of the inverters.

The tests performed, divided into mandatory [M] and optional [O], are listed below:

[M] – Harmonic current measurement (power quality test on grid compatibility)

Figure 2. Moment of test execution.

[M] – Anti-islanding protection detection (protection intervention test on grid connection)

[M] – DC current injection measurement (power quality test on grid compatibility)

[M] – PV leakage current protection detection (protection intervention test on safety)

[O] – Efficiency measurements (performance test; see [2]),

[O] – Measurement of MPPT (maximum power point tracker) accuracy when PV shadowing occurs (performance test).

The round-robin test was conducted to adhere to the defined test procedures (described in the DERlab 'PV inverter testing procedures' document), using the same inverters under the same test set-up and according to the same standards but with different devices, instruments and environment. The DERlab partners decided to follow the Italian standards because, as there is no EU standard, the two inverters' parameters are configured according to Italian standards.

A common understanding of the differences and remarks collected during the analytic phase of the round robin yielded refinement of the testing procedures and the elaboration of suggestions to standard committees.

The analysis of the results and considerations about the following mandatory tests are pertinent to this paper:

- Test on anti-islanding protections
- Test on harmonic current
- Test on DC current injection.

The analysis of these tests is extended to general considerations and to open questions, the outcome of which will be reported later in the paper.

Test on anti-islanding protections

The aim of the test is to evaluate the inverter's behaviour during lulls in grid connection in order to evaluate their capability for islanding prevention. In Italy, an anti-islanding protection test detects grid failures and disconnects PV generators to avoid feeding of the grid in an uncontrolled manner. Anti-islanding protection is steered by a European standard (EN-50348); however, this code

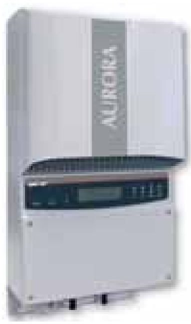
Aurora Power-one PVI-3.0-OUTD-IT	SMA SunnyBoy 4000TL
Nominal power (AC): 3,000W Voltage range (DC): 90 – 580VCC No. of MPPTs: 2 Protections equipments: detection of DC current injection in AC (transformerless inverter), min/max V, min/max f, df.	Nominal power (AC): 4,000W Voltage range (DC): 125 – 440VCC No. of MPPTs: 2 Protections equipments: detection of DC current injection in AC (transformerless inverter), min/max V, min/max f, df.
	

Table 1. Inverters circulated among DERlab laboratories for round-robin testing purposes.

Method of protection intervention requested by Italian grid code		Thresholds Mandatory/ optional
MIN & MAX voltage detection	0.8 x Vn (t < 0.2 s) < V < 1.2 x Vn (t < 0.1 s)	Mandatory
MIN & MAX frequency detection	49 or 49.7 Hz < f < 50.3 or 51Hz (without any requested delay)	Mandatory
Frequency deviation	df < 0.5Hz/s	If requested by the grid operator

Table 2. Method of protection intervention as defined by CEI 11-20 grid code.

contains many gaps and derogations that stipulate that each country has to provide its own grid code with different methods and values for anti-islanding protection.

Italy's MV/HV connections have to follow the specifications of CEI 0-16, the Italian standards committee, that include guidelines for LV connections and modifying the CEI 11-20 standard.

"The grid simulator must guarantee a maximum voltage THD (total harmonic distortion) less than 1%."

Although the EU standard committee is working on a common test procedure at international level (IEC 62116) for anti-islanding protection detection, the method of resonant circuit as defined by IEC 62116 is still missing the approval of CENELEC. Methods of protection intervention are implemented by the manufacturers themselves according to the national grid code.

In Italy, the CEI 11-20 grid code for LV connections requires a set of protective measures to be implemented by manufacturers in the Italian market. Table 2 shows the threshold values of voltage and frequency that cause the protection intervention and the maximum delay allowed for this intervention.

The method requested by the Italian grid code, based on minimum and maximum voltage and frequency, is intrinsically inadequate as it can fail when an equality between generated and used power occurs. Additional 'active' protections could be used to address this problem, an approach that is being investigated by the Italian National committee in the form of a new version of the CEI 11-20 grid code. Fig. 3 shows the basic circuit used by protections as requested by the Italian grid code for photovoltaic applications.

