ON THE SPECIFICATION AND TESTING OF INVERTERS FOR STAND-ALONE PV SYSTEMS

J. Muñoz and E. Lorenzo

Instituto de Energía Solar. Universidad Politécnica de Madrid (IES-UPM).

Ciudad Universitaria s/n. 28040 Madrid.

e-mail: javier@ies-def.upm.es

Tel: +34 91 544 10 60

Fax: +34 91 544 63 41

Keywords: Stand-alone PV system, inverter, testing, efficiency, reliability, technical specification.

SUMMARY

Inverter features are reviewed from a PV systems perspective, with a view to contributing to possible codes, procurement specifications and testing procedures, in order to assure the technical quality of these systems. A laboratory testing campaign has been carried out on a representative set of sixteen currently available inverters and a set of the most common AC appliances. The results of the tests are discussed with the aim of divulging the particular features of operating AC appliances in PV systems and the provisions to be taken into account in PV system design. The development of testing procedures has followed the motto "*keep it as simple as possible*", in order to make their application easier in conventional laboratories in developing countries.

1. INTRODUCTION

The presence of inverters is becoming widespread in stand-alone PV systems for rural electrification purposes. In fact, national agencies in different countries, such as Thailand[1] or Brazil[2], have included inverters in their recent initiatives. To a large extent, this is happening because inverter technology is overcoming the barriers that have prevented their use in the past, namely: low reliability, high cost and poor conversion efficiency.

Inverters allow PV systems to power conventional AC appliances, which represents an undeniable advantage in terms of delivered service and user satisfaction. However, standard AC appliances are designed for operating in the particular conditions of the conventional grid (well regulated voltage and frequency, low voltage harmonic distortion, large surge power capability, etc.), which are sometimes not maintained by inverters. This implies the risk of improper functioning, even damage, to the appliances, which should be taken into consideration in PV system design. Moreover, while the use of AC appliances connected to the grid is highly standardised and certified using internationally validated procedures, there are no equivalent standards, certifications and procedures available for PV inverters.

This paper is intended to contribute to future technical standards for PV inverters. For that, a set of 16 commercially available PV inverters has been tested in combination with most common AC appliances. The results are discussed below in an attempt to assess the different aspects (power capability, voltage regulation, protections, etc.) of interest for general PV standards, and also for the procurement specifications issued by national agencies in the promotion of rural electrification programmes. Testing inverter activities carried out by other laboratories have been also taken into consideration[3-5].

To a great extent, this paper follows along the lines of the *Universal Technical Standard for Solar Home Systems*[6] and the consecutive testing campaigns of commercial PV components[7-9]. It should be made clear that this particular approach for technical quality assurance does not involve the accreditation of testing laboratories by international certification bodies (ISO 25[10]) as a prerequisite. Instead, it is based on the idea that technical quality in PV rural electrification is more a matter of will than of technical sophistication. Rather simple local testing (in conventional laboratories of agencies, utilities, universities, etc.) can be a very effective technical quality assurance tool if it is clearly established in contractual agreements between vendors and customers. We should clarify that this *ad hoc* alternative neither tries to compete with accredited laboratories nor exclude them. Rather it is motivated by the persistence of technical problems in the field that, today, remain out of the scope of international standards. As a matter of fact, our laboratory, at the IES-UPM, despite not being internationally accredited, maintains a regular and increasing activity on PV components testing (PV generators, lamps, regulators, batteries and, now, inverters) upon request. Therefore, the motto "*keep it as simple as possible*" has been paramount in the definition of testing procedures, as well as for the selection of the required instrumentation.

It is important to note that the users of PV inverters must be protected against electric shock, which is matter of vital importance as a result of the potential risks of AC voltages greater than 50 V. This can be done in different ways, for example, following the recommendations of the well-known IEC 60364 standard[11]. However, simply for presentation reasons, their discussion takes place in a further paper. Here, we have restricted ourselves to testing the inverters' capability for activating the so-called "Residual Current Devices", which are at the core of most protective schemes.

2. AC LOADS AND INVERTER REQUIREMENTS

Standard characterization of AC loads assumes that they are operated by the grid, which is (or should be) close to an ideal voltage source, i.e., pure sinusoidal voltage, zero internal impedance, unlimited output current, etc. This approach has the advantage that it is independent of the voltage source and closely represents the load behaviour when operated by different utility grids.

However, inverters are far from being ideal voltage sources because their output current is limited, and also, because their voltage waveform cannot necessarily be sinusoidal. As a matter of fact, square and quasi-square waveforms are also present in the current market (Figure 1) and can be acceptable in many practical situations. Therefore, AC loads can behave differently when they are operated by inverters. Furthermore, standard parameters, such as the power factor, PF, or the total harmonic distortion, THD_X[12] (where x=V,I for voltage and current waveforms, respectively), can differ significantly under non-sinusoidal conditions.

Figure 1. Voltage waveforms of different inverters found in the current PV market. (a) Sinusoidal. (b) Quasi-square. (c) Square.

As an illustrative example, figure 2-a shows the starting of a domestic electric drill (induction motor) operated on the grid. It can be seen that the surge power (1800 W) is eight times greater than the rated one (225 W). Figure 2-b shows what happens when the same electric drill is powered by an inverter. The surge power is now reduced by a factor of 5.6 (1800/320), but the motor is correctly operated, although it takes more time (1.3 versus 0.5 seconds). Hence, this inverter should be accepted in practice, despite its inability to provide the surge power associated to its grid operation.

Figure 2. Starting of a domestic electric drill (induction motor) operated on (a) the grid, (b) an inverter.

These operational differences between the grid and inverters limits the real effectiveness of possible inverter specification approaches based on standard parameters. For example, faced with a specific PV application (SHS, schools, etc.) one can imagine requiring something like: “Inverter power capability must be X times larger than the rated power”. However, this represents rather little help in anticipating whether the inverter is capable of starting a particular load, because the X value is only slightly related to its surge power under grid conditions. Therefore, this approach to inverter specification should be restricted to the case in which the elements making the load cannot be anticipated. Think, for example, of the provision of standard PV systems to a large number of schools whose AC equipment is from diverse origins. Then, it could be of interest to specify the surge inverter capabilities by simply referring to the inverter itself, and disregarding the load. It is worth mentioning that, for such cases, the GEF/World Bank specifies the following requirements[13, 14]: *“The inverter must operate safely at an ambient temperature of 25 ºC for a minimum of: a) four hours at full rated output power, b) one minute at 125% of the rated power, and c) two seconds at 150% of the rated output (to simulate high surge currents due to starting of motors)”.*

However, when all the particular elements making up the load can be precisely defined, the inverter specifications can focus simply on assuring the proper operation of all these elements and disregarding other electrical parameters. This is just the case in many PV projects. Particularly when rural electrification is concerned, the elements making up the load used to be provided within the same project frame as the PV systems themselves. In such cases the load can be defined, for example, in terms of: a XX inch, XX W television (or even, the television model XX from XX, or similar); a standard XX W drill, etc. Moreover, additional information describing the expected pattern of load use is also required in order to determine, both, the simultaneously allowed load elements, and the energy requirements. The first is needed for inverter specification, while the second should be known for PV-system sizing purposes.

Keeping in mind the research into this way of inverter specification, we have carried out a laboratory testing campaign combining commercially available inverters and real AC loads. The following aspects have been analysed separately:

On the AC side:

- Rated power and surge capabilities.
- Voltage and frequency regulation.
- Harmonic distortion.

On the DC side:

- Low voltage disconnection.
- Ripple.

General features:

- Power efficiency.
- Reliability.
- Other aspects.

