On the testing, characterization and evaluation of PV inverters and dynamic MPPT performance under real varying operating conditions

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Grant sponsor: Spanish Ministry of Education and Science; grant number: DPI2003-08887-C03-03.

This is the peer reviewed version of the following article: Sanchis, P., López, J., Ursúa, A., Gubía, E. and Marroyo, L. (2007), On the testing, characterization, and evaluation of PV inverters and dynamic MPPT performance under real varying operating conditions. Prog. Photovolt: Res. Appl., 15: 541-556. https://doi.org/10.1002/pip.763, which has been published in final form at https://doi.org/10.1002/pip.763.

ABSTRACT

The increasing number of photovoltaic inverters that are coming on to the PV market stresses the need to carry out a dynamic characterization of these elements and their MPPT algorithms under real operating conditions. In order to make these conditions repeatable at the laboratory, PV array simulators are used. However, actual simulators, including the commercial simulators, recreate only a single or small set of PV array characteristic curves in which quite commonly theoretical calculations are included in order to simulate irradiance and temperature artificial variations. This is far from being a recreation of the real and long dynamic behaviour of a PV array or generator. The testing and evaluation of the performance of PV inverters and MPPT algorithms has to be carried out when the PV system moves dynamically according to real operating conditions, including processes such as rapidly changing atmospheric conditions, partial shadows, dawn and nightfall. This paper tries to contribute to the analysis of this problem by means of an electronic system that both measures the real evolution of the characteristic curves of PV arrays at outdoor operation and then recreates them at the laboratory to test PV inverters. This way the equipment can highlight the different performance of PV inverters and MPPT techniques when they operate under real operating conditions. As an example, two commercial inverters are tested and analyzed under the recreated behaviour of a PV generator during two singular days that include processes of partial shading and fast irradiance variations.

KEYWORDS

Photovoltaic inverters characterization, solar array simulators, maximum power point tracking

I INTRODUCTION. LIMITATIONS OF ACTUAL PV ARRAY SIMULATORS

The importance of the photovoltaic systems in the generation of electricity is rapidly increasing at this moment. In fact, this growing is one of the highest in the field of the renewable energies and this tendency is expected to continue in the next years [1]. As an obvious consequence, an increasing number of new PV components and devices, mainly arrays and inverters, are coming on to the PV market [2]. The need for PV arrays and inverters to be characterized has then become a more and more important aspect [3-7]. Due to the variable nature of the operating conditions in PV systems, the complete characterization of these elements is quite a difficult issue.

At this moment, the performance of the PV inverters is mainly characterized by means of their energetic efficiency, being this efficiency calculated by testing the inverter at different power levels established beforehand. As a matter of fact, this is usually the only information concerning the inverter performance that is provided by the manufacturers. Due to this way of characterizing PV inverters, only their electric power losses are taken into account. However, no information is provided concerning the operation of the PV inverter under real operating conditions, particularly the performance of its maximum power point tracking (MPPT) algorithm. The MPPT performance is a very significant aspect of the characterization of PV inverters since the PV systems, like in general the systems based on renewable energies, must extract the maximum energy available at every moment from the renewable resource. The global efficiency of the MPPT algorithms depends on its ability to make the inverter operate at the maximum power point (MPP) at every moment. In order to do it, the MPPT algorithm has to track accurately the variations of the MPP, which can be caused by factors such as irradiance and temperature variations and partial shading processes. Obviously, this accuracy will be strongly influenced by both the amplitude and the dynamics of the variations of the MPP. The dynamic characterization of PV inverters and their MPPT performance have to be carried out under real operating conditions, that is, under the real evolution of the characteristic curves of PV arrays.

In order to make the characterization and evaluation of PV inverters and MPPT algorithms at the laboratory, PV array simulators have to be used. Conceptually, they are power electronic converters whose output voltage and current are controlled so as to reproduce or emulate the electrical behaviour of a PV array or generator. A broad variety of simulators have been either proposed in the scientific literature or developed by manufacturers.

The simplest PV array simulators emulate a single and particular current-voltage characteristic curve. In general, this curve is previously calculated theoretically from the array parameters [8-9]. However, it can also be obtained directly from the data sheet of the manufacturer and then programmed in a microcontroller [10]. Obviously, these simulators are only able to test the behaviour of PV inverters and MPPT techniques over a single and static curve. The operating point of the inverter moves along the characteristic curve, but the curve is always the same. That is, the inverter operates dynamically over a static behaviour of the PV array or generator.

Other PV array simulators, greater in number than the previous group of simulators, claim that they are able to include irradiance and temperature variations in the emulation. Some of them include these variations by means of theoretical expressions applied to the original *I-V* curve [11]. However, more often they allow a small set of different characteristic curves, which can correspond to different temperatures and irradiances, to be previously programmed [9,12-13]. In so doing, these simulators try to include some kind of dynamic evolution in the characteristic curves. Although they represent an improvement over the previous group of simulators, which only emulated a single *I-V* characteristic curve, their way of emulating is far from being an emulation of a real and long dynamic evolution of a PV array or generator and cannot be used to analyze problems such as partial shading processes and rapidly changing atmospheric conditions.

A variety of commercial simulators can also be found in the market. They have the same limitations as the previous simulators. Two representative commercial simulators are those from Ainelec [14] and Agilent [15]. Quite often, like the simulator from Ainelec, the commercial simulators claim in their data sheet that they are able to simulate a settable range of PV generators. However, the curve simulated is in practice an extremely simplified curve calculated from particular points such as the short circuit current, the open circuit voltage and the voltage and current at the maximum power point, or even from the slopes of the curve at the short-circuit and open-voltage points. The recreated curve consists of two straight lines joining the first one the short circuit and the maximum power points, and the second one the maximum power and the open circuit points. As a result, the simulator only simulates two slopes of a single characteristic curve.

Other commercial simulators like the one from Agilent, which is a low-power unit, are more complete and include different operating modes [15]. In one mode, the simulator from Agilent recreates a single curve from the four parameters previously mentioned (open circuit voltage, short circuit current, and voltage and current at the maximum power point). In another mode called "table mode", the user can define curves by means of tables (up to approximately 30 tables stored in a non-volatile memory and another 30 in a volatile memory). Then, these curves can be modified by means of current and voltage offsets in order to simulate changes in the operating conditions of the PV array.

Another commercial simulator is the Elgar Solar Array Simulator [16]. This simulator is not a widely-used system and is more complex, but has a wider power range and better controllability. The simulator consists of building blocks (FPCS, Fast Profiling Current Source), each one simulating one or two array strings. These blocks are series or paralleled with other FPCS modules to simulate larger array segments. The FPCS are programmed by means of four parameters that reproduce the I/V curves.

Although a particular amount of curves can be programmed in the commercial simulators, these do not represent the real evolution of a PV generator during a long period of time (for instance one day), as it will be shown in the paper.

Finally, we also have to mention the digital simulators. They are simulators that propose theoretical models [17-18] or equivalent circuits [19-20] of the PV arrays in order to be used in computer simulations. More developed proposals are the real-time digital simulators [21]. These are used to analyze by simulation PV generation systems and include libraries in order to simulate the different components of a PV system, including the simulated PV array and the inverter. All these simulators claim that they can be used to simulate and test PV inverters and their MPPT performance. Although they are easy to use since they are based on simulation, they obviously do not perform any testing of PV inverters under real operating conditions.