Both low and high voltage protection methods and low and high frequency protection methods have been tested during the round-robin testing procedure for this study. Further protection methods such as the rate of frequency change, impedance tests, frequency shift etc. may be used in other EU countries as stipulated by countries' grid codes, but this study's remit is limited to the two protection methods mentioned above.

Test equipment and preparation

The inverter is connected on the DC side to a PV field (or to a PV simulator) and on the AC side to an adjustable grid simulator, which allows the test operator to adjust voltage and frequency settings. The grid simulator must guarantee a maximum voltage THD (total harmonic distortion) less than 1%. A grid analyser is then positioned on the AC side, used to acquire both voltage and frequency AC signals (see Fig. 4).

Procedure

The test procedure describes the steps that should be followed to measure:

- the output limit values (AC voltage and frequency) for protection intervention;
- the time between the crossing of a frequency and voltage threshold and the intervention of the inverter anti-islanding protection.

Tests on anti-islanding protections are performed by the measurement of each threshold and the verification of the status of the disconnecting device (contactor). Furthermore, the operation delays are also measured in order to be in accordance with those results reported in Table 2.

The test method depicted in Fig. 5 shows the continuous variance of the voltage and frequency of the grid simulator. The slope of the frequency variation must be lower than the value of the rate

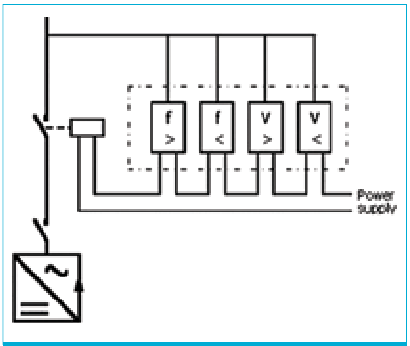


Figure 3. Basic circuit for anti-islanding protections (contactor is normally open).

of frequency change threshold (if this intervention method is implemented by the inverter manufacturer; see [3]). The test begins from the central point (nominal voltage 230V; nominal frequency 50Hz), moving towards the first target until the device trips or a safety limit is reached. This action is then repeated for each protection.

For example, in order to verify the high-voltage protection device, the voltage is slowly increased and the value that causes the trip is registered and noted as the high voltage threshold of the inverter. The initial conditions are restored, at which point an instantaneous variation of voltage is made from the same central point to a value above the measured high-voltage threshold. The time between the voltage step and the intervention of the protection is measured and noted as representing the time of high voltage protection intervention.

Results

Tables 3 and 4 summarize the results obtained in three different laboratories for threshold values and times, respectively. Both of the inverters have respected the thresholds defined by the CEI 11-20 Italian standard (limit values regarding over and under frequency time are available in Table 2).

Test on harmonic current

The aim of this test is to assess the current harmonics injection of the PV inverter into the grid using between 5% and 120% of the inverter nominal power. Several tests have been performed in compliance with the requirements of EN 61000-3-2, Annex

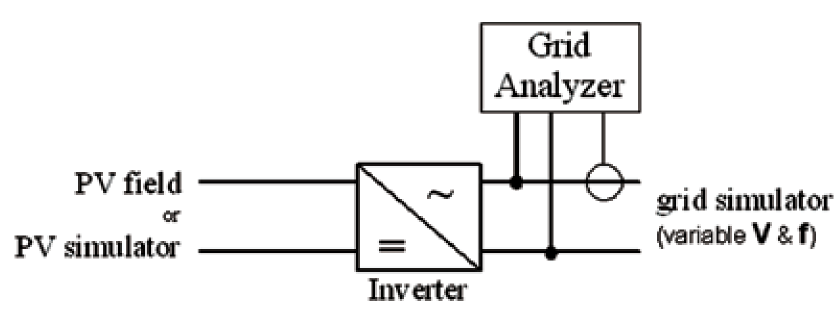


Figure 4. General architecture of anti-islanding protection measurement system.

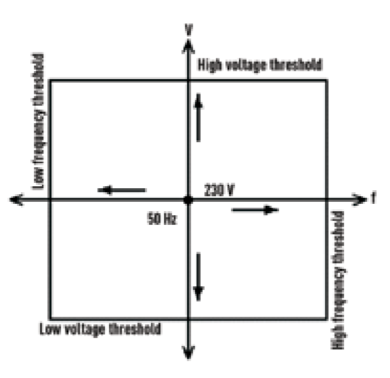


Figure 5. Grid simulator test method.