3. TESTING CAMPAIGN

Sixteen commercial inverters from 13 different suppliers and 6 different countries have been tested (table 1). Rated power ranges from 0,14 to 10 kVA. Fifteen are one-phase 230V/50Hz and only one is three phase 230V/400V. According to their voltage elevation topology, two inverter types can be distinguished: high-frequency, which are switched at high frequency and use a small and light transformer made of ferrite, and low-frequency, which refers to inverters that incorporate bulky iron transformers. According to the output voltage waveform, inverters can be classified as sinusoidal, quasi-square and square, as already described in figure 1. Inverters I1 to I10 have been directly acquired by the IES-UPM, while inverters I11 to I16 have been tested at the request of private companies and organizations involved in PV rural electrification projects. Certain testing results may not be available for all inverters because some of them broke down during the tests.

Table 1. Main characteristics of the tested inverters.

Table 2 lists the AC loads that we have used in the testing campaign. Roughly, they represent the vast majority of AC appliances currently powered by PV systems. Most tests (voltage and frequency regulation, power efficiency, overload etc.) require the load power to be varied within a suitable range, adapted to the particular rated power of each inverter. For that, we have relied on resistive loads. The simple combination of several commercial incandescent lamps allows the range below 1 kW to be covered by steps of 25 W (figure 3-a). For high power levels, up to 15 kW, a resistive load bank has been implemented using water heaters (figure 3-b). These resistive loads are widely available, cheap and easy to use, which are important advantages when looking into local testing application. Other loads have been used for testing particular inverter features: surge capabilities, harmonics, electromagnetic interference, etc.

Table 2. Electrical characteristics of the AC loads used for inverter testing.

Figure 3. Resistive loads used for inverter testing. (a) Incandescent lamps (up to 1 kW) (b) Water heaters (up to 15 kW).

Inverters must be tested at the maximum ambient temperatures of the final site, which is usually greater than the ambient temperatures of our laboratory. This has led us to develop a climatic chamber. Again, looking for local applicability, this chamber has been built using conventional materials: a garden shed, thermally-isolated with expanded polystyrene and aluminium sheets to protect it against fire (figure 4-a). The control of temperature is carried out using a standard thermostat that measures the chamber temperature and controls an electric heater placed inside (figure 4-b).

Figure 4. (a) Climatic chamber. (b) Ambient temperature control.

Finally, it must be mentioned that the precise characterization of general AC performances require specific instrumentation (watt meters, power quality analyzers, digital oscilloscopes, etc.) capable of measuring parameters such as PF or THD_X. However, when the elements making up the load can be precisely anticipated, an alternative means of characterization requiring only common instrumentation (true RMS voltmeters and calibrated shunts) can be applied. Because of its simplicity, special attention has been paid to this last alternative.

4. RESULTS AND DISCUSSION

4.1 Rated and surge power

Obviously, the PV system design must ensure that rated inverter power is equal to or greater than the sum of the rated power of all the simultaneously permitted individual AC loads. Furthermore, the inverter must ensure the safe starting of whatever individual load in any normal operating condition, i.e., with the rest of the simultaneously permitted individual loads maintained in steady state operation (it is reasonable to assume two or more individual loads will not start at the same time).

On the lack of a precise load definition, we have tested the inverters at their rated power at 25 ºC for one hour using pure resistive loads. All the inverters passed this test. We have also tested the inverter starting capabilities with all the compatible loads, i.e., loads whose rated power is equal to or lower than the rated power of the inverter. As a result, most inverters are capable of starting any individual load when no other loads are operated simultaneously. However, in some cases, even starting a single load can cause inverter shutdown. For example, the inverter I1 requires several ON/OFF switchings to start the TV. In general, as the total of rated power of simultaneously connected loads increases, the greater the difficulty for the inverter to start a particular load, especially motors. However, it is difficult to generalize and anticipate the inverter behaviour for a particular combination of elements making up the load, which advises matching the inverter to the specific load as far as is possible.

Under starting conditions, the surge power can exceed the rated one and some inverters behave as sources of current limiting the output current and, therefore, reducing the output voltage, which can drop more than 40% below the nominal value (figure 5). Such transient voltages can negatively affect the proper operation of other

AC loads connected in parallel, which may require a certain load management in order to avoid the simultaneous operation of incompatible loads.

Figure 5. Voltage and current evolution at inverter I12 output during the starting of a motor. For about 3 seconds, the voltage drop reaches 40%.

4.2 Voltage and frequency regulation

AC loads should generally be operated at a fixed voltage and frequency. Several problems can rise from both over voltage and under voltage: load damage, not-ignition, poor luminosity, etc. Besides, frequency variations can affect equipment using frequency as a reference for their operation, such as internal clocks or timers. Regulation refers to the inverter's ability to maintain the steady state AC output voltage, V_{OUT}, and the frequency, f_{OUT}, close to the nominal value face fluctuations of DC input voltage and load power demand (the previously described starting transient phenomena are excluded from this concept). We have tested this inverter capability, again with resistive loads, by measuring V_{OUT} and f_{OUT} for DC input voltages ranging from 11 to 15 V (12 V reference), and for load power ranging from zero to the inverter rated power. The resulting V_{OUT} range has thus been described in terms of the average RMS value, V_o, the maximum, $V_o + \Delta V$, and the minimum, $V_o - \Delta V$. The frequency range is also described in this way. Table 3 summarizes the results. This test must cover the expected ranges of operating output power and DC input voltages. In general, it is sufficient to carry out the test at three output power levels (0%, 50% and 100% of inverter rated power) and three input voltages (90%, 100% and 120% of nominal input voltage).

Table 3. Voltage and frequency regulation of the tested inverters. DC input voltage is varied from 11 to 15 V; meanwhile load power is varied from zero to the inverter rated power.

It can be seen that frequency regulation is usually good. Conventional grid standards[15, 16] usually establish a limit of 2% (± 1 Hz), or even 1%, for frequency fluctuations. These rules can be extended to PV inverters. A good possibility is to choose 2% as a compulsory value, and 1% as a recommended one. All the tested inverters, except I1, comply with these comfortably. In general, voltage regulation is not as good as frequency regulation, and several inverters behave poorly. It is worth commenting that most inverters have a better regulation when they operate at a fixed input voltage and a varying output power. However, their regulation is worse when DC input voltage changes. As representative examples, figure 6-a shows the variations in V_{OUT} versus the DC input voltage for three tested inverters operating at a fixed output power.

Quasi-square inverters deserve a further comment. In order to regulate the RMS value of V_{OUT}, the pulse width is modulated in each semi period of the voltage waveform, by decreasing the width pulse when the DC voltage increases and vice versa. The important point is that, despite this procedure stabilizing the RMS value, the peak voltage remains unregulated and can reach high values. Figure 6-b shows an example of this.

Figure 6. (a) RMS output voltage versus DC input voltage for three different tested inverters operating at a fixed resistive load. (b) AC output voltage (RMS and peak values) of inverter I9 versus DC input voltage operating at a fixed resistive load.

Voltage regulation standards for the conventional grid vary from country to country. For example, in Europe, the voltage regulation must be within ± 10%[15], while in the USA, national standards require a regulation within ± 5% of the nominal voltage[17]. These rules can also be extended to the RMS value of PV inverters. A good possibility is to choose 10% as a compulsory value, and 5% as a recommended one. As far as the grid is concerned, as the voltage is sinusoidal, the peak voltage is proportional to the RMS one (√2xVrms) and their relative fluctuations are the same. However, as stated above, the same is not true for quasi-square inverters, whose peak voltages can reach high values. For these inverters, it seems advisable to limit the peak voltage to the maximum allowed for the sinusoidal ones, for example, to 1,55 (√2x1,1) times the nominal RMS voltage as compulsory limit.