Along the previous paragraphs, the problems and limitations of actual PV array simulators have been stressed. As a summary, it can be said that they are not able to recreate at laboratory the same and real operating conditions for PV inverters as they would experience in an outdoor operation. Due to these limitations, they are not suitable to carry out a reliable and thorough testing, characterization, evaluation and comparison of PV inverters and, particularly the MPPT performance under real varying operating conditions. The simulators that emulate a single curve are only valid to test the static operation of an MPPT algorithm. Concerning the simulators that include irradiance and temperature variations, they do it in such a way (by means of theoretical calculations or a small group of previously programmed curves) that can only test whether the MPPT algorithm can take the inverter from a static maximum power point to another. Finally, the commercial simulators recreate a characteristic curve or a set of curves previously programmed, and have therefore the same limitations as the previous simulators. The MPPT testing has to include not only its performance at two or more different characteristic curves, but also how it tracks the maximum power point during the transient between these curves. This is very important especially when the atmospheric conditions are changing quickly, and can lead to differences in the MPPT efficiencies [22-23]. In addition, another important aspect in the evaluation of the MPPT performance are the real partial shadows [24]. In these situations, relative maximum power points appear that vary and move dynamically depending on both the atmospheric conditions and the geometric layout of the PV installation. The appearance of these local maximum points can also make the MPPT performance decrease. As a conclusion, testing of the MPPT algorithms has to include also their performance when the PV system moves dynamically according to real operating conditions, including real variations of the atmospheric conditions, partial shadows, dawn, nightfall, and other varying processes.

This paper focuses on the problem of the evaluation and characterization of PV inverters and their MPPT performance under real operating conditions. With the help of specially designed electronic equipment, the paper shows how the testing and characterization of the MPPT performance is not such an easy issue as actual solar array simulators suggest, and that real operating conditions have to be recreated in order to have a rigorous analysis and evaluation. In this way, the paper can contribute to the possible improvement and development of standards for dynamic testing and characterization of PV inverters and MPPT performance. Some proposals for these standards have been recently made [25].

In order to test thoroughly PV inverters under real conditions, the *I-V* characteristic curves of the PV arrays have to be first systematically measured at outdoor conditions during a period of time. The number of measured curves per second has to be such that the curves represent very closely the real evolution of the array operation during that period of time. After that, these curves have to be physically reproduced in real time to test the PV inverters. In so doing, the recreated operating conditions will be virtually those a PV inverter would have experienced in an outdoor real operation. The measurement of the real evolution of the characteristic curves makes possible to define different patterns of operating conditions that can then be used to test and analyze thoroughly the real operation of the MPPT performance of PV inverters by means of a very reliable emulation at laboratory of the electrical behaviour of the PV arrays or generators.

Unlike the actual PV simulators, including the commercial simulators, the electronic equipment developed by the authors is able to do this characterization. It first measures the real outdoor evolution of the *I-V* characteristic curves of photovoltaic arrays and generators during a period of time. Then, it emulates in real time the real evolution of these characteristic curves so as to reproduce at the laboratory the real outdoor operation conditions for the inverter. A 15kW prototype of the proposed electronic equipment has been experimentally designed and developed. A basic preliminary approach to this prototype with particular emphasis on the electronic conversion stage and its control loops was given previously [26].

After the description of the electronic equipment, the paper shows the usefulness and interest of the equipment in the research on the MPPT performance of PV inverters by means of experimental results. The proposed testing system reveals that, under real operating conditions, the PV inverters have a real behaviour that depends on the climatic and environmental conditions. This behaviour, which has an impact on their MPPT performance, is not being evaluated by actual simulators since they have not been designed, and therefore are not able, to reproduce these real operating conditions. In short, the paper tries to reveal a deficiency that exists in the actual methods of testing of PV inverters and contribute to the improvement of the standards concerning the characterization PV inverters.

II DESCRIPTION OF THE ELECTRONIC EQUIPMENT

The schematic description of the proposed equipment is shown in Figure 1. It consists of an electronic converter, a microcontroller and a data storage unit. The electronic converter includes a measuring card with current and voltage sensors for both measuring the *I-V* characteristic curves of the PV arrays and implementing the control loops. The microcontroller drives the electronic converter by means of generating the proper current and voltage references. In addition, it organizes and controls the information flowing between the converter, the measuring card and the data storage unit. This storage unit is basically a database where the *I-V* characteristic curves are stored.

II.1 The electronic converter

The scheme of the electronic converter is given in Figure 2. It consists of a three-phase diode bridge, a dc-dc converter, an output filter and an energy dissipation circuit. The diode bridge provides a rectified three-phase ac voltage for the dc-dc converter. This converter is an IGBT-based bi-directional converter through which the power can flow in both directions. When the equipment is used to test PV inverters, the converter behaves as an energy source and operates as a Buck converter supplied by the rectified ac voltage. When the equipment is used to measure the dynamic evolution of the characteristic curves of a PV generator, the converter behaves then as a variable load and operates as a Boost supplied by the PV generator. In this case, the energy coming from the generator is dissipated in the energy dissipation circuit, which consists of an IGBT, a resistor and a free-wheeling diode. The electronic converter includes an inner control loop that controls the current through the main inductor L_m. This is a variable-hysteresis control loop that makes possible the short-circuit operation that is required to both measure and emulate the PV arrays operation [26]. Finally, the output filter consists of two capacitors, an inductor and a damping resistor. This filter attenuates the current and voltage switching harmonics and makes the short and open-circuit operation possible, as it is required in PV systems.

II.2 The operating modes of the equipment

In order to test PV inverters and their MPPT performance under real conditions, the real evolution of the *I-V* characteristic curves of PV arrays or generators is first measured and then recreated at laboratory. With this aim, the equipment has two different modes of operation, namely the measuring and the emulating modes of operation.

Measuring mode of operation

The measuring mode of operation is designed as shown in Figure 3. In this mode, the PV arrays or generators are connected in parallel to the electronic converter, which operates as a controlled variable load to make them cover completely their *I-V* characteristic curves. The curves are covered along the voltage axis. This option achieves more accurate results than covering the curves along the current axis due to the lower slope of the curve in the first case. Several arrays or generators can be connected in parallel at the same time at the terminals of the electronic converter. The common voltage (v_o) and the different currents (i_1, i_2… i_n) are continuously measured and filtered in the measuring card. The data are stored in a database. The microcontroller processes these data and compact the information in order to optimise the size of the database as well as its handling. The characteristic curves are then systematically organized, classified and stored in the data storage unit together with the corresponding time when they were measured.

In order to make the PV generators cover continuously their characteristic curves along the voltage axis, an additional voltage control loop is programmed in the microcontroller [26]. This loop, which is used only in this mode of operation, controls the converter output voltage, which is the same as the one at the terminals of the PV generators. As shown in Figure 3, this loop acts as an outer control loop that provides the reference for the inner current loop of the converter. Both loops constitute a cascade control structure that makes possible a robust and accurate control of the voltage at the terminals of the PV generators. In order to generate the reference for the voltage control loop, the open circuit voltage of the generators is first measured, and then the reference is varied from this value up to the short-circuit condition. A parabolic shape is used for this reference in order to increase the measuring accuracy around the maximum power point. The high switching frequency of the converter makes it possible to design the cascade control structure with fast dynamics and then to achieve an accurate tracking of fast voltage references. As a consequence, the *I-V* characteristic curves can be covered and measured with enough quickness (milliseconds) to have a reliable real-time measuring of their evolution.

From the information stored in the database, different test patterns can be defined corresponding to different evolutions of the PV arrays and generators under different weather conditions such as a sunny day, cloudy day, dawn, nightfall, foggy day, warm or cold day, and partial shadows. Subsequently, these patterns can be recreated in real time by the equipment during the emulating mode of operation to test at the laboratory several PV inverters with the same pattern. In addition, the stored characteristic curves can be used to develop further analyses concerning aspects such as performance of the arrays and generators and optimal configuration of the PV generator.

Emulating mode of operation

The emulating mode of operation is shown in Figure 4. In this mode, the PV inverter that is to be tested is connected at the output of the converter. Now, the converter operates as a power supply for the PV inverter and recreates in real time the same evolution of the *I-V* characteristic curves as they were measured and stored in the database during the measuring mode. From the database, the microcontroller takes the desired characteristic curves pattern, which includes the previously measured characteristic curves and their corresponding time base. Then, according to the measured voltage at the PV inverter terminals and the characteristic curves pattern, the corresponding current that has to be delivered at every moment to the PV inverter by the electronic equipment is calculated. This current is the reference for the converter current loop. Due to the high dynamics of the current loop and the high cut-off frequency of the output filter, the current at the inverter terminals recreates accurately in real time the current that the real PV generator would have delivered according to the measured voltage. In this way, the equipment behaves as a real-time emulator of any PV array or generator whose behaviour has been previously measured in the measuring mode of operation. This recreation can be repeated as many times as necessary at the laboratory to test several inverters under the same conditions.