	Limit value	Lab 1	Lab 2	Lab 3
Over Voltage	276.00 V	272.20 V	273.00 V	272.82 V
Under Voltage	184.00 V	185.30 V	186.00 V	185.56 V
Over Frequency	50.30 Hz	50.28 Hz	50.28 Hz	50.27 Hz
Under Frequency	49.70 Hz	49.70 Hz	49.71 Hz	49.72 Hz

Table 3. Threshold values measured for an inverter in three different laboratories.

	Limit value	Lab 1	Lab 2	Lab 3
Over Voltage time	100 ms	90 ms	84 ms	81 ms
Under Voltage time	200 ms	180 ms	180 ms	181 ms
Over Frequency time	no intent.delay	100 ms	92 ms	91 ms
Under Frequency time	no intent.delay	90 ms	74 ms	82 ms

Table 4. Threshold times measured for an inverter in three different laboratories.

A (see [4,5]). Due to the fact that the actual voltage THD may have a strong impact on the inverters' current THD, the requirements specify the limit values for test voltage and harmonic ratios of the test voltage:

- The test voltage shall be maintained within ±2.0% and the frequency within ±0.5% of the nominal value (230V and 50Hz for single-phase supplies).
- The harmonic ratios of the test voltage (U) shall not exceed the following values with the EUT connected as in normal operation:
  - 0.9% for harmonic in order 3;
  - 0.4% for harmonic in order 5;
  - 0.3% for harmonic in order 7;
  - 0.2% for harmonic in order 9;
  - 0.2% for even harmonic in order from 2 to 10;
  - 0.2% for harmonic in order from 11 to 40.
- The peak value of the test voltage shall be within 1.40 and 1.42 times its r.m.s. value and will be reached within 87° and 93° after the zero crossing. This requirement does not apply when Class A or B equipment is tested.

Test equipment and preparation

The inverter is connected on the DC side to a PV simulator that provides the required harmonics measurements for different fixed power outputs (equal to 5%, 10%, 20%, 25%, 50%, 75%, 100% and 120% of the inverter rated power). The inverter is connected on the AC side to an adjustable grid simulator, or to an LV single-phase real grid (only if it fulfils the requirements of EN 61000-3-2, Annex A for voltage harmonics). A power analyser is then positioned on the AC side for the harmonics measurement. Fig. 6 shows the harmonic current measurement configuration.

Procedure

The test procedure describes the steps that should be followed to measure the current harmonics from 2nd to 39th. The inverter is turned on and the current harmonics are measured on the inverter output by means of a grid analyser installed on the AC output; the current THD and the current harmonics are recorded and their values are verified according to the limits expressed by the IEC 61000-3-2 (Table 5). The current THD and the current harmonics from 2nd to 39th must be recorded for values of output power equal to 5%, 10%, 20%, 25%, 50%, 75%, 100% and 120% of the inverter rated power.

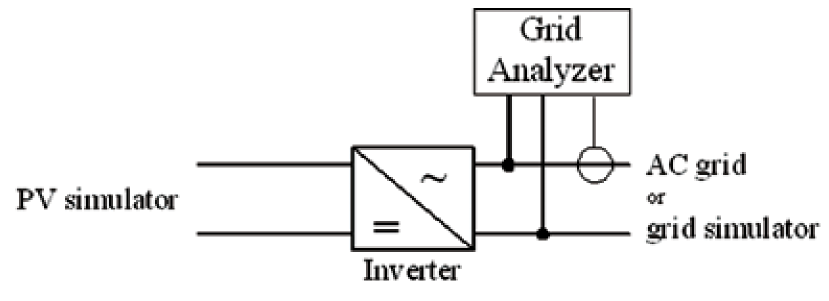


Figure 6. Harmonic current measurement configuration.

Results

The testing procedure measures the amplitude of the harmonic distortion of the inverter output current, relating to different values of the power supplied. Measures have been performed for single harmonic, till the 40th one and computation has been done for the THD factor as shown in Equation 1.

Fig. 7 shows the trend of THD (%) related to the output power supplied by the same photovoltaic inverter. The consistency among the measures performed in the different laboratories is quite good; the measures' scattering increases when the power supplied by the inverter becomes lower.