4.3 Harmonic distortion

Grid related standards involve a divided responsibility between consumers and utilities. The latter being responsible for the quality of supply, they must ensure that the total harmonic distortion of voltage waveform, THD_V, is always kept below certain limits. And, for that, they resort to limiting the harmonic content of the current consumed by users, applying harmonic limits to individual appliances[18, 19]. For example, in Europe, the THD_V of public and industrial supply networks must always be (regardless of the load condition) less than 8%[15]. The IEEE recommends[19] a lower limit: $THD_V \leq 5\%$. However, the alternative of extending these strict THD_V limits to the case of common PV inverters does not appear to be necessary. In this regard, Sandia suggests for large hybrid inverters[20] that: *"Requiring the total harmonic distortion to be less than 5% regardless of the load is an arbitrary and unnecessary restriction on* *power sources … unless an application has loads which are very sensitive to voltage distortion, a* THD_V *specified as < 5% for all linear loads is appropriate*“.

Most tested sine wave inverters have THD_V< 5% with resistive loads. Although in several cases, such as the inverter I3, the THD_V exceeds 10% near its rated power, even with pure resistive loads. On the other hand, the THD_V of quasi-square inverters, with resistive loads, ranges from 25% to 50% and, according to the previous regulations, their use should not be recommended for powering AC loads. However, these kinds of inverters have been satisfactorily tested with AC loads in our laboratory and we have not found justifiable reasons for discouraging their use, providing the voltage distortion neither hampers the operation of the permitted loads nor puts their reliability in danger. The test carried out at our laboratory simply consisted of powering AC loads for an hour and checking whether their operation is correct. It should be mentioned that this test only allows the functionality of appliances to be verified. Hence, it should be recognized that the potential negative effects of non-sinusoidal waveforms, such as their impact on the lifetime of the appliances may remain obscure.

To add more controversy, quasi-square inverters supplying non-linear loads can lead to a better PF and fewer current harmonics (THD_I) than sine wave inverters operating at the same load (figure 7), which has led some authors to even recommend their use for powering this kind of load[21]. As to the question of harmonics, the GEF/World Bank has stated that[13] “*inverters with sine-wave outputs are preferred but not required as long as suppliers can demonstrate that the proposed inverter is suitable for powering the anticipated loads*”. A similar opinion is given by the IEEE[22]: “*Generalization in regard to converter harmonics is difficult. It is recommended that* *each prospective application of a self-commutated converter be analysed for the effects of harmonics in light of application specifics".*

Figure 7. Current waveforms of a colour TV powered by (a) the grid (b) the inverter I1.

To summarize, the question of harmonics is still an open one. Thus, any attempts of quantify the maximum allowable harmonics content would demonstrate a lack of practical use in this context. Instead of that, our proposal on this issue is to simply ensure the proper operation of all the permitted appliances and to avoid electromagnetic interference, always maintaining a preference for the lower harmonic content of sinusoidal inverters.

4.4 Voltage disconnection thresholds

Inverters, besides ensuring a proper operation of AC loads, must not negatively affect other BOS components, such as the batteries. Stand-alone PV systems incorporate charge regulators to protect the battery against both overcharging and deep discharging. In principle, in order to preserve the latter, inverters should be considered as an additional DC load and be connected to the load output of the charge regulator (Figure 8-a). This requires the charge regulator to be able to support the entire current required by the inverter, which is not always possible in practise, especially where surge currents are concerned. In fact, the common installation practise is to connect the inverter directly to the batteries (Figure 8-b). In this configuration, it is of paramount importance to ensure the inverter protects the batteries against deep discharging. However, inverters generally turn off when the DC input voltage falls below a certain threshold, which is usually selected rather as an inverter self-protection, disregarding the protection of the batteries. As an example of this, table 4 details the low voltage disconnection values, LVD (12 V reference), of tested inverters. Most of these LVDs are simply too low to provide any protection to the batteries[9, 23]. Hence, severe LVD corrections are needed before connecting these inverters directly to batteries. But this is seldom possible, because of the lack of facilities for voltage threshold adjustment. Besides, inverter turn-off is generally not delayed, which may cause undesired interruptions in supply when the inverter has to start induction loads, e.g. motors, since the surge current may cause the battery voltage to drop below the LVD during starting.

Figure 8. Connection between the inverter and the PV system. (a) To the load output of the charge regulator. (b) Directly to batteries.

On the other hand, inverter protection against DC over-voltage should also be considered. Connection to the batteries indirectly provides an effective protection, because battery voltage is intrinsically limited to values, which are not usually dangerous for inverters. However, unusual service conditions can occur in PV systems. Operation without a battery can be potentially dangerous (which can happen during the maintenance of the battery or when a battery protection fuse blows). Then, if no specific protection is provided, the PV generator imposes the voltage which can become great high enough to destroy the electronic devices. Well-designed PV systems include protection against this “non-battery” operation condition in the charge regulator. Again, connecting the inverter to the load output of the charge regulator guarantees the required protection. Inverters themselves are usually protected against high input voltage. Table 4 also shows the high-voltage disconnection (HVD) and reconnection (HVR) thresholds of tested inverters.

Table 4. Voltage disconnection and reconnection threshold (12 V reference) of the aforementioned tested inverters.

To summarize, provisions must be taken to ensure the adding of an inverter is not detrimental to the prescribed protections of the corresponding PV system. In particular, battery protection against deep-discharging, and inverter protection against DC over-voltage must be guaranteed, either by connecting the inverter to the load output of the charge regulator or by including protection features in the inverter itself.

4.5 DC ripple

All tested inverters are "*stand-alone*"[24] and require a battery at the input (they are not designed for a direct connection to the PV generator). However, contrary to expectations, the current demanded by one phase inverters (or three phase ones with unbalanced load) from the batteries is not purely DC because it includes an AC component that can be significant, particularly when the inverter operates close its rated power. As an example, figure 9-a shows the DC current of inverter I12 supplying a resistive load at different output power levels. As can be seen, the current waveform resembles a sine wave whose frequency is 100 Hz (twice the output frequency). For example, at 120% of rated inverter power, the average current is 123 A, while the RMS value reaches 151 A. AC loads with power factors below 1 may require even larger DC current RMS values. For example, figure 9-b shows the DC input current of inverter I4 supplying an inductive load (electric fan).

The significant point is that, because heating in conductors and fuses is related to RMS values, PV codes must consider RMS values (and not average ones) to size the wiring and the protective fuses[25]. It is also interesting to observe that the topology of the latter inverter (I4) allows reactive power to be transferred back to the batteries. That explains why a part of the DC current cycle reaches negative values in figure 9-b, thus leading to a kind of charge-discharge battery “micro-cycling”. Several authors have addressed the impact of these “micro-cycles” over the battery lifetime[26, 27], but definitive conclusions on this issue can still not be drawn.

Finally, depending on the upward inverter impedance (internal impedance of battery, resistance of conductors between battery and inverter, fuses, etc.), DC current ripple can induce also DC voltage ripple, which could interfere the proper operation of the inverter and other BOS components connected to the batteries, such as the charge regulator. Figure 9-c shows the DC current voltage waveform and the induced voltage ripple of inverter I12, which is nearly 180º out of phase with the current (meaning the upward inverter impedance is essentially resistive).

Figure 9. (a) DC current waveforms of inverter I12 supplying a resistive AC load at different power levels, expressed as a percentage of the rated inverter power. (b) DC current waveform of inverter I4 supplying an inductive load (electric fan). (c) DC current and voltage waveforms of inverter I12 supplying a resistive load at 90% of its rated power.

To summarize, PV system specification (battery capacity, sizing of cables, etc.) must consider DC current RMS values for wiring sizing, and must ensure the induced DC voltage ripple does not interfere with the correct operation of any BOS component as well as the inverter itself. For the latter, a RMS value of the voltage ripple of less than 5% of the nominal DC voltage is particularly recommended.

4.6 Power efficiency

Obviously, inverter energy efficiency must be calculated for PV sizing purposes. This calculation depends on both the load profile and the power efficiency. Among other factors, power efficiency depends on the input voltage, output power level and load type. Generic tests with different loads: resistive, reactive, non-linear and complex loads (or any combination of these) have been proposed[28] in order to characterize the full inverter behaviour. However, such measurements require specific instrumentation (watt meters, power quality analysers, digital oscilloscopes, etc.), which are seldom available in conventional laboratories.