By means of the emulating mode of operation, the MPPT performance and efficiency of different PV inverters can therefore be reliably tested and evaluated. A reliable comparison between different MPPT techniques can then be made, especially when the tracking algorithms have to deal with real situations such as quick-varying atmospheric conditions [22] and partial shadows [24], in which they have to show their real capability to extract effectively at every moment the maximum power from the PV generators.

III EXPERIMENTAL RESULTS AND DISCUSION. DYNAMIC EVALUATION OF PV INVERTERS AND MPPT ALGORITHMS

III.1 Description of the prototype equipment

In order to validate the capability of the electronic equipment to both measure the real evolution of the *I-V* characteristic curves of PV arrays and emulate in real time this behaviour to test PV inverters, a prototype has been experimentally designed and developed. The physical implementation of the prototype is shown in Figure 5. The prototype can measure and recreate the behaviour of PV generators up to 15kW, with maximum short-circuit currents and open-circuit voltages of 30A and 500V, respectively. The electronic converter is supplied by means of a three-phase 380V ac source. SKB 30/08, SKM50GB123D and SKM50GAL123D modules from Semikron are used for the power semiconductors (IGBTs and diodes) of the diode bridge, the dc-dc converter and the dissipation circuit, respectively. The values for the converter components are given in Table I.

The current control loop is implemented in an analog board. The switching frequency at normal operation is 10kHz. The measuring board includes the voltage and current sensors as well as their associate filtering and conditioning circuitry. LEM LA 55-P sensors are used for the currents and LEM LV 25-P for the voltages. The converter includes electronic protections against overvoltages and overcurrents. The microcontroller is a DSP DS1104 from dSPACE, which is integrated in a PC. It drives the equipment during the measuring and emulating modes of operation and implements digitally the output voltage control outer loop, which is required in the first mode. It also manages the storing of the measured data in the database, which runs in the PC. In this way, they are accessible from MATLAB or any other programming language. For this application, the database mySQL has been chosen due to its quickness and capability to store a large amount of data. The PC can also be used to make a real-time monitoring of the *I-V* characteristic curves.

The prototype is capable to measure continuously three times per second the full *I-V* characteristic curves of up to seven different PV arrays or generators. The curves are covered in an averaged time of 200ms. The high measuring rate (three times per second) is possible due to the fast dynamics of the cascade control structure. This rate makes it possible to carry out later an accurate emulation of the behaviour of the PV generators.

III.2 Experimental results. Dynamic evaluation of PV inverters and MPPT performance by recreating the behaviour of a PV generator

This section shows why the recreation of the real operating conditions is important for the testing and evaluation of PV inverters and MPPT techniques and how the proposed equipment can do it. First, the electrical behaviour of a PV generator was measured with the equipment operating in the measuring mode. Its *I-V* characteristic curves were measured three times per second and stored in a database together with their corresponding time. The PV generator is placed on the roof of the Department of Electrical and Electronic Engineering of the Public University of Navarra at Pamplona, Spain. It consists of 60 BP585 modules that are organized in three groups of 20 modules connected in series. The three groups are then connected in parallel to form the generator. At standard conditions, that is, at an irradiance of 1000W/m^2, an AM1.5G solar spectrum and a temperature of 25°C, these modules have a peak power of 85W, a short circuit current of 5A, an open circuit voltage of 22.1V, and a maximum power point current and voltage of 4.72A and 18V, respectively. That means that the generator has, at standard conditions, a peak power of 5.1kW, an open circuit voltage of 442V, a short circuit current of 15A and a maximum power point current and voltage of 360V and 14.16A, respectively.

After testing the PV generator during several days, two interesting days were chosen for a later testing of PV inverters, specifically January 29 and 30, 2005. Obviously, the definition of patterns for possible incorporation to PV inverter performance standards would require an additional and deep research. The two days are selected with the aim of showing that the testing of PV inverters under real operating conditions, and particularly under special phenomena such as varying atmospheric conditions and partial shading processes, is important for a reliable and thorough characterization, and that the proposed equipment can do this testing and help to pave the way for improving the standards concerning inverters performance. The first day corresponds to a sunny day that additionally is affected by a partial shading process at the end of the day. The second day corresponds to a cloudy day in which atmospheric conditions are varying quickly. Figure 6 shows the evolution during both days of the maximum power of the generator, obtained from the measured *I-V* characteristic curves. With this information it is possible to calculate the real maximum energy that could have been obtained with this generator during both days. This value will be compared later with the energy effectively extracted by the tested PV inverter. As an example of the measured *I-V* characteristic curves, Figure 7 shows their evolution, in the way they are stored in the database, during the period of the first day going from 16.5h to 17.5h, that is, one hour long (note that the time is shown in increasing hours with decimal notation). In order to make the figure clearer, the represented curves are only a part of the curves stored in the database, which are approximately 10,800 per hour. The period shown in the figure corresponds to the part of the day in which the PV generator is affected by the partial shading process. Due to this process, the *I-V* characteristic curves exhibit during the different transitions more than one maximum power point that can make the MPPT algorithms track local instead of absolute maximum power points.

The two selected days are now the patterns to recreate at laboratory in real time the same electrical behaviour of the PV generator during both days. These patterns can be recreated as many times as required for testing of PV inverters and MPPT techniques. A first commercial PV inverter is then tested and its MPPT performance evaluated under both patterns. This inverter is a 5kW PV commercial inverter for connection to a 50Hz-230V grid, and has an input voltage range between 125V and 450V. A second 5kW 50Hz-230V PV commercial inverter, with similar input voltage range, will also be tested for the first day pattern in order to compare the different performance of both inverters under the same pattern.

The results of the testing of the first inverter when it operates under the conditions of the first day (January 29, 2005) are shown in Figures 8 to 11. Figure 8 shows the evolution of the maximum power point voltage of the PV generator (blue line) together with the operating voltage imposed by the commercial inverter at the generator terminals, that is, the voltage determined by the MPPT algorithm of the inverter. Concerning Figure 9, it presents two pair of graphs. The first pair is the evolution of the power extracted by the inverter versus the power corresponding to the generator maximum power point at every moment. The second pair of graphs shows the evolution of the energy extracted by the PV inverter versus the maximum energy that could have been delivered by the generator. Both Figures 8 and 9 show how, during most of the day, the MPPT algorithm tracks quite well the generator maximum power point and makes the inverter extract the maximum power. However, at the final part of the day and due to the process of partial shading, the MPPT algorithm fails to track the evolution of the generator maximum power point. Then, the power extracted by the inverter from the generator goes lower than the maximum power, as shown in the second pair of graphs of Figure 9. At the end of the day, the performance of this MPPT algorithm in terms of energy extracted from the generator (MPPT efficiency) is 96%, that is, 4% of the energy has been lost due to the fact that the MPPT algorithm has not done its work correctly as it cannot handle properly this situation.