In spite of the good consistency of THD measures, some differences are observed for the measures of single harmonic components related to the same inverter situation (see Fig. 8).

In order to increase the results' repeatability, a better definition of the characteristics of the measurement equipment is necessary, as is a more accurate indication of the measures' elaboration, in particular for the average computation. As a matter of fact, execution of the measures can produce a harmonic spectrum that is time dependent; for the harmonic calculation it is necessary to use a time slot large enough to represent the average level of the current harmonics. The value scattering shown in Fig. 8 can likely be produced by the use of time slots of different lengths and by application of an inadequate data average.

Test on DC current injection

The aim of this test is to detect the value of the DC current injected in the AC grid. Although the DERlab test procedure can measure the DC component, it cannot detect the protection intervention.

The Italian grid code (CEI 11-20-V1, see [6]) requires a galvanic separation between the inverter and the grid, allowing derogation for small-sized inverters. In this case the DC current injection must not exceed the threshold $I_{DC} < 0.5\% \, I_{NOM}$.

The specifications of the two inverters tested state that they are both provided with protection against DC current injection in the AC grid. However, in this

Harmonics	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}	I_{12}	I_{13}	$I_{n\geq14}$	$I_{n\geq15}$	THD	PWTHD
Max permissible harmonic current (I < 16 A)	1.08	2.30	0.43	1.14	0.30	0.77	0.23	0.40	0.18	0.33	0.15	0.21	0,23*8/n	0,15*15/n	X	X

Table 5. Limit values for current harmonics.

$$THD = \sqrt{\sum_{n=2}^{N} \left(\frac{I_n}{I_1} \right)^2}$$

With:

I_1 : Amplitude of the current component at basic frequency

I_n : Amplitude of the current component at nth harmonic frequency

Equation 1.

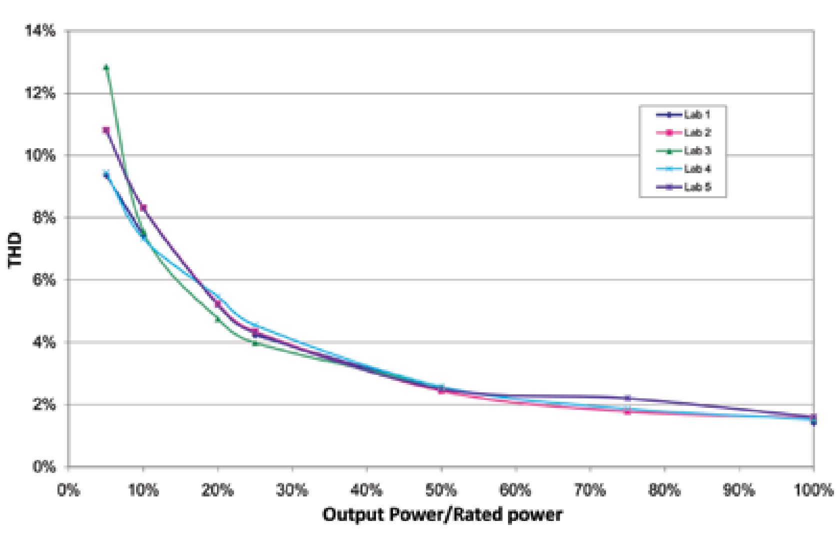


Figure 7. THD measures for the same inverter in different laboratories.

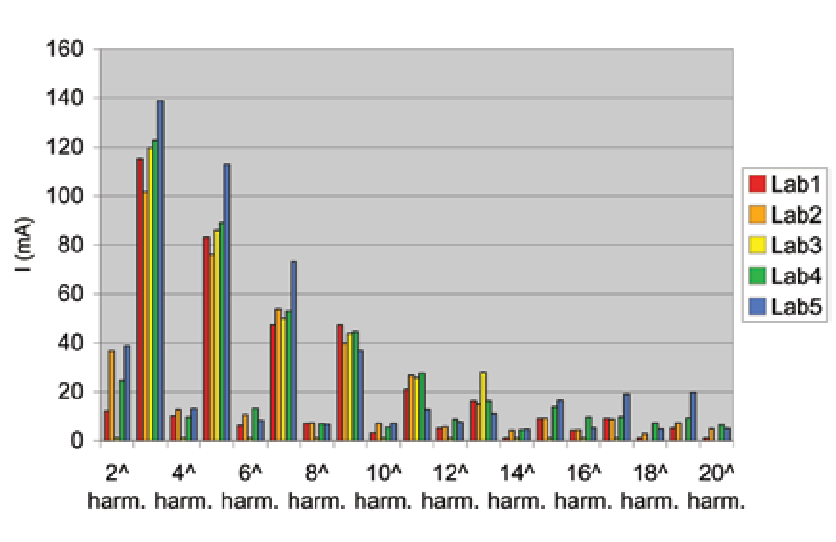


Figure 8. First 20 current harmonics measured in different laboratories (P/Pn= 50%).