We have restricted our tests to the case of pure resistive loads, which can be measured with more general instrumentation (true RMS voltmeter and calibrated shunts for measuring current). Since PF=1 in this case, AC power is given by the simple product of the RMS values of AC voltage, V_{OUT}, and AC current, I_{OUT}.

Moreover, it should be considered that both the DC current and voltage include a ripple component, which, as noted in the previous section, are nearly 180° out of phase. Consequently, the DC input power is not exactly the product of the average input voltage, V_{DC}, and the average input current, I_{DC}. Despite this, we can calculate the so-called conversion factor[28], η_C, which is a good approximation of the power efficiency, η_P[28]:

$$\eta_C = \frac{V_{OUT} x I_{OUT}}{V_{DC} x I_{DC}} \qquad \eta_C \leq \eta_P$$

The conversion factor represents a lower limit of the power efficiency, which can be very useful for specification purposes. Finally, it must also be considered that power efficiency depends on the battery voltage, which typically ranges from 11 to 14 V (12 V reference). Measurements of DC input power at fixed DC voltages can be made either using a programmable power supply or regulating the voltage of a battery with DC lamps[29]. Again, the latter is within the scope of conventional laboratories.

Table 5 summarises the average conversion factors of tested inverters using resistive loads (average refers to input voltages between 11 and 14 V). Values are given at rated power and also for the power level corresponding to the maximum conversion factor. The differences between the presented conversion factors and the power inverter efficiencies (measured with power quality analysers) are less than 2%.

Although sine wave inverters tend to be less efficient than square wave ones with resistive loads, the efficiency of both with induction motors may be comparable and even better for the former[30, 31]. Furthermore, it must be taken into account that the power efficiency with resistive loads represents an upper limit of the general case, because, maintaining the same power, inductive and non-linear loads require larger currents, which increase the corresponding power losses[31-34]. In other words, considering only the power efficiency with resistive loads tends to underestimate the real DC energy consumption, which is the key parameter for PV sizing purposes. However, the estimation of real AC energy consumption (requiring complex instrumentation for the measurement of PF values) is not strictly necessary if AC loads are well specified. In that case, it is enough to measure the DC input power of the inverter and the envisaged AC loads, which only require simple instrumentation (true RMS voltmeter and calibrated shunts for measuring current).

In a no-load condition, inverters still drain power (the so-called no-load loss[28]) to keep themselves in operation. Consequently, not only the output power but also the power efficiency is zero. The corresponding energy losses may greatly influence the overall energy efficiency, especially, if AC loads are sporadically used. Table 5 shows the no-load losses of tested inverters at the nominal input DC voltage in normal operation (i.e. with AC voltage at inverter output) and also in stand-by mode, which reduces the no-load loss (output voltage is turned-off and substituted by some means of load detection). It can be seen that this latter mode is not usually available in low-power inverters.

It is interesting to account for the fact that power efficiency, η_P, depends on the ratio between the power delivered to the load, P_{LOAD}, and the rated power of the inverter, P_{RATED}. This dependence may be represented by[35]:

$$\eta_P = \frac{p}{p + k_0 + k_1 p + k_2 p^2}$$

Where $p = P_{LOAD}/P_{RATED}$ and k_0, k_1 and k_2 are parameter characteristic of each inverter. k_0 represents the no-load loss in normal operation, k_1 represents the losses that depend linearly on the current (voltage drop across diodes, etc.) and k_2 represents the losses that depend on the square of the current (resistive losses, etc). Table 5 also shows these parameters calculated for each inverter, which is a valuable tool for energy efficiency calculations in practical designs (k_0 has been calculated as the ratio of the no-load loss to the rated inverter power, and k_1, k_2, fitting the experimental measurements with the model).

Table 5. (a) Average conversion factors of the tested inverters with resistive loads. Average refers to input voltages between 11 and 14 V. Values are given at rated power and also for the power level corresponding to the maximum. (b) No-load loss of tested inverters. Values are given for normal operation and also for stand-by mode, and at nominal DC voltage. (c) Model parameters k_0, k_1 and k_2.

PV system specification must impose a certain limit for DC/AC conversion losses. A good possibility is to keep them below 30% of total AC energy consumption. Whatever the case, minimum inverter quality requirements should also be imposed by fixing a minimum efficiency at rated power (for example, 75% as compulsory, and 85% as recommended), as well as maximum no-load losses (for example, 3% of rated power as compulsory, and 1% as recommended).

4.7 Reliability

Whatever the restrictions imposed on the specified load, unexpected service conditions can occur, for example, because the connection of other than permitted loads or because of accidental wiring faults. If no specific protection is provided, both, the inverter and the permitted loads could be damage. We have tested the inverter resistance under the following anomalous operating conditions: overload (power load equal to 150% of inverter rated power, for 10 minutes at 25ºC), short-circuit (shorting the output when the inverter operates at rated power), sudden DC supply disconnection (opening the connection between battery and inverter when the latter operates at rated power) and input reverse polarity (connecting the inverter to the batteries with the wrong polarity and no-load condition).

The need for overload and short-circuit protection is out of the question. The sudden disconnection of the DC supply may take place when the charge regulator disconnects the load to protect the battery. Hence, this protection appears to be highly necessary when the inverter is connected to the load output of the charge regulator. However, the need for protection against reversed polarity is more controversial, because this anomalous condition can only happen during installation or maintenance activities, which is usually under the responsibility of well-qualified professionals.

Table 6 shows the testing results (Inverters I12 to I16 have not been tested against power supply disconnection because their high rated power usually requires a direct connection to the batteries). Despite talking about a good general state-of-art of inverter technology, it is also clear that the PV system specification should not forget protection aspects. Particularly in stormy areas, it is also recommendable to ensure the inverter protection against induced over-voltages in both DC and AC, since PV generators and AC wiring usually contains large conductive loops, where these over-voltages can be induced by nearby lightning strikes.

Table 6. Protections of tested inverters.

4.8 Other aspects

Obviously, inverters must avoid electromagnetic interference (EMI) and ensure a correct operation of AC loads. The presence of radiated EMI has been detected with some PWM inverters, especially at high power levels, whose worst effects have been appreciated in PC monitors and AM radios situated in the surroundings (< 2 m). Regarding the conducted EMI, we detected a background buzz when powering HI-FI equipment with some non sinusoidal inverters. Flicker (visual effects produced by the changes of emitted light from lamps as a result of fluctuations in the output AC voltage) has been detected in only one inverter (I1) when the input voltage exceeds 13,5 V. Therefore, provisions against EMI must be taken in PV system specifications.

As mentioned in the introduction, the analysis of user protection against electric shock will appear in future work. However, we have considered that so-called Residual Current Devices, or RCDs, are at the core of most practical protective schemes. For example, the vast majority of conventional household electrical installations (most probably, the reader’s home) simply rely on a combination of an RCD and a protective earthed conductor as the basic safety measures. Because of this, we have tested whether inverters with different voltage waveforms are able to activate an RCD placed at the AC inverter output in the event of an insulation fault. Fortunately, all inverters have passed this test. Thus, protective measures considered in grid electricity standards (IEC 60364, for example) can also be applied in the case of PV systems including inverters.

5. CONCLUSIONS

DC/AC inverter features have been reviewed from a PV systems perspective, with a view to contributing to possible codes, procurement specifications and testing procedures, in order to assure the technical quality of the concerned PV systems.

A representative set of sixteen commercial inverters has been tested in depth, in combination with most common appliances found in current PV systems. Testing procedures have been developed under consideration that they could be applied not only in specialized laboratories in industrialized countries, but also in conventional laboratories in developing countries.