The operation of the inverter during the process of partial shading is shown in detail in

Figures 10 and 11. The first figure shows, for the part of the day corresponding to the process of partial shadow, the evolution of the inverter operation over the recreated *I-V* characteristic curves depicted now in terms of power versus voltage (*P-V*). In this figure, the pink line gives the operation of the inverter while the black line shows the maximum power point of the *P-V* curves at every moment. As it is shown in the figure, the process of partial shading affects progressively the PV generator. The process is not linear and different transitions appear that take the absolute maximum power point to the left, generating at the same time local maximum power points on the right that decrease very quickly. Along the process of partial shading the inverter fails to track the absolute maximum power point while it finds and tracks quite often the local (relative) maximum points. This behaviour makes the energy extracted by the inverter be lower than the energy available from the PV generator. It is shown in detail in Figure 11, which shows five curves corresponding to the moments of time t=16.5 h, 16.52 h, 16.56 h, 16.7 h and 16.9 h together with the trajectory of the inverter operating point. At the beginning, the maximum power point appears on the right-hand side of the first curve (t=16.5h). Then, due to the partial shading, another maximum power point appears in the curves on the left-hand side. The maximum on the right of the curves decreases very quickly, while the one on the left turns quickly into the new absolute maximum power point. However, the inverter tracks the local maximum power point on the right, deviating thus from the new absolute maximum. After t=16.7 h., the local maximum power point on the right disappears and the inverter resumes MPP tracking toward the absolute maximum power point, which is located on the left.

In order to compare the different dynamic behaviour of two commercial inverters under the same real varying operating conditions, the second inverter is now tested under the same day pattern. Since the most interesting part of the day for the MPPT performance is the process of partial shading, the results of the testing during this process is shown in Figure 12, together with the results for the first converter that were presented in Figure 10. As it can be observed in Figure 12, the MPPT algorithm of the new inverter deviates less from the absolute MPP and then tracks the MPP better than the first inverter.

The results of the testing of both inverters under the same day pattern show how the system makes it possible to better evaluate the dynamic behaviour of inverters and MPPT algorithms. When the operating conditions of the solar installation are smooth, stable and move slowly, which is the case of most of the first day pattern, PV inverters track in general the MPP with no problem, as shown in Figures 8 and 9 for the first inverter. Existing solar array simulators are able to reproduce only one or a small set of these I-V curves. If any of these simulators were used to test both inverters, it would also find that the MPP is tracked correctly for any of the curves corresponding to the region of the first day in which the conditions are nearly stable or vary slowly. However, when the operating conditions vary quickly or show partial shading processes, the inverters exhibit different behaviours, as shown in Figure 12, that lead them to a different MPPT performance and efficiency. Existing solar simulators cannot reproduce these real varying operating conditions and therefore, they would not have been able to both find the difference in behaviour between both inverters and evaluate and compare them. In short, actual solar simulators are able to test inverters and MPPT techniques performance over a single characteristic curve, but cannot analyze this performance under real varying operating conditions such as those shown in the paper. On the contrary, the proposed system can analyze this performance, revealing that differences can exist between inverters, and suggesting that this kind of tests should be taken into account when improving the standards on the performance of PV inverters.

The results for the testing of the first commercial inverter with the second day pattern (January 30, 2005) are shown in Figures 13 and 14, in the same way as those shown for the first day. The day pattern is now a cloudy day with quick variations in the atmospheric conditions most of the day. Now, the MPPT efficiency of the inverter in terms of energy extracted from the PV generator reduces to 95% for the whole day. As it is shown in Figure 14.b, which presents an enlarged area of the first graph, during the quick irradiance variations, the MPPT algorithm behaves relatively well, with a small delay in the MPP tracking that causes a small reduction in the power extracted from the PV generator in comparison with its maximum power. However, the transient generated by some irradiance variations that are very quick causes the inverter activate its protections and shut down. In these cases, the power goes to zero (see Figure 14.a) and the operating voltage of the inverter goes to the open circuit voltage of the PV generator (see Figure 13). As it is shown in the figures, this happens five times along the day (at 11.3h, 12.05h, 12.55h, 12.85h and 13.95h). After some time (around two minutes for this inverter), the PV inverter starts operating again. However, the power corresponding to these two minutes has been lost, and the inverter efficiency decreases. This test shows the importance of recreating at laboratory real operating conditions, in this case real irradiance variations both in terms of amplitude and dynamics of the variations, and how the proposed equipment can carry out this recreation, contrary to actual solar array simulators.

IV CONCLUSIONS

The characterization of PV inverters is an important aspect in PV systems. However, it is also quite a difficult issue, since the variable nature of the operating conditions for these inverters has to be taken into account. These conditions are given by the real outdoor evolution of the *I-V* characteristic curves of the corresponding PV arrays and generators. In order to test and characterize at laboratory the performance of PV inverters and MPPT algorithms, PV array simulators are used. However, actual PV simulators only recreate at laboratory a particular or a set of characteristic curves and therefore are not able to recreate real operating conditions for the PV inverters.

The real operating behaviour of a PV generator is the real and dynamic evolution of its characteristic curves. This paper describes an electronic system that is able to both measure the real evolution of the *I-V* characteristic curves of PV arrays and generators and recreate them in real time to test PV inverters. With this equipment it is then possible to carry out a thorough systematic characterization and testing of PV inverters and MPPT performance under real operating conditions such as rapidly changing atmospheric conditions, processes of partial shading, dawn and nightfall operation.

In order to show the usefulness and interest of the equipment, the operation and performance of a commercial 5kW PV inverter is tested and evaluated at the laboratory under the recreation of the electrical behaviour of a PV generator during two singular days. The first day is a sunny day in which a process of partial shading occurs at the end of the day. The second day is a day with quick irradiance variations. Additionally, a second inverter is tested during the first day in order to compare the different behaviour between both inverters. The results show that both singular situations, the partial shading and the quick irradiance variations, make the inverter efficiency during the day, that is, the energy extracted by the inverter from the PV generator in comparison with the maximum energy that the generator could have delivered according to its maximum power point at every moment, decrease. In short, the tests show how the testing and characterization of the MPPT performance is not such an easy issue as actual solar array simulators suggest, and that real operating conditions have to be recreated in order to have a rigorous analysis and evaluation, as it is carried out by the proposed equipment.

The equipment and the analysis shown in the paper are a first step to show the importance of characterizing PV inverters and MPPT algorithms under real operating conditions and can help to pave the way for improving the standards concerning inverters performance. The proposed equipment can help to investigate, in a further step, the possible definition of standard operating conditions and patterns as a function of factors such as the characteristics of the location of the PV installation, the atmospheric conditions and the PV application. This step should include the analysis of the effect of processes like partial shading on the I-V curves. Furthermore, the equipment can be used to test installed PV arrays and generators and analyse local shading issues. All this would make it possible to carry out a systematic characterization of PV inverters under the corresponding pattern and help in the improvement of actual MPPT techniques and design of new ones.

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FIGURES

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Figure 1. Overall system description.

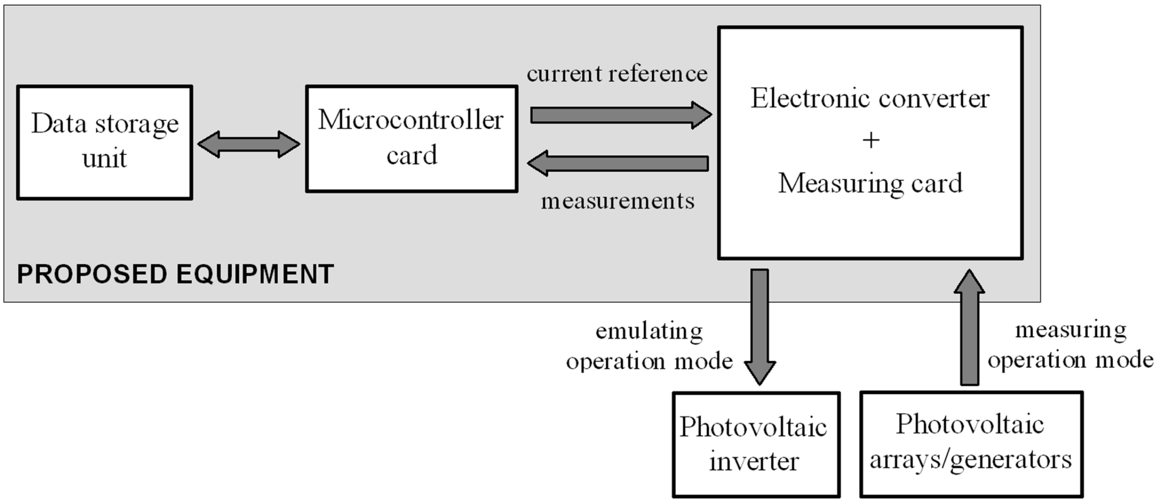

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Figure 2. Scheme of the electronic converter.