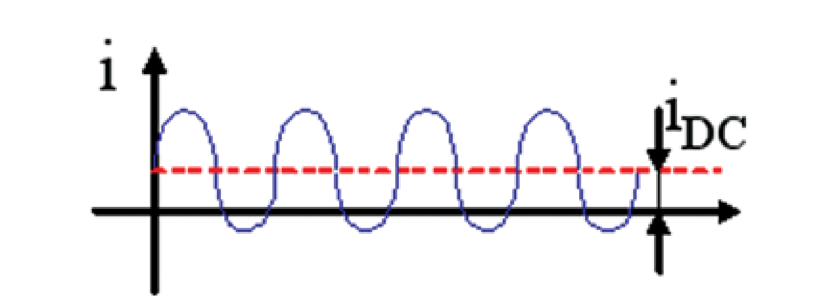


Figure 9. Representation of the DC current injection in the AC grid.

case, measurement of this intervention is not possible as the essence of the study is to investigate how to cause the protection intervention.

Test equipment and preparation

The inverter is connected on the DC side to a PV simulator that provides the required harmonics measurements for different fixed output power (equal to 5%, 10%, 20%, 25%, 50%, 75%, 100% and 120% of the inverter rated power). The inverter is connected on the AC side to an adjustable grid simulator, or to an LV single-phase real grid. A multi-meter is then positioned on the AC side for the measure of the output DC current, the configuration for which is shown in Fig. 10.

Procedure

The test procedure describes the steps required to measure the output DC current. The test is carried out for values of output power equal to 5%, 10%, 20%, 25%, 50%, 75%, 100% and 120% of the inverter rated power.

Results

DC current injection from the inverter to the grid should be avoided: indeed, the DC current component can increase losses in the nucleus of the transformer supplying the grid (and also its magnetization current and the acoustic noise level). The worst-case scenario can be garnered by adding, for each phase, the DC component values of the different generators connected to the grid. On the basis of these considerations, the CEI 11-20 standard, assumed as a reference for the round-robin test, requires, for a single generator, a DC current injection not higher than 0.5% of its nominal current. As the amplitude of these DC current components is very small in relation to the amplitude of the inverter nominal current, it can be difficult to measure (see Fig. 11).

The DC current components are injected to the grid from the same inverter, performing the measure at different levels of the output power supplied. The results are largely scattered and the measure has clear problems regarding repeatability. Fig. 12 shows a schematic of the testing configuration used. The DC current component is measured on the base of the voltage level on the shunt between the inverter and the grid (or the grid simulator).

Next, a small DC component should be measured, overlapped by a high AC current. This usually occurs when the inverter is at maximum power supply, and the measure error can be high. Furthermore, during the measure, the inverter has to be maintained in a stable condition; the PV inverters, in turn, continuously modify their working point because of the MPPT mechanism.

In order to minimize these effects, it is important to evaluate average values in a sufficiently long time slot in order to ensure that enough measurements can be collected.

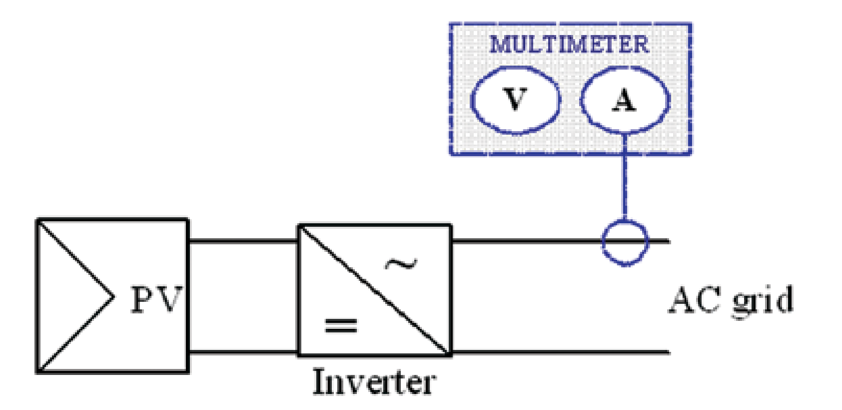


Figure 10. DC current injection measurement configuration.