This testing campaign has confirmed that inverter technology is currently at a high degree of maturity, especially in terms of protection and energy performance. However, it is worth mentioning that the tests carried out can only detect early inverter failures, and also, that current long-term reliability, with mean time to first failure (MTTF) of about five years[36], is still low and should be improved in the future.

Finally, the testing campaign has also revealed that significant technical deficiencies are sometimes found in current inverters. Particularly important is the lack of protection against battery over-discharge, and AC output unregulated voltages. Thus, specific attention should be paid to the inverter when drawing up PV system specifications.

Acknowledgements

This work has been supported in part by contract JOR3-CT97-0275 ("*Certification and Standardisation Issues for a Sustainable PV Market in Developing Countries*") in the framework of the JOULE II programme. The authors would like also to thank the review and suggestions made by Professor Fernando Yeves.

References

1. W. P. Hirshman. Electrifying surprise in Thailand. *Photon International* 2003; **7**: 46.
2. ANEEL. *Sistemas Individuais de Geração de Energia Elétrica com Fontes Intermitentes – SIGFI.* Audiência Pública nº 012/2004. ANEEL (Agência Nacional de Energia Elétrica). www.aneel.gov.br. 2004.
3. R. H. Bonn, J. Ginn, S. Gonzalez. *Stand-Alone Generic Test Plan*. Sandia National Laboratories. 1998.
4. R. H. Bonn, J. Ginn. *Standard evaluation plan for hybrid photovoltaic inverters*. Sandia National Laboratories. 1997.
5. F. Chenlo, N. Martín. *Testing procedures and acceptance criteria for stand-alone photovoltaic inverters*. Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, CIEMAT. 1995.
6. *Universal Technical Standard for Solar Home Systems*. Thermie B SUP 995-96. EC-DGXVII. 1998.

7. E. Caamaño-Martín, E. Lorenzo, C. Lastres. Crystalline silicon photovoltaic modules: characterization in the field of rural electrification. *Progress in Photovoltaics: Research and Applications.* 2002; **10**: 481-493
8. L. Narvarte, J. Muñoz, E. Lorenzo. Testing of fluorescent DC lamps for Solar Home Systems. *Progress in Photovoltaics: Research and Applications*. 2001; **9**: 475-489.
9. P. Díaz, E. Lorenzo. Solar Home System battery and charge regulator testing. *Progress in Photovoltaics: Research and Applications*. 2001; **9**: 363-377.
10. ISO/IEC 17025. *General requirements for the competence of testing and calibration laboratories*. 1999.
11. IEC Standard 60364. *Electrical Installations of buildings. Part 4: Protection for safety. Chapter 41: Protection against electric shock*. 2001.
12. IEEE Standard 1515-2000. *IEEE Recommended Practice for Electronic Power Subsystems: Parameter Definitions, Test Conditions, and Test Methods*. 2000.
13. GEF/World Bank-Assisted China PV project. *Solar photovoltaic systems and photovoltaic/wind hybrid systems specifications and qualifying requirements*. The World Bank. 1999.
14. G. H. Atmaram, J. D. Roland. *Training Manual for Quality Improvement of Photovoltaic Testing Laboratories in Developing Countries.* Chapter 5. Test Procedures for Photovoltaic Inverters, DC Fluorescent Lights, and PV Systems. Quality Program for Photovoltaics (QuaP-PV). The World Bank. 2001.
15. EN Standard 50160. *Voltage characteristics of electricity supplied by public distribution systems*. 1999.

16. IEC Standard 61000-2-2. *Electromagnetic compatibility (EMC) - Part 2-2: Environment - Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems*. 2002.
17. ANSI Standard C84.1-1989. *Electric Power Systems and Equipment Voltage Ratings (60 Hz)*. 1989.
18. IEC Standard 61000-3-2. *Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current ≤ 16A per phase)*. 2001.
19. IEEE Standard 519-1992. *IEEE recommended practices and requirements for harmonic control in electrical power systems*. 1992.
20. R. Bonn, J. Ginn. *Static inverter handles nonlinear loads*. BOS testing brief. Sandia National Laboratories. 1995.
21. M.A. Barros, J.T. Pinho. Análise do desempenho de inversores de pequeño porte con diferentes formas de onda. AGRENER 2002. *4º Encontro de Energia No Meio Rural*. Sao Paulo. 2002.
22. ANSI/IEEE Standard 936-1987. *IEEE Guide for Self-Commutated Converters*. Appendix A. Harmonics in converters. 1987.
23. J. P. Dunlop, B. N. Farhi. Recommendations for maximizing battery life in photovoltaic systems: a review of lessons learned. *Proceedings of Forum 2001 Solar Energy: The Power to Choose*. Washington. 2001.
24. W. Bower. Inverters – Critical Photovoltaic Balance-of-system Components: Status, Issues, and New-Millennium Opportunities. *Progress in Photovoltaics: Research and Applications*. 2000; **8**: 113-126.

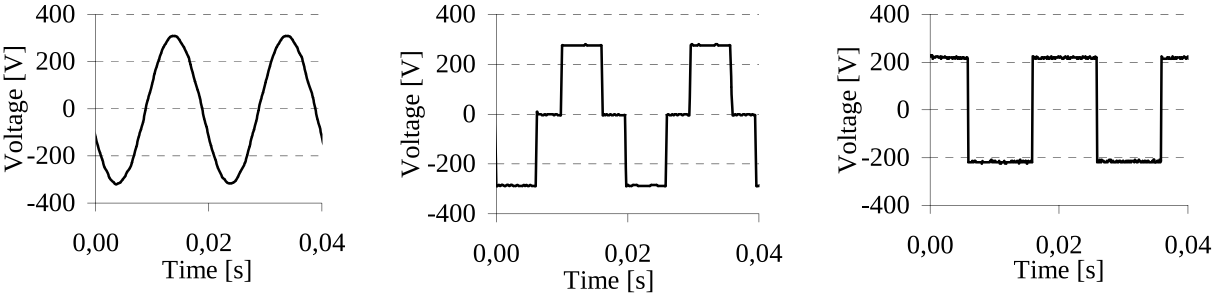
25. J. Wiles. *Photovoltaic Power Systems and the National Electrical Code: Suggested practices*. Sandia Report SAND2001-0674. Sandia National Laboratories. 2001.
26. A.J. Ruddell, A.G. Dutton, H. Wenzl, C. Ropeter, D.U. Sauer, J. Merten, C. Orfanogiannis, J.W. Twidell, P. Vezin. Analysis of battery current microcycles in autonomous renewable energy systems. *Journal of Power Sources* 2002; **112**: 531–546.
27. C. Protogeropoulos, J. Nikoletatos. Examination of ripple current effects on lead-acid battery ageing and technical and economical comparison between 'solar' and SLI batteries. *14th European Solar Energy Conference*. Barcelona. 1997.
28. IEC Standard 61683. *Photovoltaic systems - Power conditioners - Procedure for measuring efficiency*. 1999.
29. W. Durisch, S. Leutenegger, D. Tille. Comparison of small inverters for grid-independent photovoltaic systems. *Renewable Energy* 1998; **15**: 585-589.
30. R. Bonn, J. Ginn. *Motor starting using PV inverters*. BOS testing brief. Sandia National Laboratories. 1995.
31. W. Bower, S Philips, F. Schalles. Performance and characteristics of inverters in remote and stand-alone applications. *20th IEEE Photovoltaic Specialist Conference*. 1988.
32. J. Ginn, R. H. Bonn, G. Sittler. *Inverter Testing at Sandia National Laboratories*. Sandia National Laboratories. 1998.
33. N. M. Chivelet, F. Chenlo, M.C. Alonso. Analysis and modelling of DC/AC inverters with resistive and reactive loads for stand-alone PV systems. *12th European Photovoltaic Solar Energy Conference*. Amsterdam. 1994.