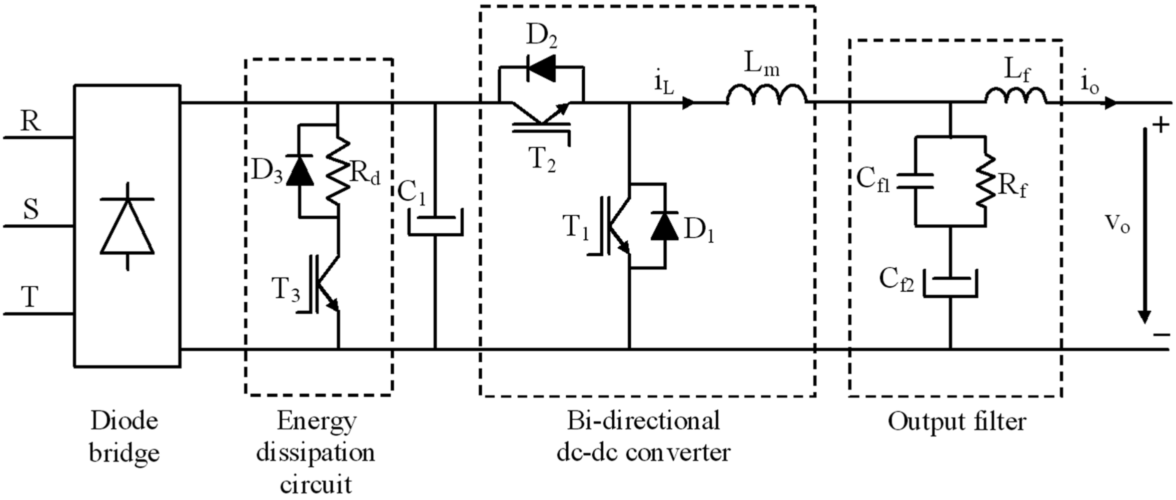

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Figure 3. Scheme of the measuring mode of operation.

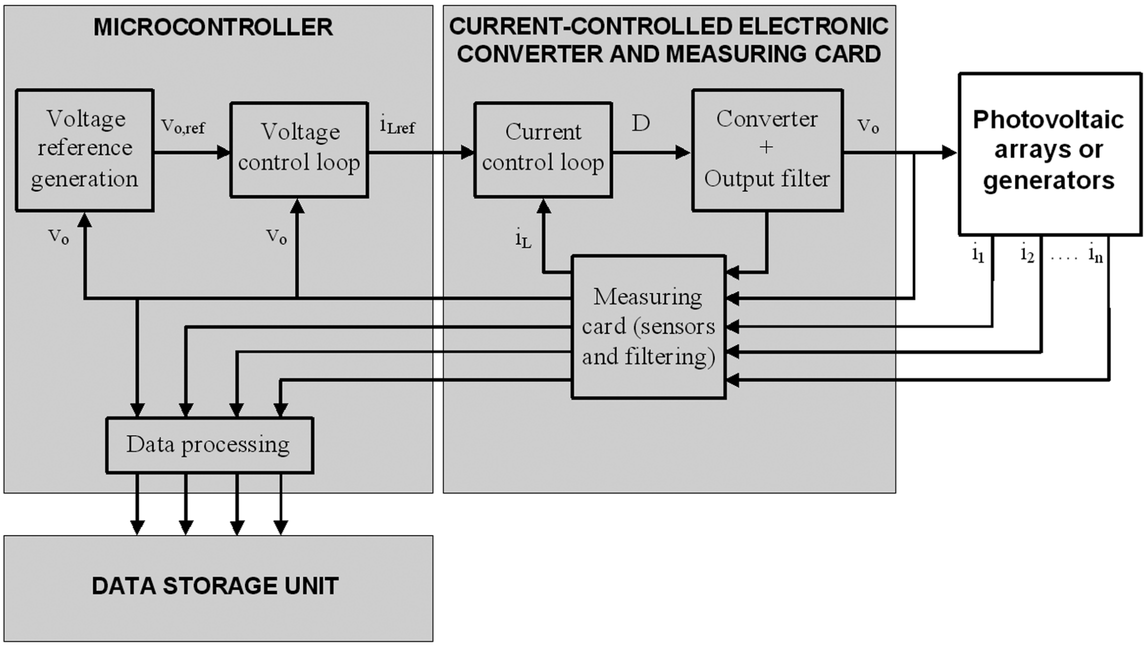

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Figure 4. Scheme of the emulating mode of operation.

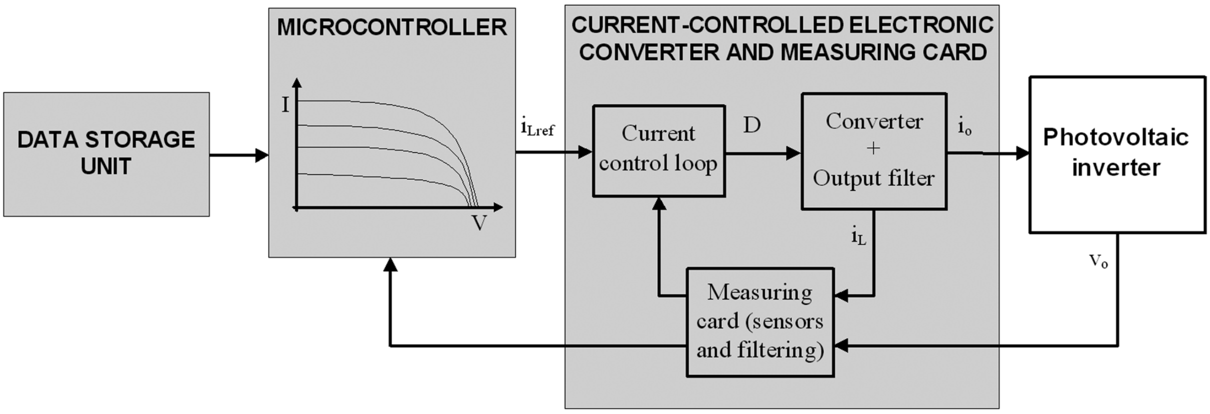

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Figure 5. 15kW prototype equipment.