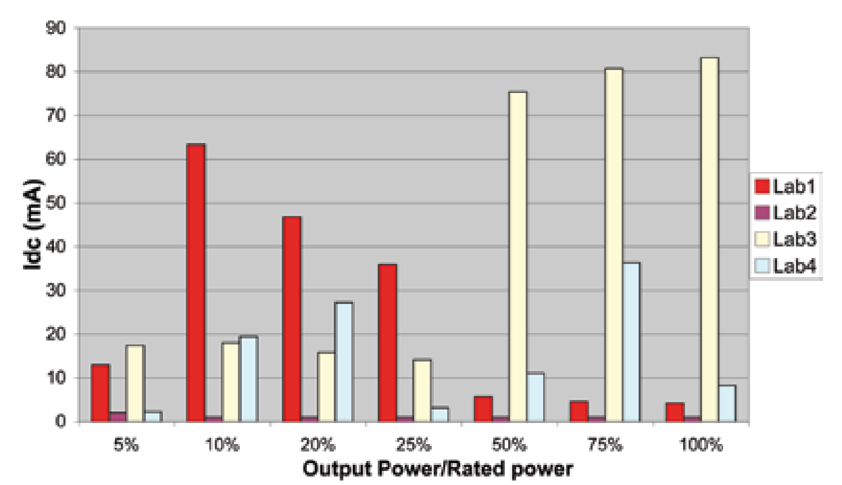


Figure 11. DC current injection measures.

Test equipments: final considerations

Testing a PV inverter that is connected to the electric network requires a DC source that can provide the due DC input to the inverter, and an AC grid – or grid simulator – that is able to supply the right voltage value and to receive the power produced by the inverter under test. However, the round-robin test brought to light some concerns in relation to these pieces of equipment, detailed in the following section.

DC supply

The DC source for the inverter tests can be a DC generator, a DC generator with a series resistance, or a photovoltaic simulator. Test procedures usually define exact values of power produced by the inverter and stable functioning conditions are required during the test. A DC generator usually cannot fulfil this requirement: in fact, the working point, defined by the MPPT, usually corresponds to the current limitation point of the generator and that produces a sudden variation. The MPPT, continuously changing the working point, interferes with the limitation control of the generator, which means that the working point cannot be stable. This factor is more relevant when the ratio between the output power and the nominal power of the inverter is low.

In order to reduce this problem and smooth the I–V curve, it is possible to use a series resistance between the generator and the DC input of the inverter. The best solution is a photovoltaic simulator that can produce the necessary photovoltaic-specific P–V curve (see Fig. 13). Attention must be paid to the characteristics of the photovoltaic simulator, as its control must be faster than the MPPT control of the inverter to be tested in order to avoid interferences and guarantee an adequate stable test condition.

The DERlab round-robin test has highlighted a problem specific to multi-string inverters (i.e. inverters connected to several photovoltaic fields). Such inverters usually have a DC-DC converter for each photovoltaic input and the outputs of these converters are linked to a common DC bus; this DC bus is connected to a DC-AC converter (see Fig. 14).

An MPPT is included in each DC-DC converter, setting up the value I_{DC} of the current required from the photovoltaic module, and consequently defining the relationship I–V of the photovoltaic module and the value of the voltage V_{DC} towards the DC–AC converter.

In practical situations, each DC input is connected to a different photovoltaic field, usually with different orientation, and the related MPPT ensures the maximum power from the photovoltaic field. For a multi-string inverter, the maximum power condition can be reached only if all the DC inputs are used and supplied with the maximum power.

Testing multi-string inverters requires clarification of the test condition related to DC inputs. Some laboratories connected a single DC generator to all the DC inputs of the inverters for data-gathering purposes. However, in order to better simulate a real use scenario, separate generators – one for each DC input – should be used. This approach avoids reciprocal interferences among the different MPPTs, which can lead to difficulties in maintaining the inverter in a stable test condition.