34. W. Durisch, D. Tille. Testing of small sinusoidal-inverters for photovoltaic stand-alone systems. *Applied Energy* 1999; **64**: 417-426.

35. M. Jantsch, H. Schmidt, J. Schmid. Results of the concerted action on power conditioning and control. *11th European Photovoltaic Solar Energy Conference. Montreux*. 1992.

36. R. West, K. Mauch, Yu Chin Qin, N. Mohan, R. Bonn. *Status and Needs of Power Electronics for Photovoltaic Inverters.* Report SAND2002-1535. Sandia National Laboratories. 2002.

LIST OF FIGURES



(a) (b) (c)

Figure 1. Voltage waveforms of different inverters found at the current PV market. (a) Sinusoidal. (b) Quasi-square. (c) Square.

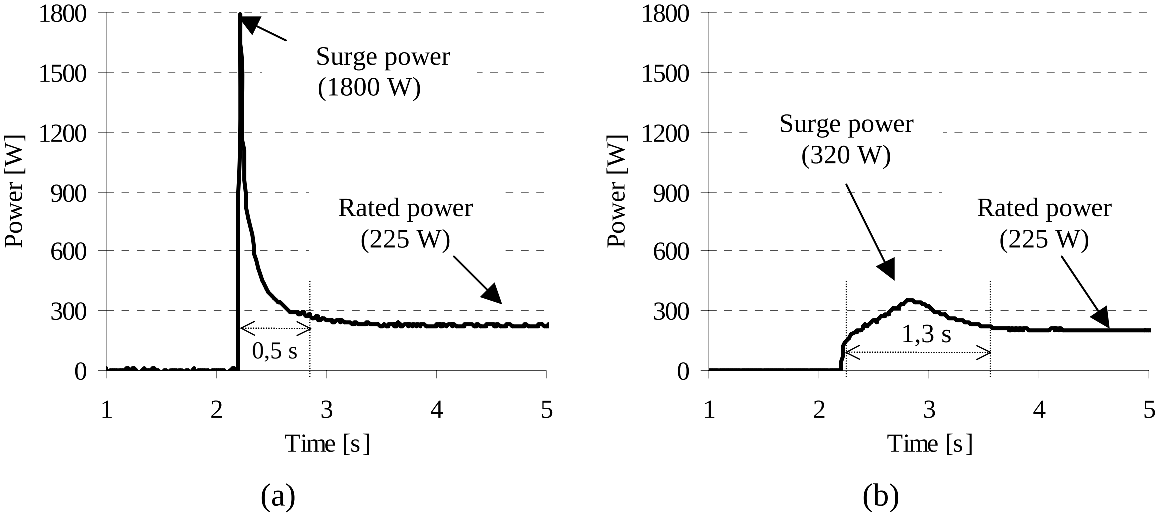
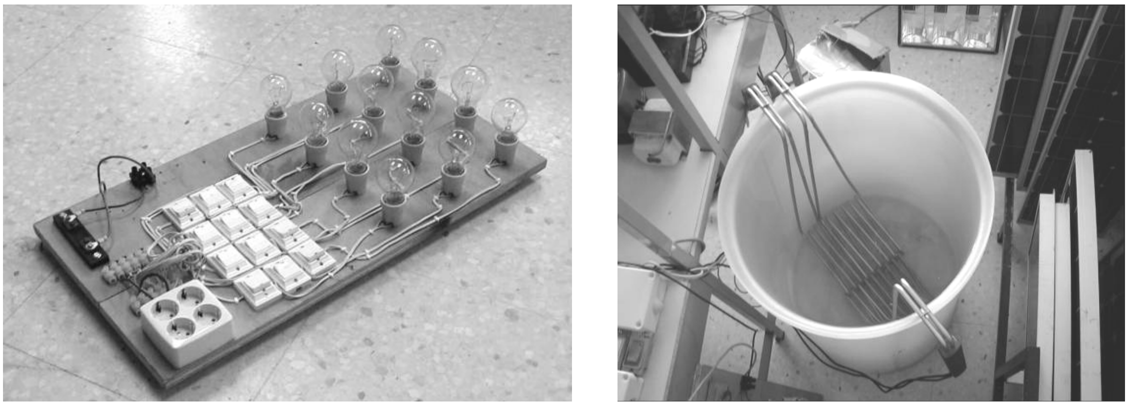
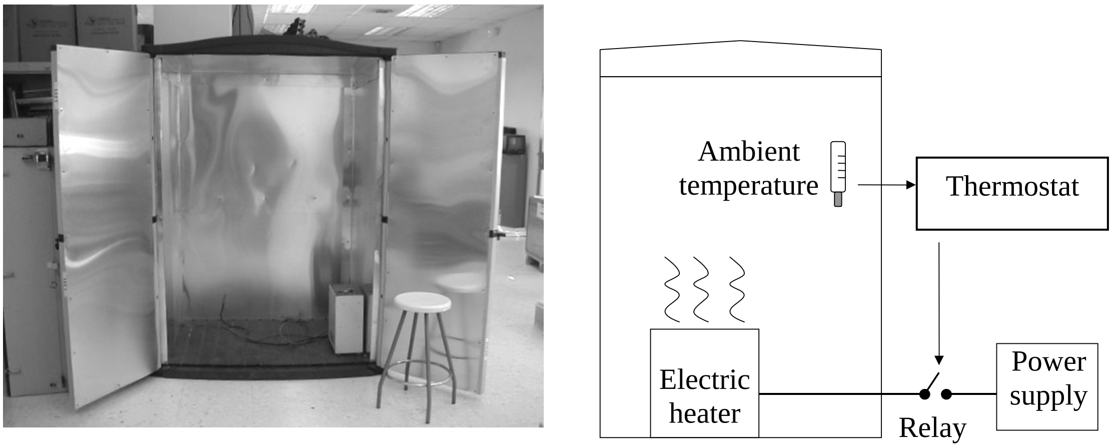


Figure 2. Starting of a domestic electric drill (induction motor) operated on (a) the grid, (b) an inverter.



(a) (b)

Figure 3. Resistive loads used for inverter testing. (a) Incandescent lamps (up to 1 kW) (b) Water heaters (up to 15 kW).



(a)

(b)

Figure 4. (a) Climatic chamber. (b) Ambient temperature control.