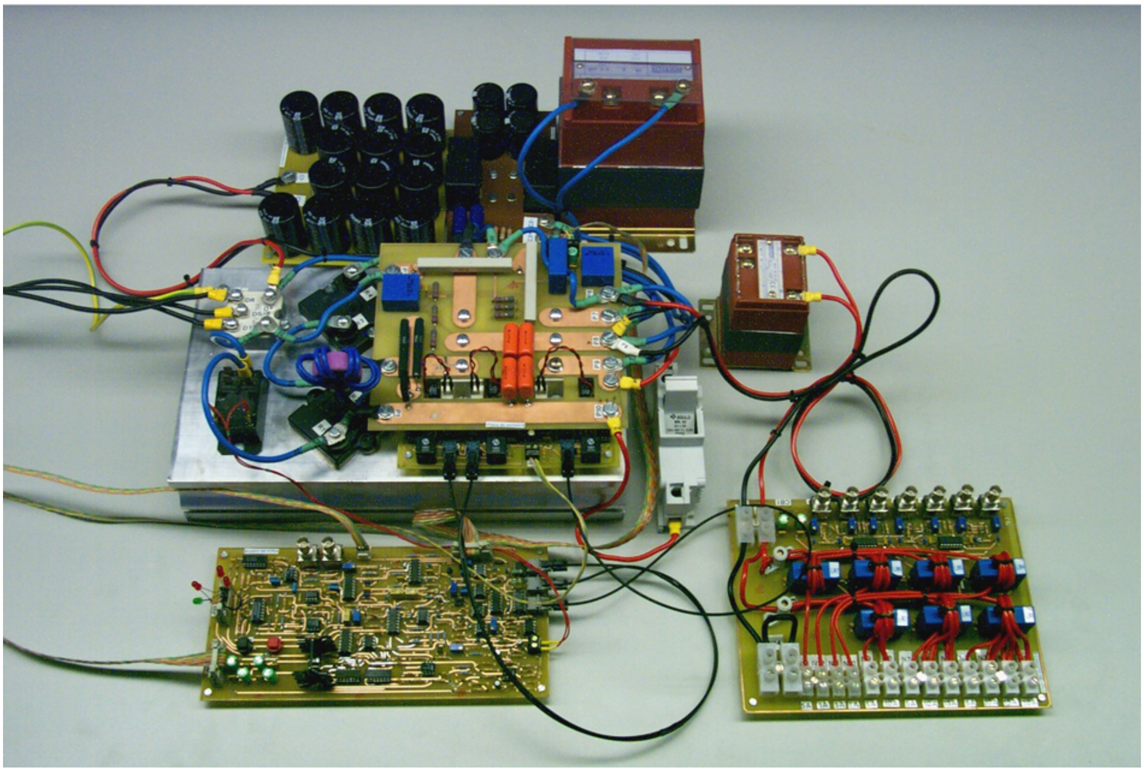

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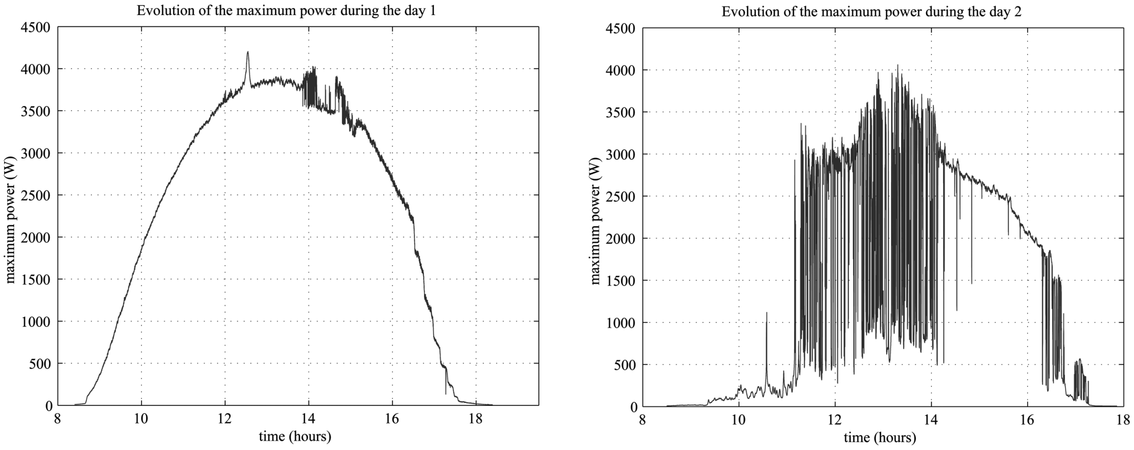
Figure 6. Testing of a 5.1kW PV generator during two days, evolution of the maximum power: a) day 1 (January 29, 2005), b) day 2 (January 30, 2005)



a) b)

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Figure 7. Evolution of the measured and stored I-V characteristic curves of the 5.1kW PV generator, period from 16.5h. to 17.5h of the day 1.

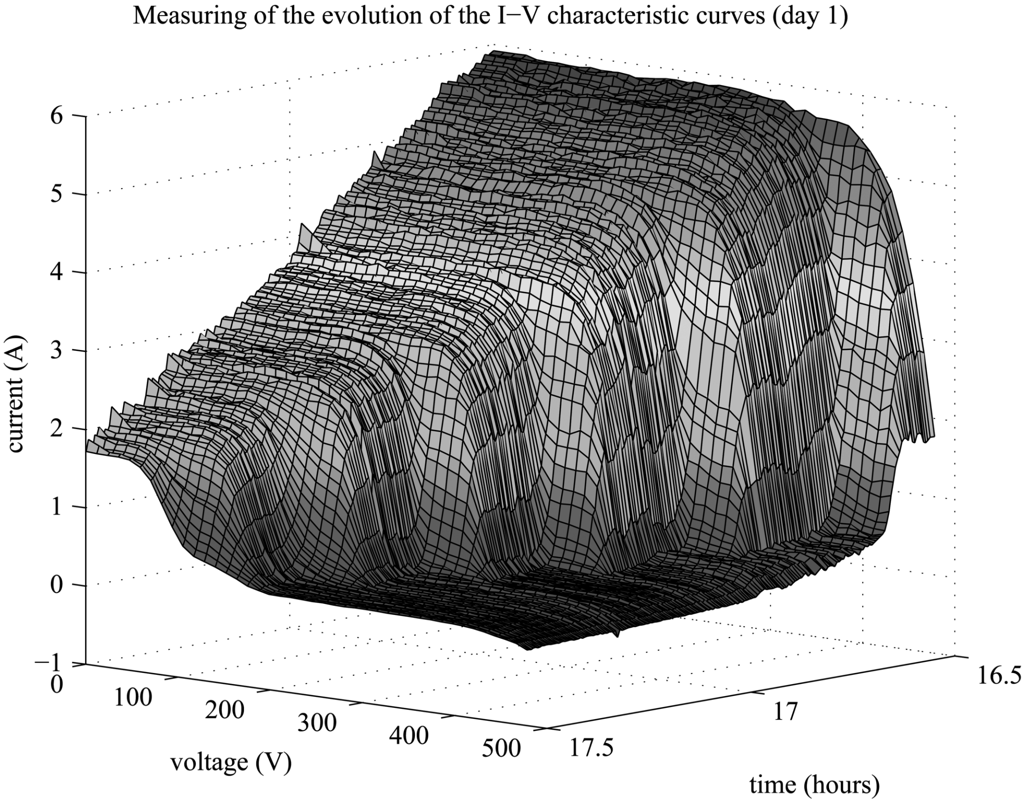

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Figure 8. Test and characterization of a PV commercial inverter (day 1): operating (green line) and MPP (blue line) voltages.

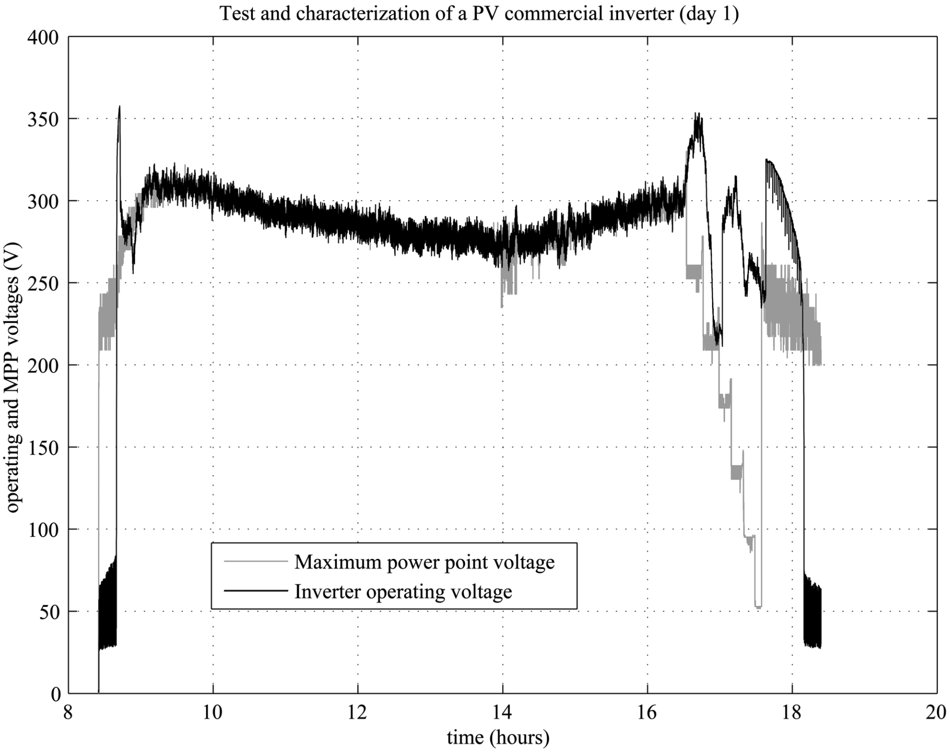

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Figure 9. Test and characterization of a PV commercial inverter (day 1):
inverter (green line) and MPP (blue line) power and energy (scaled in kWh/200)