AC grid simulator

The grid simulator must be capable of providing a sinusoidal voltage without harmonic distortion. In addition, the simulator must be able to absorb the AC power generated by the inverter under test – without this capability, the operator will need to connect a balanced load to the output of the inverter. The load must have characteristics that are suited to a continuous connection at the maximum power value.

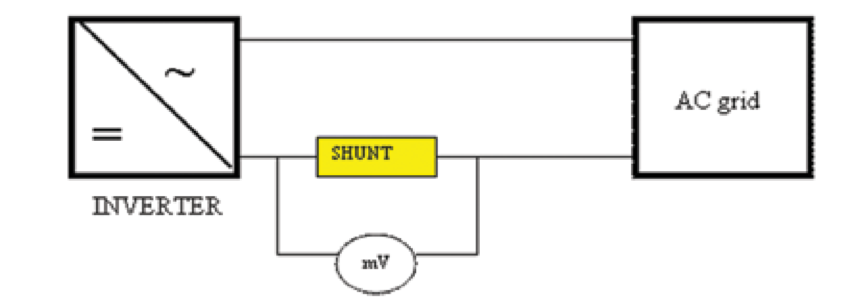


Figure 12. Testing configuration for DC current measurement.

Conclusions

The round-robin test performed throughout several laboratories of the DERlab Consortium allowed for comparison of different approaches among different testing situations, and highlighted a series of clarifications needed in order to obtain repeatable and comparable results. These experiences and the related analysis will be placed at the standard bodies' disposal, in the hope of making a contribution towards the clarification and

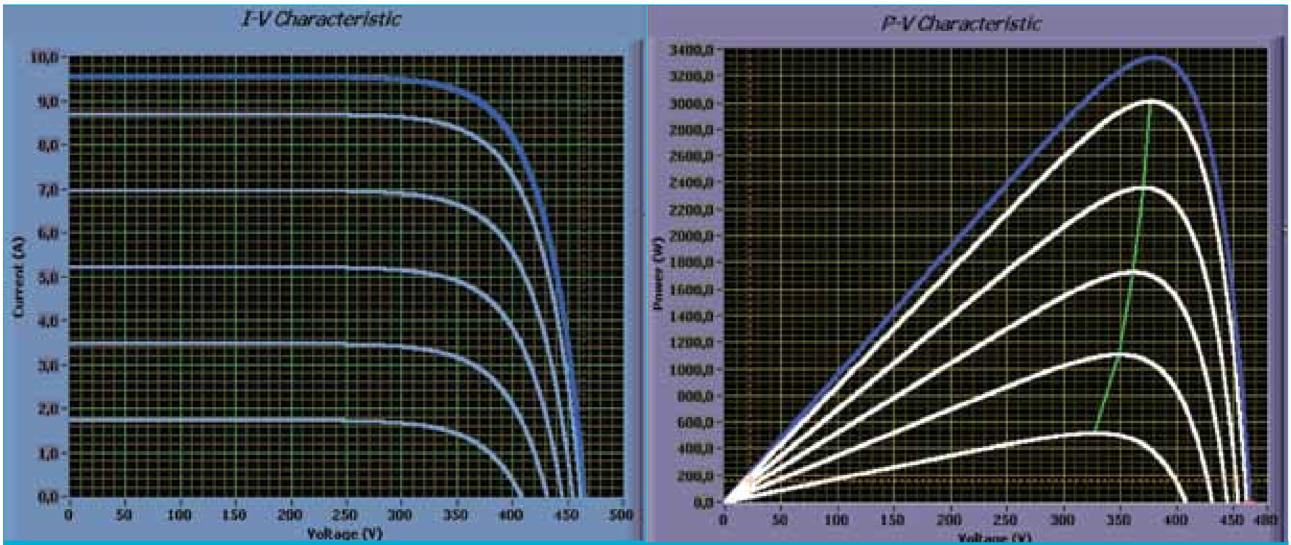


Figure 13. Photovoltaic PV curves.

the enhancement of the existing norms. The DERlab round robin approach, with the development of common testing procedures and the definition of the requirements of the testing equipment, allowed DERlab partnership to increase its common offering in this testing field.

Acknowledgements

The authors would like to acknowledge the participation of DERlab partner members in the data collection for this study.