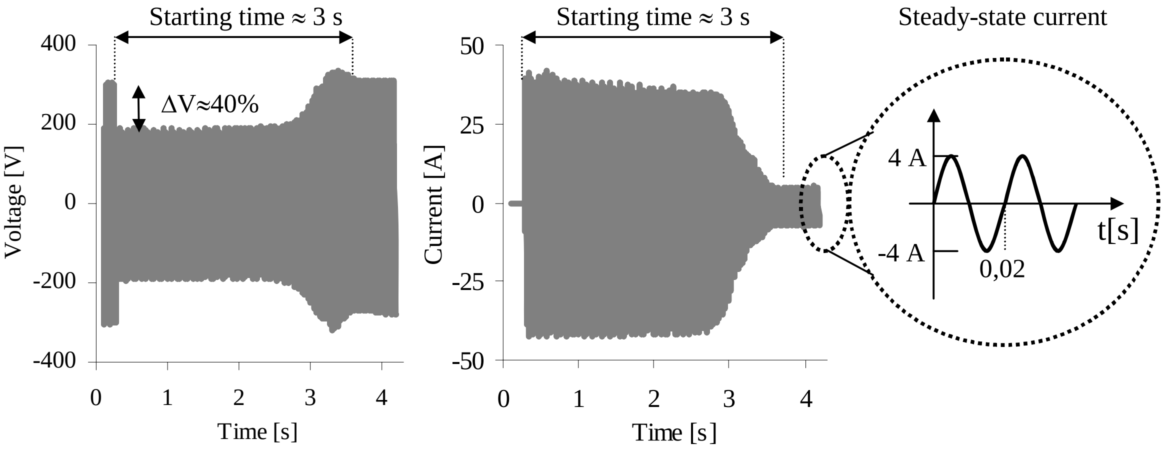
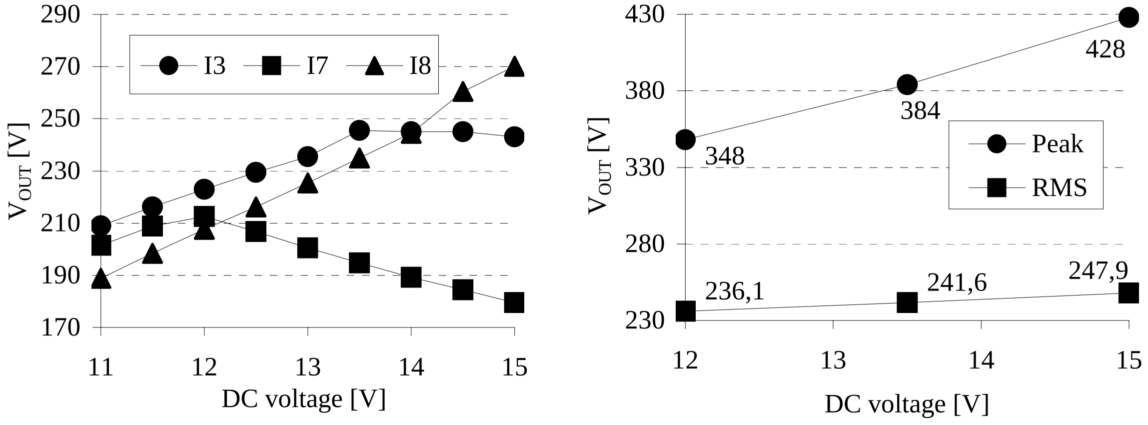


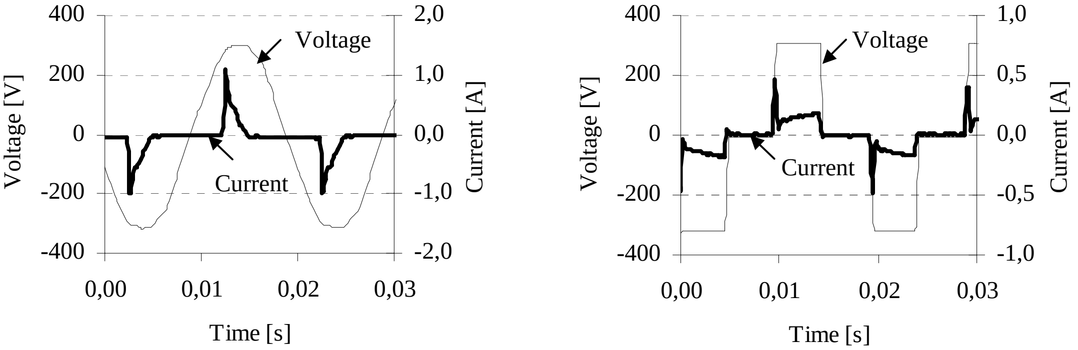
Figure 5. Voltage and current evolution at inverter I12 output during the starting of a motor. For about 3 seconds, the voltage drop reaches 40%.



(a)

(b)

Figure 6. (a) RMS output voltage versus DC input voltage for three different tested inverters operating at a fixed resistive load. (b) AC output voltage (RMS and peak values) of inverter I9 versus DC input voltage operating at a fixed resistive load.

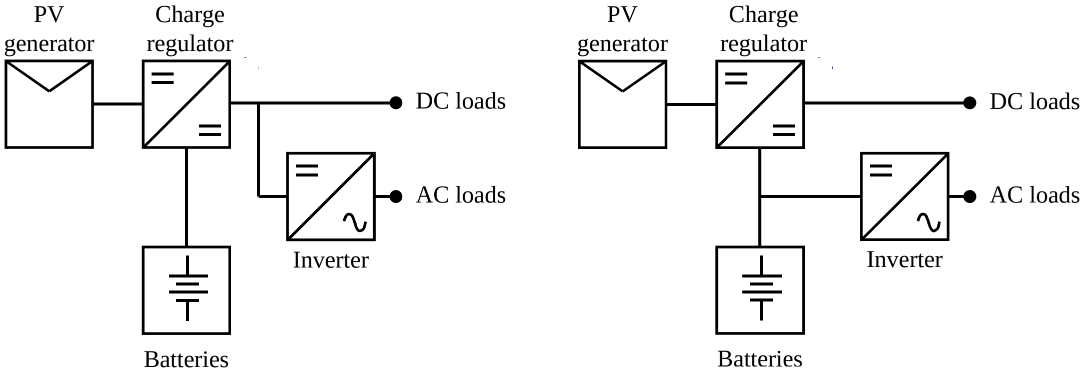


THD_I=130% (THD_V=3,6%)
PF=0,56

THD_I=75% (THD_V=48,9%)
PF=0,86

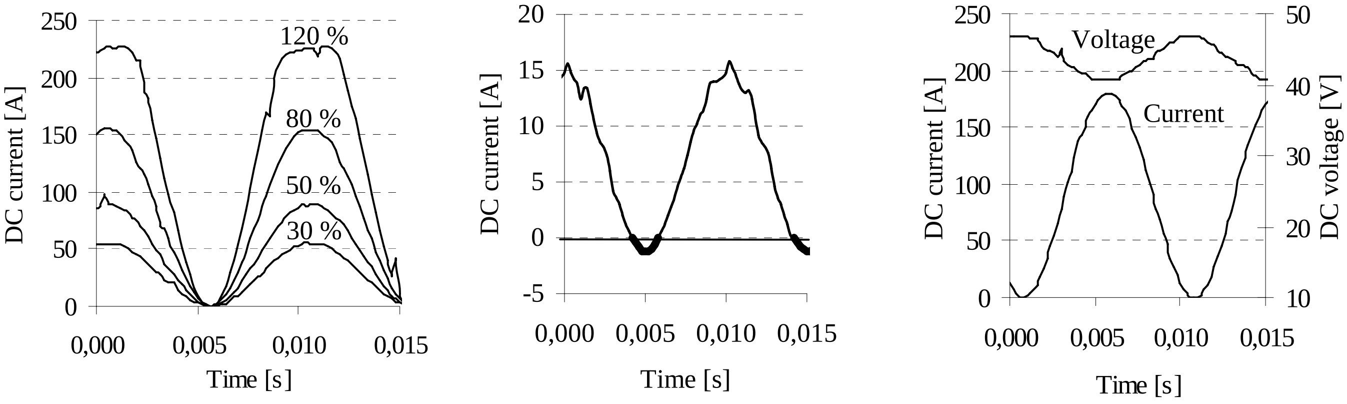
(a) (b)

Figure 7. Current and voltage waveforms of a colour TV powered by (a) the grid (b) the inverter I1.



(a) (b)

Figure 8. Connection between the inverter and the PV system. (a) To the load output of the charge regulator. (b) Directly to batteries.



(a) (b) (c)

Figure 9. (a) DC current waveforms of inverter I12 supplying a resistive AC load at different power levels, expressed as a percentage of the rated inverter power. (b) DC current waveform of inverter I4 supplying an inductive load (electric fan). (c) DC current and voltage waveforms of inverter I12 supplying a resistive load at 90% of its rated power.