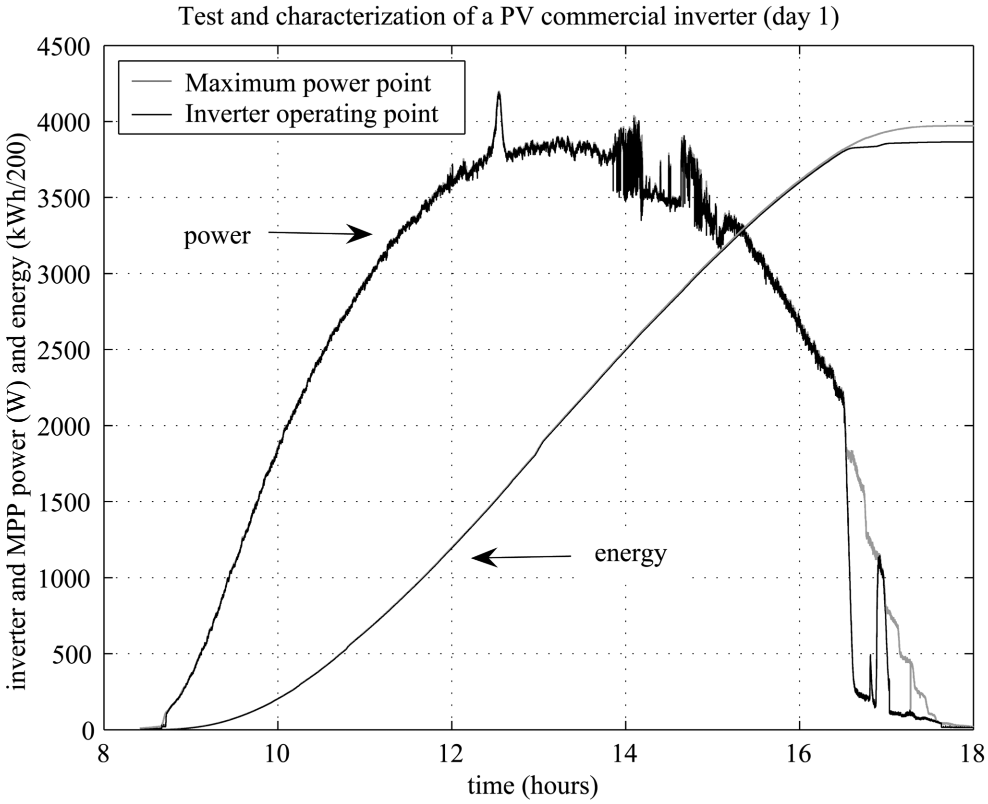

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Figure 10. Test and characterization of a PV commercial inverter over the recreated I-V characteristic curves (day 1), inverter operating point (pink line) and PV generator MPP (black line)

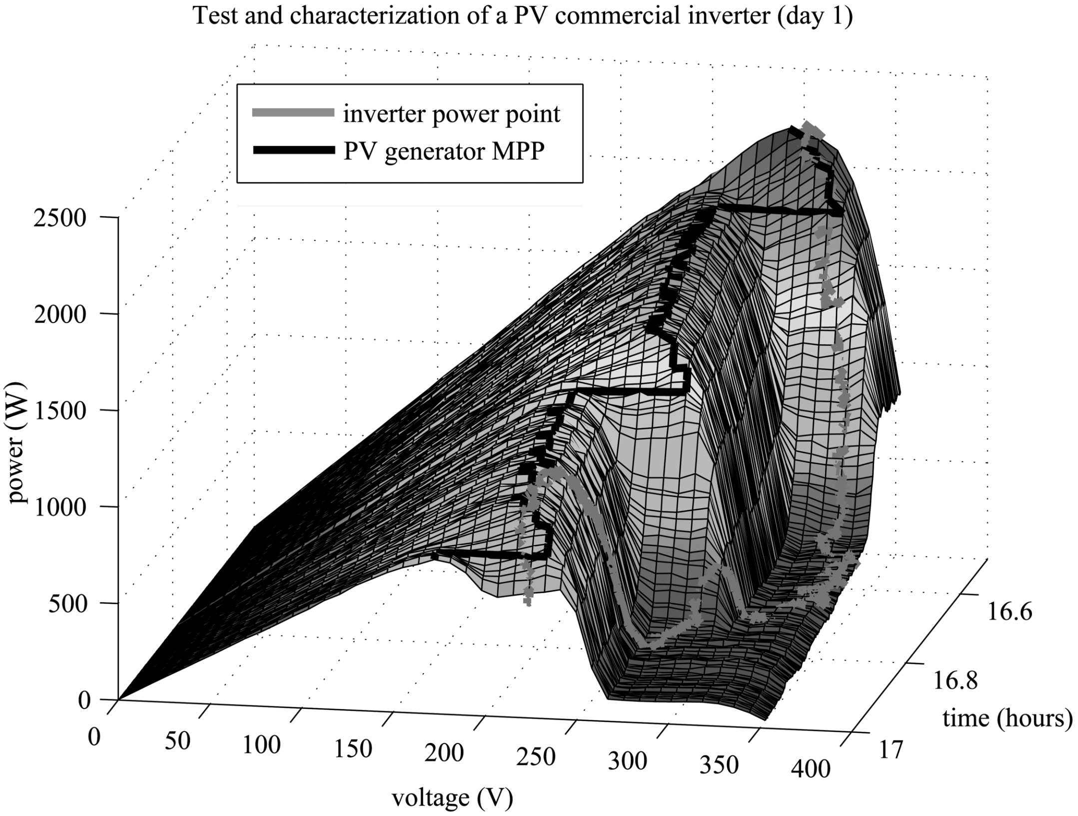

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Figure 11. Evolution of the inverter operating point (black points) over the recreated characteristic curves

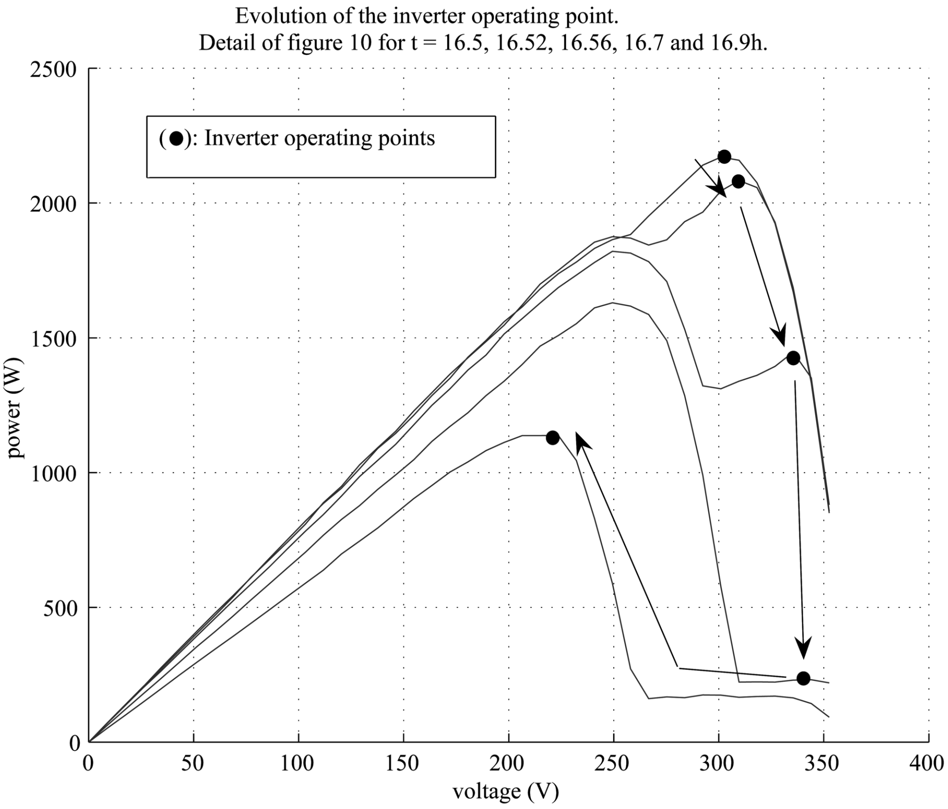

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Figure 12. Test and characterization of two commercial PV inverters over the recreated I-V characteristic curves (day 1), inverter #1 operating point (gray), inverter #2 (blue) and PV generator MPP (black)