References

[1] DERlab and DERri Projects [available online at http://www.der-lab.net; http://www.der-ri.net].

[2] IEC 61683: Photovoltaic Systems – Power Conditioners – Procedure for Measuring Efficiency [available online at http://webstore.iec.ch/preview/info_iec61683%7Bed1.0%7Den.pdf].

[3] Groppi, F. 2007, "Testing of anti-islanding protections for grid-connected inverters", *International conference on Clean Electrical Power* (ICCEP2007), Capri, Italy.

[4] EN 61000-4-30: Electromagnetic compatibility (EMC), Part 4-30. Testing and measurement techniques – power quality measurements methods.

[5] EN 61000-3-2: Electromagnetic compatibility (EMC), Part 3-2. Limits, Section 2: Limits for harmonic current emissions (equipment input current <16A per phase).

[6] CEI 11-20 V1: Electrical energy production system and uninterruptible power systems connected to I and II class network.

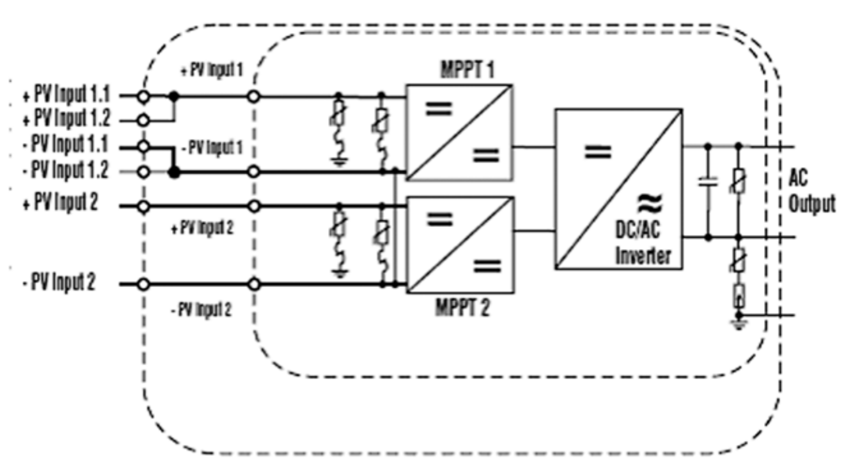


Figure 14. Usual structure of a multi-string inverter.

About the Authors

Dr. Ing. Omar Perego (ERSE) graduated in mechanical engineering in 2000 from the Politecnico di Milano, Italy. He is involved in projects dealing with Distributed Energy Resources (DERs) related to renewable energy, poly-generation and energy efficiency development, environmental aspects and system optimization.

Dr. Ing. Paolo Mora (ERSE) graduated in electronic engineering from the University of Bologna, Italy. As ERSE leader for the DERlab Project and co-ordinator of the DERri Project, he is involved in several projects on the topics of demand side management, automation and control of electric networks and smart grids.

Dr. Ing. Carlo Tornelli graduated in electronic engineering in 1986 at the Politecnico di Milano, Italy. He is working on several projects in the areas of automation and control of microgrids and smart grids. He is also researching technologies for active networks including power electronics for distributed energy resources and information and communication technologies for the electric system.

Dr. rer. nat. Thomas Degner holds a diploma in physics and received his Ph.D. for work on the layout and control of wind diesel hybrid systems. He leads the Electricity Grids Group within the Engineering and Power Electronics R&D Division and is coordinator of DERlab and active in the CENELEC working group WG03 of TC8X. His research activities include microgrids, ancillary services, interconnection requirements, testing procedures and network protection concepts for distribution networks.

Dipl. Ing. Wolfram Heckmann graduated in 1997 from the Technical University of Karlsruhe, Germany, with a degree in electrical engineering (Dipl.-Ing.) and worked for nine years as an energy consultant. He joined the Electricity Grids Group at ISET e.V. in 2006, where his work focuses mainly on grid integration of distributed energy resources and energy management in micro-grids.

Enquiries

Power System Development Department
ERSE
Via Rubattino, 54
20134 Milan
Italy

Emails: omar.perego@erse-web.it
paolo.mora@erse-web.it
carlo.tornelli@erse-web.it
tdegner@iset.uni-kassel.de
wheckmann@iset.uni-kassel.de