LIST OF TABLES

Inverter	Manufacturer (Country)	Model	Nominal DC voltage [V]	Rated power [VA]	Output voltage waveform	Voltage elevation topology
I1	Samlex (Netherlands)	SI -140 HP	12	140	QS	HF
I2	Atersa (Spain)	CP-150	24	150	SQ	LF
I3	ASP (Switzerland)	Piccolo 12 150W	12	150	SW	LF
I4	Studer (Switzerland)	Joker J201	12	200	SW	LF
I5	Conver (Spain)	CPS – 200	12	200	QS	LF
I6	Solener (Spain)	Solener –250W/12V	12	250	QS	LF
I7	HT (Argentina)	Inv-12/220-600-CBT	12	450	QS	LF
I8	HT (Argentina)	Invsol-12/600-CBT	12	500	QS	LF
I9	Unitek (Taiwan)	Unitek G-12-060	12	500	QS	HF
I10	Fronius (Austria)	Solarix 900 I	24	900	SW	LF
I11	Isofoton (Spain)	Isoverter 1.2	24	1200	SW	LF
I12	Mastervolt (Netherlands)	Dakar Combi 48/5000	48	4000	SW	LF
I13	Mastervolt (Netherlands)	Dakar Combi 48/5000	48	4000	SW	LF
I14	Enertron (Spain)	Oasis	120	8000	SW	LF
I15	Enertron (Spain)	Oasis	120	8000	SW	LF
I16	Ecotecnia (Spain)	Ciclops	120	10000	SW (3-phase)	LF
Output voltage waveform: sine wave (SW), quasi-square (QS) and square (SQ). Voltage elevation topology: high-frequency (HF) and low-frequency (LF).						

Table 1. Main characteristics of the tested inverters.

Load type	**Measured with the grid**	
	Rated power	**PF**
Linear loads		
- Incandescent lamps	25-1000 W	1
- Fluorescent lamps (electromagnetic ballasts)	30-80 VA	0,33-0,42
- Induction coil	600 VA	0,15
- Resistors (water heaters)	1-15 kW	1
Non-linear loads		
- TV	60 VA	0,60
- Video	34 VA	0,46
- Computer (CPU + display)	190 VA	0,63
- Fluorescent lamps (electronic ballasts)	20-50 VA	0,43-0,57
- Hair-dryer (half-wave operation)	830 VA	0,70
- Stereo system (CD and radio)	8 VA	0,82
Motors		
- Electric fan	97 VA	0,73
- Electric drill	230 VA(1)	0,98
- Water pump	940 VA(1)	0,34
- Grain mill	973 VA(1)	0,77
- Fridge	390 VA	0,74
(1) Unloaded. Starting tests are usually carried out under this operating condition.		

Table 2. Electrical characteristics of the AC loads used for inverter testing.

Inverter	**V_{OUT}**			**f_{OUT}**	
	Vo [V]	**+ΔV [%]**	**-ΔV [%]**	**fo [Hz]**	**± Δf [%]**
I1	218,6	2,4	3,0	50	3,10
I2	230,3	8,5	2,9	50	--
I3	224,8	9,2	7,0	50	0,48
I4	223,7	2,3	2,2	50	0,06
I5	219,0	3,7	4,6	50	0,68
I6	219,1	5,4	8,8	50	0,26
I7	205,0	8,9	12,4	50	1,30
I8	217,6	24,1	22,8	50	--
I9	233,4	6,2	1,6	50	0,90
I10	227,5	6,0	11,8	50	0,10
I11	234,8	0,8	0,5	50	0,12
I12	222,0	2,7	3,9	50	0,06
I13	227,2	1,1	3,1	50	0,14
I14	235,1	0,2	2,7	50	0,02
I15	231,6	0,2	0,2	50	0,02
I16	227,0	0,7	3,1	50	0,20

Table 3. Voltage and frequency regulation of the tested inverters. DC input voltage varies from 11 to 15 V; meanwhile load power varies from zero to the inverter rated power.

Inverter	LVD	LVR	HVD	HVR	Legend
I1	10,1	MA	15,0	14,7	LVD Low-voltage disconnection. LVR Low-voltage reconnection. HVD High-voltage disconnection. HVR High-voltage reconnection. MA The inverter must be manually switched OFF/ON by the user. ND The inverter does not disconnect. AT Adjustable thresholds.
I2	ND	NA	ND	--	
I3	9,6	12,4	15,8	15,6	
I4	10,5	10,5	16,3	MA	
I5	ND	NA	ND	--	
I6	10,5	12,2	15,9	MA	
I7	10,5	10,5	ND	--	
I8	10,0	MA	15,7	MA	
I9	10,1	MA	ND	--	
I10	11,0	MA	ND	--	
I11	11,7	13,2	16,0	13,8	
I12	10,0	11,0	15,5	15,2	
I13	10,0	11,0	15,5	15,2	
I14	AT	AT	AT	AT	
I15	AT	AT	AT	AT	
I16	AT	AT	ND	--	

Table 4. Voltage disconnection and reconnection threshold (12 V reference) of the aforementioned tested inverters.

Inverter	**(a) η_C [%]**		**(b) No-load loss [W]**		**(c) Model parameters**		
	Maximum @ power level [%]	**At rated power**	**Normal operation**	**Stand-by mode**	**k_0**	**k_1**	**k_2**
I1	87,3 @ 48	86,1	1,9	-	0,014	0,089	0,059
I2	82,5 @ 53	79,7	7,9	-	0,053	0,011	0,192
I3	86,3 @ 20	72,1	2,0	-	0,014	0,020	0,354
I4	88,1 @ 14	67,9	1,8	-	0,009	0,006	0,458
I5	91,6 @ 16	77,9	1,4	-	0,007	0,003	0,273
I6	87,0 @ 30	80,4	4,1	-	0,016	0,039	0,188
I7	87,1 @ 27	78,3	7,9	0,8	0,018	0,017	0,243
I8	87,0 @ 17	68,2	6,0	0,5	0,012	0,002	0,452
I9	88,4 @ 34	82,4	11,3	-	0,023	0,001	0,190
I10	90,4 @ 25	83,4	9,5	2,4	0,011	0,022	0,168
I11	92,9 @ 43	91,6	10,2	2,2	0,008	0,037	0,046
I12	91,1 @ 25	85,0	37,1	5,1	0,009	0,025	0,144
I13	92,6 @ 28	87,4	39,5	6,8	0,010	0,010	0,124
I14	87,7 @ 70	87,1	294,5	14,8	0,037	0,033	0,078
I15(1)	76,2 @ 45	73,2	287,2	14,3	0,036	0,153	0,177
I16(2)	95,4 @ 26	91,2	62,5	-	0,006	0,002	0,089
I16(3)	92,0 @ 17	90,5	62,5	-	0,006	0,011	0,228

[1] Tested with 96V batteries (nominal DC voltage=120V)

[2] Balanced resistive loads.

[3] Only one phase loaded.

Table 5. (a) Average conversion factors of the tested inverters with resistive loads. Average refers to input voltages between 11 and 14 V. Values are given at rated power and also for the power level corresponding to the maximum. (b) No-load loss of tested inverters. Values are given for normal operation and also for stand-by mode, and at nominal DC voltage. (c) Model parameters k_0, k_1 and k_2.

Inverter	**Protections**				**Legend**
	OL	**SC**	**PSD**	**IRP**	
I1	Yes	Yes	Yes	Yes	OL Overload. SC Short-circuit. PSD Power supply disconnection. IRP Input reverse polarity. Yes Inverter succeeding the test. **No** Inverter failing the test. NT Not tested. NP Not protected according to manufacturer's specification.
I2	Yes	Yes	Yes	NP	
I3	Yes	Yes	Yes	Yes	
I4	Yes	Yes	Yes	Yes	
I5	Yes	Yes	Yes	**No**	
I6	Yes	Yes	Yes	Yes	
I7	Yes	Yes	Yes	Yes	
I8	Yes	NT	**No**	Yes	
I9	Yes	**No**	Yes	NP	
I10	Yes	Yes	Yes	Yes	
I11	Yes	Yes	Yes	**No**	
I12	Yes	Yes	NT	NP	
I13	Yes	Yes	NT	NP	
I14	Yes	Yes	NT	NP	
I15	Yes	Yes	NT	NP	
I16	Yes	Yes	NT	NP	

Table 6. Protections of tested inverters.