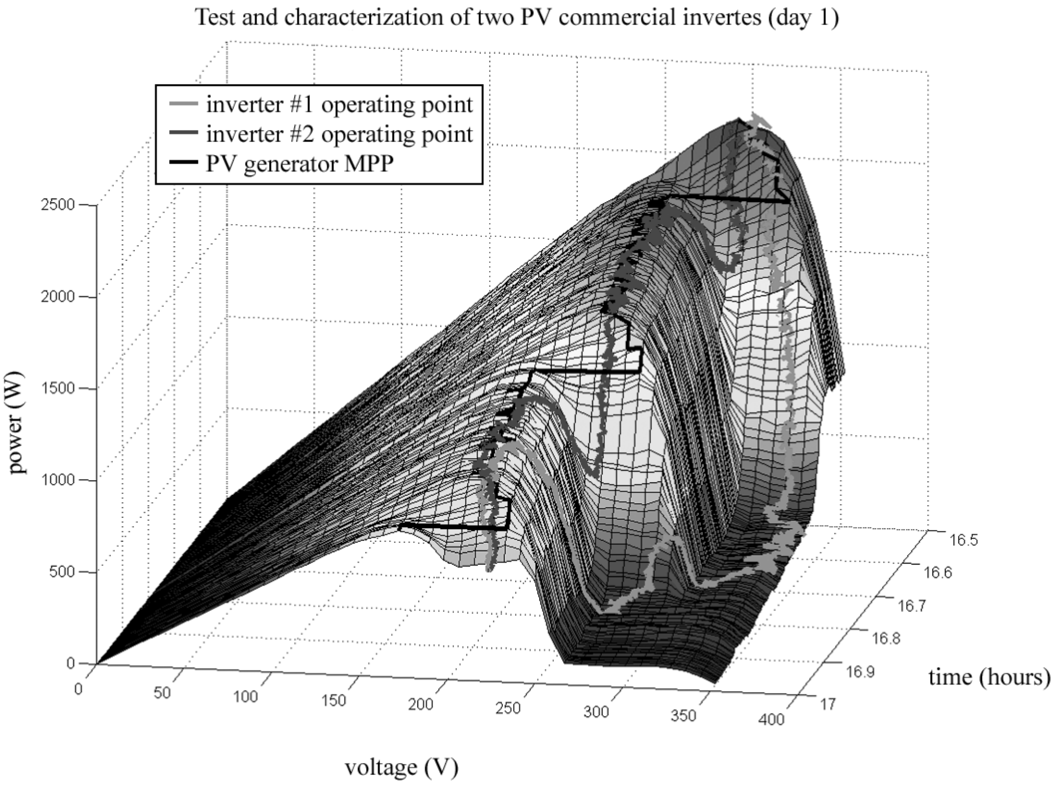

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Figure 13. Test and characterization of a PV commercial inverter (day 2): operating (green line) and MPP (blue line) voltages.

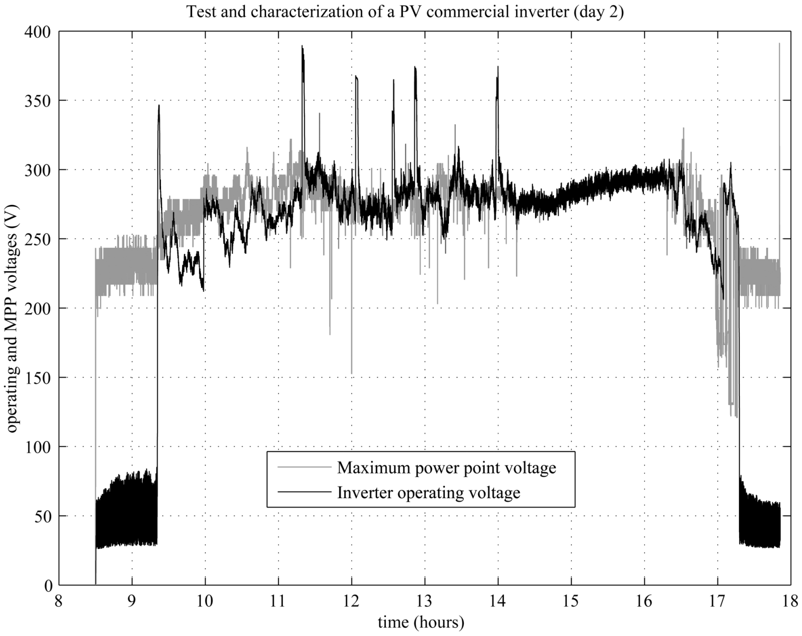

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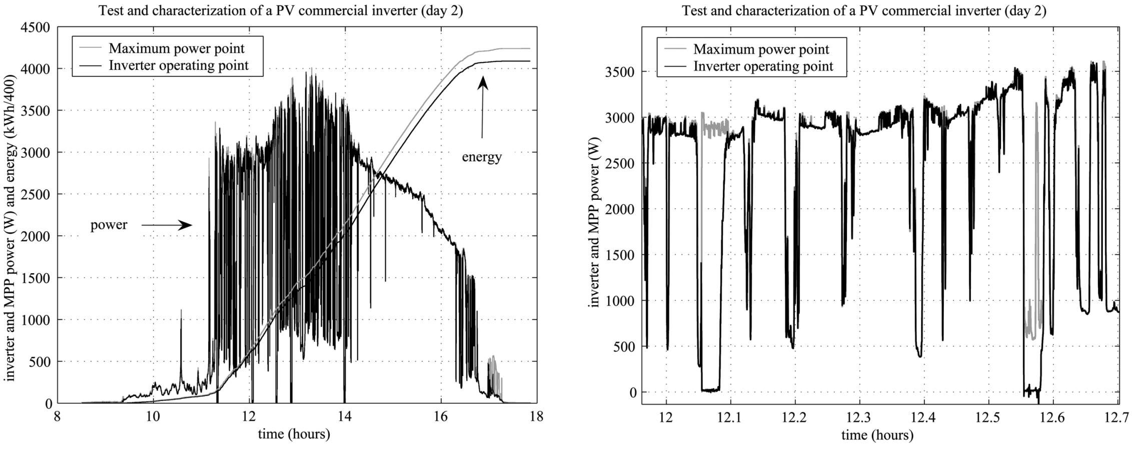
Figure 14. Test and characterization of a PV commercial inverter (day 2): a) inverter (green line) and MPP (blue line) power and energy (scaled in kWh/400), b) enlargement of first graph.



a) b)

TABLE I. Values for the converter components

$L_m = 4.5\text{mH}$	$L_f = 100\mu\text{H}$	$C_1 = 2.35\text{mF}$	$R_d = 15\Omega$
$C_{f1} = 110\mu\text{F}$	$C_{f2} = 235\mu\text{F}$	$R_f = 3\Omega$	